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GRAND CHALLENGES
CENTENNIAL COLLECTION

Effects of Ecological Restoration Measures on Soil Erosion Risk in the Three Gorges Reservoir Area Since the 1980s

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Key Points:

- The government's restoration programs, and particularly afforestation, have improved the vegetation cover and decreased soil erosion
- The temporal variation factors that controlled soil erosion suggests that effect of vegetation resulting from ecological restoration
- We found that precipitation was most important during Period I (1980 to 1984)

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Abstract Ecosystem degradation accompanied by soil erosion risk is caused by the interaction of many factors, including climate change and human activities. Therefore, before attempting the optimal form of ecological restoration, we must know the key factors responsible for soil erosion risk and determine their impacts on the ecosystem health. To test this approach, we conducted a case study in the Three Gorges Reservoir Area from 1980 to 2015, where extensive restoration (primarily afforestation) has been conducted. The results showed that climate was most important during Period I (1980 to 1984), and explained 84% of the variation in erosion. However, vegetation became equally important during Period II (1985 to 2006), when it accounted for 51% of the variation. Climate became as important as vegetation during Period III (2007 to 2015), when it accounted for 51% of the variation. The temporal variation in the dominant factors that controlled soil erosion risk suggests that the ecological effect of vegetation improvement resulting from ecological restoration in Three Gorges Reservoir Area has been gradually enhanced since the 1980s.

1. Introduction

Ecosystem degradation is causing major environmental problems around the world, including soil erosion and desertification. Ecological degradation affects 36×10^6 km^2 of land around the world, which amounts to 25% of the total land area, leading to a direct economic loss as high as US\$850 $\times 10^9$ annually (Liu & Diamond, 2008). Ecosystem degradation is particularly serious in China, where the area of degraded ecosystems accounts for one third of the total land area. As a result, the livelihood of 400×10^6 people is threatened, and 12×10^6 people have been plunged into poverty, accounting for 28.5% of China's impoverished population (Lusiana et al., 2012).

In China's Three Gorges Reservoir area, the landforms (many hills and sloping land) and human activities have contributed to increasingly serious ecosystem degradation and loss of arable land. However, as part of the reservoir construction activities, large-scale ecological restoration projects have been carried out to protect the soils surrounding the reservoir against erosion and reduce siltation of the reservoir (Chen et al., 2020). Because this is a key vulnerable ecological area that lies between the middle and lower reaches of the Yangtze River, its ecosystem health directly affects the comprehensive benefits provided by the Three Gorges Project and the ecological security of the middle and lower reaches of the Yangtze River (Xiao et al., 2017). Thus, determining the optimal form of ecological restoration to permit sustainable development of the region's resources, including recycling and improved utilization of these resources, is essential for successful development (Gou et al., 2020).

Ecosystem degradation in the reservoir area results from interactions among many natural and human factors. Landforms, climate change, and human activities all strongly influence vegetation change, and changes in the vegetation, in turn, affect the climate and human activities (Leman et al., 2016). Some natural science researchers believe that the predicted climate change will degrade ecosystems by adversely affecting the soil quality, vegetation cover, biodiversity, and hydrologic cycle. However, few studies have quantified the simultaneous effects of the interaction among multiple factors (both natural and human) based on long-term monitoring data (Valero et al., 2014). This is particularly problematic because of the importance of human

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factors; methods and data from the social sciences have not been combined with those from the natural sciences, thereby weakening the foundation for environmental management and making it difficult to improve environmental protection (Sun, Miao, AghaKouchak, et al., 2019).

Before the creation of the Three Gorges Reservoir, the region's ecosystem health was already under considerable stress from a combination of climatic factors (e.g., drought) and human activities (e.g., unsustainable agriculture in sloping land). Moreover, the regional characteristics (e.g., topography, climate) combined with changes in the region's natural environment caused by the reservoir construction, population growth, and increased pollution due to socioeconomic development, make the region's inherently fragile ecosystem become more complex and fragile due to the impacts of these external influences. To counteract these problems, China's government has invested more than US$3.22 $\times 10^9$ to carry out large-scale afforestation activities since the 1980s. It has consecutively implemented the Yangtze River Basin Shelter Forest Project, Natural Forest Protection Project, Grain for Green Program, Afforestation Project on Both Sides of the Yangtze River, and other key ecological projects. It has also established a preliminary ecological security system with the establishment of forests as the primary component, and with a combination of shrub and grassland planting as an additional component. However, few studies have quantified the effects of these ecological projects and of the ecological policy on soil erosion risk (Cao et al., 2014). Furthermore, the simultaneous effects of climate change and the Three Gorges Project on the regional climate and ecosystems make it difficult to distinguish the impacts of climate change from those of the Three Gorges Project itself (Zhao et al., 2014). Because of the huge area affected by the Three Gorges Project and its long existence, the environmental impact should be assessed on large spatial and temporal scales to adequately describe the project's impacts. Most notably, the reservoir has severely reduced flows of water into downstream regions, creating persistent drought in the lower reaches of the Yangtze River in Hubei, Hunan, Jiangxi, and Zhejiang provinces (Xiao & Xiao, 2018). The lack of water has destroyed 3×10^6 ha of farmland and has left millions of people and livestock short of water (Liu & Yang, 2012).

If we can understand how natural and human factors interact to produce degraded ecosystems in TGRA, we can manage these ecosystems in ways that permit optimal ecological restoration (Loizeau et al., 2018). To do this, we must first identify the key driving forces responsible for degradation and restoration and quantify their impacts on ecosystem health. Ecological restoration can only be successful if it accounts for both the ecological environment (e.g., climate, topography) and the productive and living behaviors of the inhabitants of the degraded area. Accounting for both natural and human factors can avoid the shortcomings of traditional projects, which neglect human factors, and thereby improve the effectiveness of ecological protection. The goal of the present study was to account for ecological factors, as well as human activities, that lead to ecosystem health changes. This knowledge can be used to support the development of effective restoration strategies based on improved utilization of soil and water resources and can thereby reduce the impacts of soil erosion risk on the ecological environment.

2. Study Area and Methods

2.1. Study Area

The Three Gorges Reservoir area is located between Chongqing City and Hubei Province and covers a total area of 57,802 km^2 that is home to a total population of nearly 20 million people. This area includes 26 cities and counties, most of which are rugged terrain (Figure 1). About 74.0% of the area is mountainous, 21.7% is hilly, and only 4.3% is plains (Bao et al., 2018). The elevation is high in the east and low in the west. The dominant soil types are Ultlsols based on USDA soil taxonomy (Xiao et al., 2019). The region has a subtropical monsoon climate. The mean annual precipitation reaches ~1,100 mm. And, for most of the year, it experiences humid conditions with an annual mean temperature of 17–19°C.

The Three Gorges Reservoir has strongly affected the Yangtze River Basin, both because the Yangtze River Basin is the largest river basin in the world and because the Three Gorges Dam is the largest hydropower project in the world (Jiang et al., 2018). The dam's construction occurred from 1993 to 2009, with a total reservoir capacity of 39.3×10^9 m^3. In the 16 years before 2009, 1.25 million people were displaced by this project as the reservoir inundated 245 km^2 of farmland and orchards, about 35 km^2 of residential areas, and 824 km of roads. The construction resulted in wide-scale land use/land cover (LULC) change and climatic change that are expected to change regional soil conservation patterns.

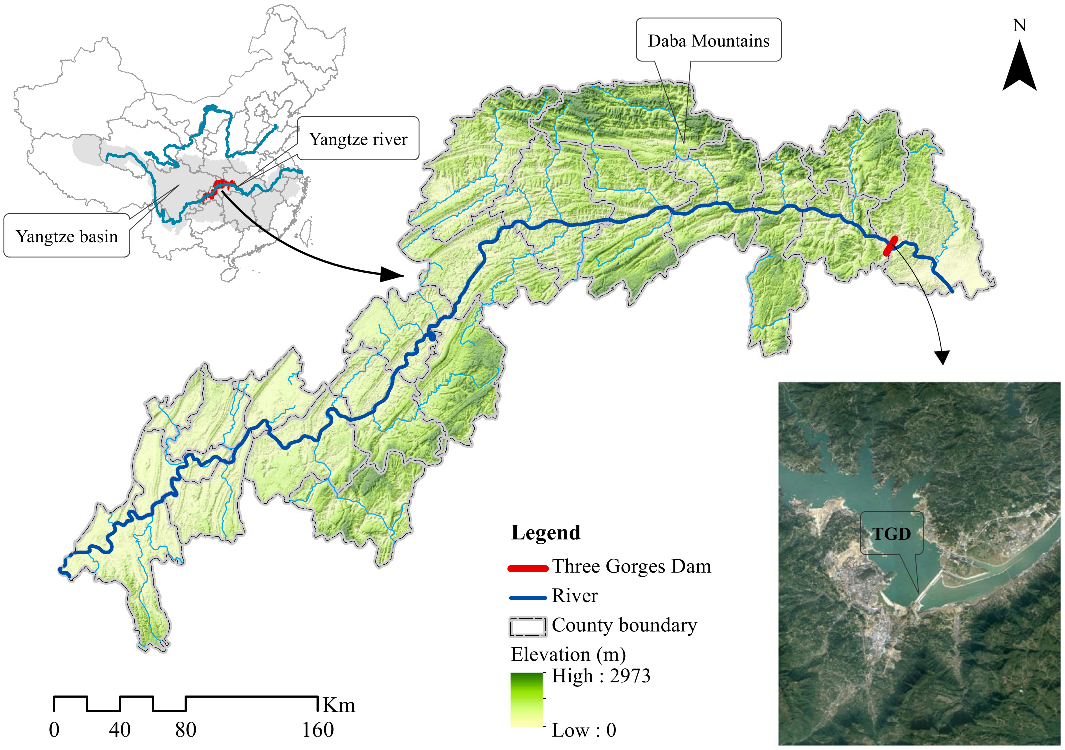

Figure 1. The location of the Three Gorges Reservoir area in China (TGD: Three Gorges Dam).

2.2. Data Sources

Because of the long time span of our study and its large area, we used Landsat images of the reservoir area with a spatial resolution of 60 m (MSS) and 30 m (TM/OLI) from 1980 (MSS), 1990 (TM), 2000 (TM), 2005 (TM), 2010 (TM), and 2015 (OLI) to extract LULC data. We selected these images according to their availability and the quality of the data set. We used version 9.3 of ArcInfo (https://www.esri.com) to superimpose images from two consecutive years to identify changes in LULC. Comparing areas with ground-based data (387 samples), the overall accuracy of LULC maps were above 89.1% for the five periods concerned. The Vegetation Cover date set from 1982 to 2015 was calculated by mixed pixel decomposition model (Ivits et al., 2013) based on the Global Inventory Modeling and Mapping Studies (GIMMS) Normalized Difference Vegetation Index (NDVI) (https://ecocast.arc.nasa.gov).

We obtained meteorological data from the China National Meteorological Information Center (http://data.cma.cn) (precipitation and temperature) and interpolated to raster data with a resolution of 0.05° by kriging method (Xiao & Xiao, 2019). Soil maps and related soil properties were obtained from the second national soil survey conducted by the Institute of Soil Science, Chinese Academy of Sciences, with a scale of 1:1000000 (http://www.issas.cas.cn). We derived a digital elevation map of the study area from the data set produced by the Terra satellite's Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER), with a resolution of 30 m (http://www.gscloud.cn). All cartographic raster data were converted to the same Albers coordinate system and spatial resolution of 100 m.

2.3. Methods

2.3.1. Model Description

Because soil erosion by water is the main cause of ecosystem degradation in the study area, excessive soil erosion and sediment deposition will both damage local ecosystems and gradually decrease the reservoir's hydroelectric power generation, and will also cause structural damage to the Three Gorges Dam. To estimate the magnitude of the annual soil erosion in the study area, we used the universal soil loss equation:

$$SE_a = R \times K \times LS \times C \times P \tag{1}$$

where SE_a represents the annual soil loss under the current LULC conditions (t ha^{-1} yr^{-1}); R is the rainfall erosion coefficient (MJ mm ha^{-1} hr^{-1} yr^{-1}); K is the soil erodibility factor (t ha hr ha^{-1} MJ^{-1} mm^{-1}); LS is a dimensionless topographic factor; C is a dimensionless vegetation cover factor; and P is a dimensionless conservation practice factor. We will describe the calculation of these variables in the rest of this section.

2.3.1.1. Rainfall Erosivity Factor (*R*)

We calculated R from 1980 to 2015 using the proposed formula based on monthly rainfall (Fu et al., 2011):

$$R = \Sigma 1.735 \times 10^{1.5\log\left(Pi^2/P\right)-0.818} \tag{2}$$

where P_i is the total rainfall (mm) in month i and P is the total annual rainfall (mm).

2.3.1.2. Soil Erodibility Factor (*K*)

Soil erodibility describes the vulnerability of soil particles to being mobilized by raindrops and surface runoff. We used the Erosion/Productivity Impact Calculator (EPIC) formula to calculate K. To make the equation applicable to the nature of the Chinese soils in the study area, we used the following parameterization:

$$\begin{aligned} K_{\text{EPIC}} = {} & \{0.2 + 0.3\exp[-0.0256 m_{\text{sand}}(1 - m_{\text{silt}}/100)]\} \times \left[m_{\text{silt}}/\left(m_{\text{clay}} + m_{\text{silt}}\right)\right]^{0.3} \times \{1 - 0.25 orgC/[orgC \\ & + \exp(3.72 - 2.95 orgC)]\} \times \{1 - 0.7(1 - m_{\text{sand}}/100)/\{(1 - m_{\text{sand}}/100) + \exp[-5.51 + 22.9(1 - m_{\text{sand}}/100)]\}\} \end{aligned} \tag{3}$$

$$K = \left(-0.01383 + 0.51575 K_{\text{EPIC}}\right) \times 0.1317 \tag{4}$$

where K_{EPIC} and K are soil erodibility factors (t ha hr $\text{ha}^{-1}\text{MJ}^{-1}\text{mm}^{-1}$) before and after revision, respectively; and m_{sand}, m_{silt}, m_{clay}, and $orgC$ are the percentages of sand, silt, clay, and organic carbon, respectively.

2.3.1.3. Topographic Factors (*LS*)

Topographic factors reflect the effects of slope length (L) and steepness (S) on soil erosion. We calculated the LS factor using improved L and S equations and an Arc Macro Language (AML) script in ArcGIS. The equations are as follows:

$$L = (\lambda/22.13)^m \tag{5}$$

$$m = \beta/(1+\beta) \tag{6}$$

$$\beta = (\sin\theta/0.089)/\left(3.0\sin\theta^{0.8} + 0.56\right) \tag{7}$$

$$S = \begin{cases} 10.8\sin\theta + 0.03 & \theta < 5.14^\circ \\ 16.8\sin\theta - 0.5 & 5.14^\circ \le \theta < 10.20^\circ \\ 21.91\sin\theta - 0.96 & 10.20^\circ \le \theta < 28.81^\circ \\ 9.5988 & \theta > 28.81^\circ \end{cases} \tag{8}$$

where LS is a dimensionless topographic factor, L is a dimensionless slope length factor; S is a dimensionless slope steepness factor that depends on the slope gradient θ (°); λ is the slope length (m); and m is the slope length index, which also depends on θ.

2.3.1.4. Vegetation Cover Factor (*C*)

Soil erosion has a negative exponential relationship with vegetation cover, which therefore plays an important role in controlling soil erosion. We determined the value of C for our study area using a look-up table based on vegetation cover and LULC (Table 1).

2.3.1.5. Erosion Control Practices Factor (*P*)

Based on previous research (Fu et al., 2011), in our study area, this factor was only relevant for cultivated farmland. This soil erosion is a key factor in our study area, since about 74% of the land is mountainous and therefore at high risk of erosion. We calculated P as follows:

Table 1
Values of the Vegetation Cover Factor (C) as a Function of Land Use and Cover Types (LULC) and Vegetation Cover (VC)

	C values based on VC (%)					
LULC	<10	10–30	30–50	50–70	70–90	>90
Forest	0.10	0.08	0.06	0.02	0.004	0.001
Shrubs	0.40	0.22	0.14	0.085	0.040	0.011
Grassland	0.45	0.24	0.15	0.09	0.043	0.011
Wetland	0					
Cropland	0.221–0.595logVC					
Built up land	0.01					
Bare land	0.7					

$$P = 0.2 \pm 0.03\,\alpha \tag{9}$$

where α is the slope gradient (°).

Based on the calculations described earlier in this section, Figure 2 shows the spatial distribution of the abovementioned parameters of the universal soil loss equation model that we used in this study.

2.3.2. Model Validation

To verify the regional applicability and reliability of the universal soil loss equation model, we verified our results using observational data from 2000 to 2010, which were obtained from the government's soil and water conservation bulletin (http://slj.cq.gov.cn). The simulated soil erosion agreed well with the observed values (Pearson's $r = 0.810$, $n = 31$, $P < 0.01$). This indicates that the model and its parameters are suitable for simulating soil and water conservation conditions in the study area.

2.3.3. Data Analyses

2.3.3.1. Trend Analyses

To detect changes in the soil erosion trend during the study period (1982 to 2015), we used least squares linear regression to fit the soil erosion variables as a function of time (year) for each pixel. The least squares linear regression method used the following equation (Xiao & Xiao, 2019):

$$y = a + bt + \varepsilon \tag{10}$$

where y represents a given soil erosion variable (SE_a), t is the year, a and b are fitted variables (a is the intercept and b is the slope, which represents the trend), and ε is the residual error. If $b > 0$, soil erosion increases. Conversely, if $b < 0$, erosion decreases. We used the t test to identify significant differences in the trends for the annual erosion time series, with significance defined at $P < 0.05$.

2.3.3.2. Abrupt Changes

We used the Mann-Kendall mutation test to identify abrupt changes in soil erosion (Yue & Wang, 2004). This test assumes that if the forward trend sequence curve UF intersects the backward trend sequence curve UB generated with the reverse data series of UF at a position above the threshold for statistical significance (±1.96), then a statistically significant mutation point exists; on the other hand, if the intersection point lies outside the threshold or if there are many intersections between the lines, then it is impossible to establish a fixed mutation point. In this case, we used the nonparametric Pettitt test to detect mutation points (Pettitt, 1979).

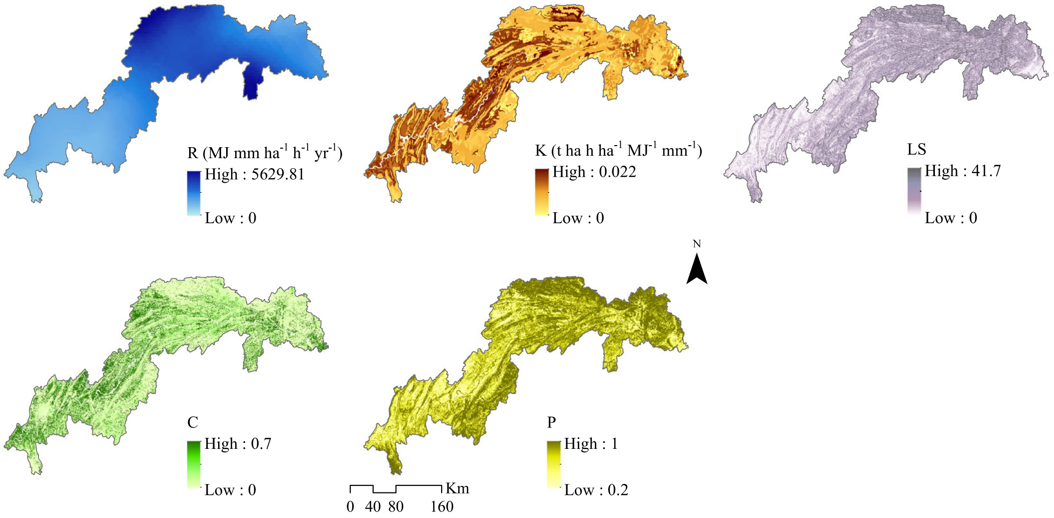

Figure 2. The spatial distribution of the parameters of the universal soil loss equation.

Table 2

Changes in the Areas of Each Land Use and Land Cover (LULC) and in the Corresponding Proportions of the Total Area From1980 to 2015

	1980		1990		2000		2005		2010		2015	
LULC	10^3 km^2	%	10^3 km^2	%	10^3 km^2	%	10^3 km^2	%	10^3 km^2	%	10^3 km^2	%
Forest	23.48	40.25	23.52	40.32	23.63	40.50	24.26	41.58	24.35	41.74	24.89	42.66
Shrubs	10.51	18.02	10.56	18.10	10.67	18.30	10.48	17.96	10.35	17.74	10.22	17.51
Grassland	4.21	7.21	4.23	7.25	4.29	7.36	4.28	7.34	4.25	7.28	4.25	7.28
Wetlands	0.84	1.44	0.84	1.44	0.84	1.44	1.23	2.10	1.46	2.51	1.72	2.96
Cropland	19.12	32.77	18.95	32.48	18.14	31.09	16.88	28.93	15.98	27.40	14.72	25.22
Built up	0.13	0.22	0.19	0.33	0.72	1.24	1.19	2.04	1.93	3.31	2.53	4.34
Bare land	0.05	0.08	0.05	0.08	0.05	0.08	0.02	0.04	0.01	0.02	0.02	0.03
Total	58.34	100.00	58.34	100.00	58.34	100.00	58.34	100.00	58.34	100.00	58.34	100.00

Note. The relative change ratio is calculated based on the following formula: Change ratio = $([\mathrm{LULC}_{2015} - \mathrm{LULC}_{1980}]/\mathrm{LULC}_{1980}) \times 100$.

2.3.3.3. Correlation and Regression

To study the relationship between the soil erosion change and the driving forces, we used Pearson's correlation coefficient (r) and stepwise regression for the relationships to reveal the relative contributions of each factor to the spatial distribution of soil erosion. The statistical unit for more than 700 samples in TGRA was analyzed in the IBM SPSS Statistics 20 (IBM Corp., Armonk, NY, USA), which were created by ArcGIS 10.3 (URL: http://www.esri.com/) fishnet tool according to the maximum resolution (8 km × km) of all data.

3. Results

3.1. LULC Trends

The dominant LULC types in the reservoir area were forest and cropland, which occupied around 40.25% and 32.77% of the land, respectively, in 1980, and 42.66 and 25.22% in 2015, respectively (Table 2). In absolute terms, there was little change in LULC during the study; for example, the area of forest only increased by 2.41 percentage points, and that of cropland changed by only 7.55 percentage points. However, these small percentage changes represented large areas (an increase of 1,404 km^2 for forest and a decrease of 4,405 km^2 for cropland). In addition, the area of built-up land increased to nearly 10 times its 1980 value during the 36-year study period. In relative terms, the area of forest increased by 5.98% during the study period, and the area of grassland increased by 1.00%. The wetland area (including rivers, lakes, and the reservoir) had almost doubled. In contrast, the area of cropland decreased by ~23.04%.

From 1980 to 2015, LULC changed remarkably (Figure 3) in spatial perspective, driven by ecological and developmental policies. Most of the changes occurred in the northeastern and central mountainous areas, For example, 60% of the increase in forest area and 70% of the decrease in cropland area occurred in these areas. Built up and forest areas are the two main LULC types that increased from 1980 to 2015. Almost all of these increases occurred in areas where cultivated land decreased. Cultivated land was the main type of LULC that decreased, with changes in this category accounting for 46.55% of the total change from 1980 to 2015.

3.2. Dynamic Characteristics of Soil Erosion

The total annual soil erosion reached 1.67×10^8 t. This represents an average rate of 28.69 t ha^{-1}. The annual mean soil erosion was highly spatially variable, with the highest values in the northern and northeastern parts of the reservoir area and smaller values in the southwestern part of the study area (Figure 4a). Areas with high soil erosion (>100 t/ha) that suffered heavy soil loss were primarily located near the Daba Mountains in the northeast.

Since 1989, many of the government's afforestation policies have been implemented in the reservoir area, including the Yangtze River Shelter Forest Project, Natural Forest Conservation Project, and Grain for Green Program. Under these programs, a large area of sloping farmland has been transformed into shrub and forest vegetation (above 1,000 km^2). The vegetation cover also increased as a result of the different afforestation programs. As a result of these changes, soil erosion fluctuated but showed a significant overall

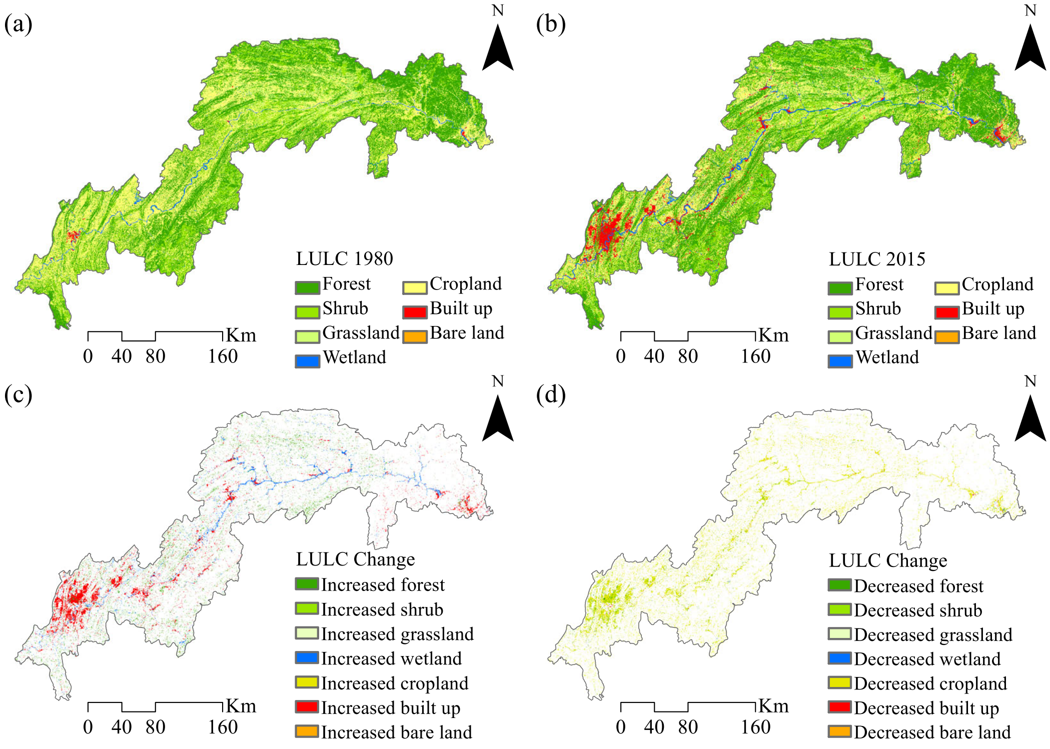

Figure 3. Spatial distribution and changes over time in the land use and land cover (LULC) types from1980 to 2015. Spatial distribution of LULC in 1980 (a) and 2015 (b); Spatial distribution of increases (c) and decreases (d) of a given category of LULC.

decreasing trend from 1980 to 2015, at -3.35×10^6 t yr^{-1}). However, not all regions had a decreasing trend (Figure 4b). The most notable decreases, many of which were statistically significant, occurred near the Daba Mountains in the northern part of the study area. In contrast, soil erosion increased slightly in the southwestern plains and in hilly areas, and some of these increases were also statistically significant.

To evaluate the long-term changes in soil erosion we identified the dates when the Mann-Kendall test revealed abrupt changes. Figure 5a shows three periods with distinctly different trends: 1980 to 1984, 1985 to 2006, and 2007 to 2015. When we separately performed regression analysis for the data from each period (Figure 5b), we found that soil erosion decreased significantly (at a rate of 1.52×10^8 t yr^{-1}, $p < 0.01$) before 1984. Subsequently, soil erosion fluctuated, but with an overall decrease by 0.06×10^8 t yr^{-1}, $p < 0.05$) until 2006. During the last period (2006 to 2015), soil erosion again decreased gradually, at an overall rate of 0.10×10^8 t yr^{-1}, $p < 0.05$).

3.3. Driving Forces for Soil Erosion Changes

The Pearson's correlation analysis results (Table 3) showed that climate and vegetation were the main correlation factor relating the soil erosion change. Moreover, their correlation coefficients changed over time, In Periods 1 and 3, climate significantly affected soil erosion change, especially on precipitation ($r = 0.7$ and 0.52, respectively). However, in Period 2, vegetation significantly affected soil erosion change, especially for on vegetation cover ($r = 0.59$).

In addition, we established statistical model to quantify the impacts of the driving forces in Table 4 on soil erosion using multiple linear regression. In Periods 1 and 3, regression analysis indicated that precipitation (standardized $B = 0.664$, and 0.637, respectively) was the significant key factor for soil erosion change. However, in Period 2, vegetation became the significant key factor for soil erosion change (standardized $B = -0.391$). All models produced good regression results ($R^2 = 0.375$–0.566; adjusted $R^2 = 0.370$–0.564).

The dominant factors that controlled soil erosion differed among the periods. The soil erosion reduction that occurred during Period I (1980 to 1984) was controlled by changes in climate, which explained 84.05% of the

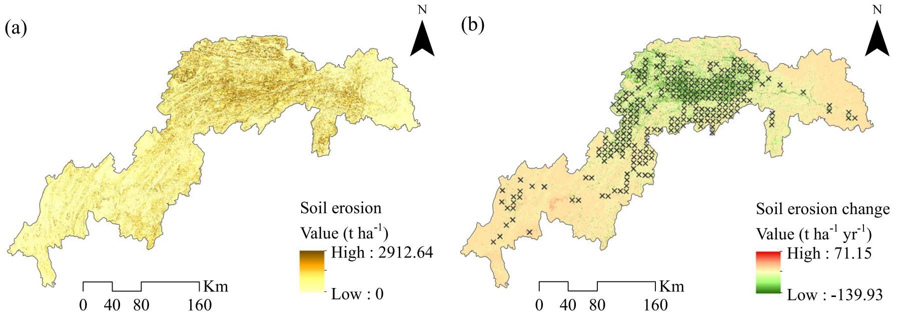

Figure 4. Spatial pattern and temporal dynamic of soil erosion (SE_a) in the Three Gorges Reservoir area from 1982 to 2015. (a) Spatial distribution of SE_a. (b) Trends in annual SE_a, with × indicating areas with a statistically significant trend ($p < 0.05$).

total variation in soil erosion. However, vegetation became as important as precipitation for controlling soil erosion during Period II (1985 to 2006), accounting for 51.35% of the variation. Finally, climate became as important as vegetation for controlling soil erosion during Period III (2007 to 2015), accounting for 51.65% of the variation. This temporal change in the factors that controlled soil erosion suggested that effects of the vegetation improvement under the government ecological restoration programs became more pronounced over time.

3.4. The Relationship Between Urban Development and Soil Erosion

The real per capita income of residents of the study area increased significantly in both urban and rural areas, but the gap between urban and rural incomes increased from a ratio of 1.8 in 1985 to 3.0 in 2015 (Figure 6a). At the same time, urbanization (migration of rural residents to cities) was accelerating in the Three Gorges Reservoir area. The proportion of the total population living in an urban area increased by 0.02 annually, from about 0.32 in 1985 to about 0.89 in 2015, and increased particularly rapidly after 2009 (Figure 6b). As large numbers of people moved into cities, the built-up area increased rapidly (Table 2). We also found a statistically significant contribution of urbanization on the decreasing of soil erosion from 1980 to 2015 (Figure 7).

4. Discussion

With ongoing environmental degradation and increasingly fragile ecosystems, environmental managers must look beyond traditional approaches that focus on ecology and begin to consider the human aspects of the problem (Feng et al., 2015). To achieve this goal, it's necessary to account for the key forces that drive ecosystem change, including both natural and human forces. We found that soil erosion in the Three Gorges Reservoir area reached 170 Mt per year in 2015. Soil erosion in the eastern region was significantly higher than that in the western region. The region with the largest amount of soil erosion was mainly located near the Daba Mountains. In general, an ecosystem's resistance to soil erosion depends on the ecosystem type and

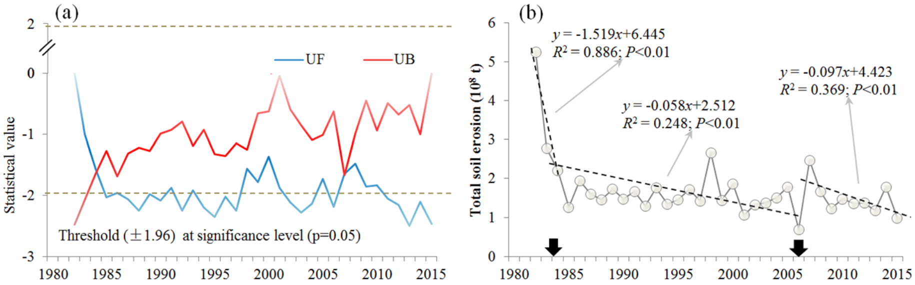

Figure 5. (a) Detection of abrupt changes in annual soil erosion (SE_a) in the Three Gorges Reservoir area from 1982 to 2015. Turning points occur where the UF and UB curves intersect at a position above the threshold for statistical significance based on the Mann–Kendall mutation test. (b) Trends of annual SE_a during the study period. Arrows indicate the significant turning points in 1984 and 2006 that were identified in (a).

Table 3
Pearson's Correlation Analysis Results for the Multiscale Factors and Time Period Indexes

Category	Independent variable	1980–1984 Period-1	1985–2006 Period-2	2007–2015 Period-3	1980–2015 whole period
Climate change	Precipitation	0.700**	0.521**	0.520**	0.273**
	Temperature	−0.320**	0.226**	0.277**	0.147*
Vegetation change	NDVI	−0.150**	−0.523**	−0.092*	−0.671**
	VC	−0.167**	−0.590**	ns	−0.667**
	Evapotranspiration	ns	ns	−0.229**	−0.197**
LULC change	Forestation	−0.108**	ns	ns	−0.105**
	Urbanization	0.113**	ns	0.104**	ns

Note. Only statistically significant values of Pearson's correlation coefficient are displayed; ns represents a nonsignificant result. Abbreviations: NDVI, the normalized-difference vegetation index; VC, vegetation cover.
$^{*}p < 0.05$. $^{**}p < 0.01$.

vegetation cover; for example, dense grasslands protect the soil better than sparse forests (Sun, Miao, Hanel, et al., 2019). The soil conservation function of different ecosystem types is strongest for forest, followed by shrub and grassland communities (Xiao et al., 2017). In addition, the higher the vegetation cover, the stronger the soil conservation function. However, our results show that in addition to these factors, the actual soil conservation function is determined by the climate, topography, and socioeconomic factors, with different relative strengths for each group of factors in different periods.

Since 1989, many ecological restoration projects have been implemented in our study area; as a result, a large amount of sloping farmland (4,280 km^2) has been transformed into shrub communities and forests, and vegetation cover has continuously increased. This increase has helped to reduce soil erosion. From 1980 to 2015, soil erosion showed an overall decreasing trend, with soil erosion decreasing by 3.36×10^6 t yr^{-1}). However, not all regions showed a decreasing trend (Kong et al., 2015). Soil erosion increased in hilly regions in the west, resulting in serious losses of soil and water. This resulted mainly from the rapid urbanization and expansion of the built-up area in this region, leading to greatly increased intensity of human activity, and from increased precipitation, which together exacerbated soil erosion in this region (Cao et al., 2017).

To evaluate the long-term changes of soil erosion, we used the Mann-Kendall mutation test to identify abrupt changes and revealed three distinct periods. In the first period, from 1980 to 1984, soil erosion decreased significantly, possibly because of the significant decrease in precipitation during this period. In the second period, from 1985 to 2006, soil erosion fluctuated, but decreased slowly overall. In the third period, which began in 2006 (around the start of construction of the Three Gorges Dam), soil erosion again showed a significant downward trend. Due to increasing urbanization after 2000 and the construction of Three Gorges Dam in 2006, the areas where LULC change occurred were mainly distributed in the eastern

Table 4
Regression Analysis Results for the Multiscale Factors and Time Period Indexes

Category	Independent variable	1980–1984 Period-1	1985–2006 Period-2	2007–2015 Period-3	1980–2015 Whole period
Climate change	Precipitation	0.664**	0.331**	0.637**	0.287**
	Temperature	−0.290**	ns	0.112**	−0.098**
Vegetation change	NDVI	ns	−0.177**	ns	−0.349**
	VC	ns	−0.391**	−0.346**	−0.371**
	Evapotranspiration	0.181**	ns	−0.167**	−0.104**
LULC change	Forestation	ns	ns	ns	ns
	Urbanization	ns	−0.207**	−0.188**	−0.176**
R^2/Adjusted R		0.566/0.564	0.490/0.487	0.375/0.370	0.553/0.549

Note. Only statistically significant values of standardized coefficients are displayed; ns represents a nonsignificant result. Dependent variables are the changing trend in per-unit-area soil erosion for Period-1, Period-2, Period-3, and Whole Period, respectively. The R^2 values represent goodness of fit for multiple linear regression models that account for the effects of the variables in each category of driving forces. Abbreviations: NDVI, the normalized-difference vegetation index; VC, vegetation cover.
$^{*}p < 0.05$. $^{**}p < 0.01$.

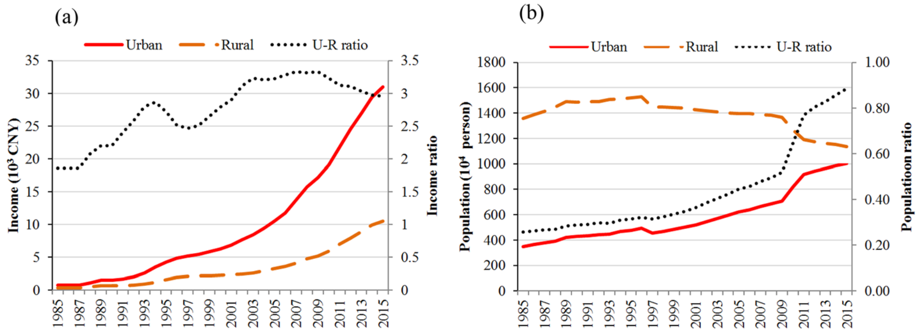

Figure 6. Changes from 1985 to 2015 in (a) the per capita real income of urban and rural residents and (b) the populations of rural and urban areas and the associated urbanization rate.

and western parts of the study area (Yang et al., 2018). The main change type in the eastern region was an increase in the area of forest, whereas the main change type in the western region was urban expansion. Both changes were at the expense of a decreased area of cropland. The expansion of forests in the east showed that the implementation of the government's ecological projects played a positive role in increasing forest cover in this region (Sun, Miao, Hanel, et al., 2019). The development of cities in the western region in response to migration of residents from rural areas to urban areas reduced the disturbance of vegetation by human activities in eastern rural areas to some extent (Dominati et al., 2014). The rapid development of cities in the western region and the increase of government revenue from taxation of economic activities in these cities may be able to support the continued implementation of the government's ecological projects.

Another possible reason for the increasing vegetation cover is that construction of the Three Gorges Dam has increased the groundwater content in areas near the reservoir and this, combined with increasing rainfall at the same time, combined to promote vegetation growth in most of the surrounding areas (Haghjou et al., 2014). The government's vegetation restoration projects clearly played a positive role in reducing soil erosion in the region. Of the driving forces we analyzed, vegetation accounted for a large proportion (70%) of the total variation in soil erosion. By acting on local ecosystem or on local constraints that control ecological restoration, accounting for these driving forces can improve restoration success (Karlen et al., 2014).

Our results are preliminary and apply best to our study area; they must be replicated and tested in areas with different characteristics to confirm the overall validity of our method and learn how to adapt it for use in other areas. Nonetheless, the problems solved by the new method deserve attention, particularly in terms of how it accounted for human driving forces such as urbanization and LULC change (Zheng et al., 2019). If the methodology is suitably modified to account for local conditions, it will allow policy makers and restoration managers in other areas to design more effective restoration strategies and will provide a theoretical basis for simultaneously improving environmental protection and socioeconomic development (Krois & Schulte, 2014). As this approach matures, it will provide important solutions to the poverty trap in China and elsewhere.

As the proportion of the rural population in our study area continued to decrease, the proportion of the labor force engaged in primary industries such as agriculture also continued to decrease. As a result of this long-term social shift, the contradiction between traditional agriculture (which creates high pressure on the environment) and ecological protection has gradually weakened, and this trend has been conducive to the natural restoration of vegetation even in the absence of government restoration programs. Previous research also found a significant positive correlation between the urbanization rate and NDVI trends in our study area (Lee et al., 2014).

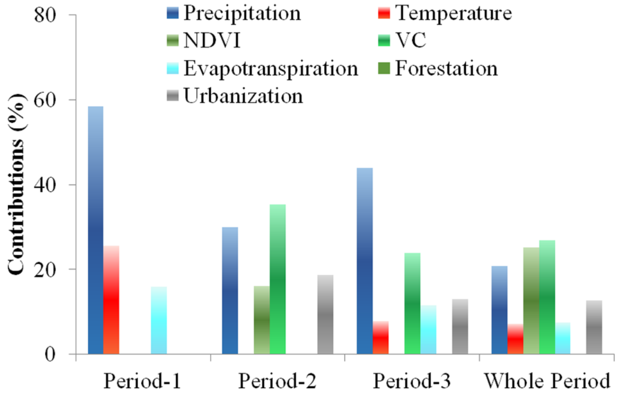

Figure 7. Relative contribution importance of the driving forces associated with changes in total annual soil erosion.

In general, environmental goals cannot be separated from economic development, since human survival depends on a healthy environment. This dependence provides a clear path to success: influencing the livelihood of residents of environmentally fragile regions so that they can continue earning a living without damaging their environment. Environmental degradation and poverty are mutually reinforcing processes (i.e., they together create the poverty trap). Investing in environmental assets and management is a crucial strategy to combat the poverty trap and simultaneously achieve both environmental restoration and poverty alleviation (Miao et al., 2019). In the Three Gorges Reservoir area, urbanization has accelerated during the study period, leading to less pressure on the rural environment and an increase in the built-up area in cities. Previous research showed that the growth rate of the built-up areas in cities was faster than that of the non-agricultural population in the urban area, which agrees with the present results (Zhang et al., 2014).

The effects of this trend are evident in our study area. Due to the rapid economic growth that has occurred in the study area, the acceleration of urbanization, and the large and growing difference between urban and rural incomes, a large proportion of the rural population has migrated to cities and towns, and much of this migration came from the northeastern mountainous areas, with former residents of these areas moving to the main urban areas in the western part of our study area. This large change in the proportions of urban and rural residents suggest that an equally huge social transformation is underway (Liebig et al., 2014).

This migration has been accompanied by the implementation of a large number of ecological restoration projects in the eastern region. The migration has weakened human impacts on the source region for the migrants, while simultaneously improving vegetation cover in this region through government projects; the result was greatly improved vegetation cover and greatly reduced soil erosion risk. Our research confirms our hypothesis that measures to control the driving forces responsible for ecological degradation through targeted ecological restoration measures can eliminate the blind spot in traditional ecological restoration planning, which focused on ecological factors and largely ignored human factors. For example, large rural populations place a proportionally large pressure on their environment (Xiao et al., 2020). To relieve this pressure, migration to urban areas can be promoted through education, which allows migrants to obtain other forms of employment, and social welfare programs, such as providing social services (e.g., access to medical care and schools for their children) that make the move to a city easier. Ecological restoration in the Three Gorges Reservoir area is aimed at achieving sustainable socioeconomic development (Marenya et al., 2014). Therefore, in dealing with the relationship between ecological restoration and this development, we should seek a balance between development and restoration rather than relying exclusively (and simplistically) on vegetation restoration.

5. Conclusions

Research such as the present study is important because it reveals the response of soil erosion to both ecological factors (climate, afforestation) and social factors (urbanization, ecological migration). In our study of the Three Gorges Reservoir area, we found that both ecological and socioeconomic factors were driving forces for mitigating soil erosion, but with different relative strengths at different times. Our study methods can, with suitable modification to account for local conditions, help guide the restoration of ecologically sensitive areas in other regions of China and elsewhere in the world. We found that soil erosion gradually decreased throughout the study period, though at different rates during different parts of the study period and with changes in the relative strengths of the driving forces between these periods. During the first part of the study period, soil erosion decreased significantly, and our correlation analysis suggested that decreasing precipitation was responsible. During the second period, soil erosion fluctuated but still decreased slowly. During the third period, soil erosion again showed a significant decreasing trend, but in this period, the change resulted from socioeconomic factors such as a rapidly increasing urbanization rate.

Our results demonstrate that the government's restoration programs, and particularly afforestation, have improved the vegetation cover and decreased soil erosion. However, they have also displaced large numbers of rural residents to the region's rapidly growing cities. Because this migration will challenge the ability of local residents to earn a living, we propose that the government continue to increase its afforestation efforts, but that they complement these efforts with programs that improve employment opportunities for displaced residents. This approach will simultaneously support economic development and ecological restoration, and particularly an ongoing reduction of soil erosion. Our proposed approach reveals that the government's programs in our study area have succeeded because they focused on the key driving forces (both ecological and socioeconomic) that cause degradation or promote restoration. Moreover, our approach revealed different dominant factors that controlled soil erosion in each part of the study period. These differences will help restoration managers understand the changing factors that control both restoration and its relationship with socioeconomic development, thereby offering opportunities to develop more effective programs for accomplishing both goals.

Conflict of Interest

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

Data Availability Statement

Our raw data are stored in Global Change Research Data Publishing and Repository, data availability statement that complies with FAIR Data standards can be downloaded from this database. The data used in the figures and tables are available at this site (http://www.geodoi.ac.cn/edoi.aspx?DOI=10.3974/geodb.2020.02.17.V1). All data sources are public record.

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