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Research Article

Estimating the Impact of Land Cover Change on Soil Erosion Using Remote Sensing and GIS Data by USLE Model and Scenario Design

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Great efforts have been made to curb soil erosion and restore the natural environment to Inner Mongolia in China. The purpose of this study is to evaluate the impact of returning farmland to the forest on soil erosion on a regional scale. Considering that rainfall erosivity also has an important impact on soil erosion, the effect of land use and land cover change (LUCC) on soil erosion was evaluated through scenario construction. Firstly, the universal soil loss equation (USLE) model was used to evaluate the actual soil erosion (2001 and 2010). Secondly, two scenarios (scenario 1 and scenario 2) were constructed by assuming that the land cover and rainfall-runoff erosivity are fixed, respectively, and soil erosion under different scenarios was estimated. Finally, the effect of LUCC on soil erosion was evaluated by comparing the soil erosion under actual situations with the hypothetical scenarios. The results show that both land use/cover change and rainfall-runoff erosivity change have significant effects on soil erosion. The land use and land cover change initiated by the ecological restoration projects have obviously reduced the soil erosion in this area. The results also reveal that the method proposed in this paper is helpful to clarify the influencing factors of soil erosion.

1. Introduction

Soil erosion is one of the major and most widespread types of soil degradation. The Inner Mongolia autonomous region has one of the most severe soil erosion problems among all of China's provinces [1–3]. The area experiencing soil erosion is about 79 million hectares (66.99% of the region's total area), with increasingly negative effects on agricultural productivity and on the sustainability of economic development [1, 2, 4]. Serious soil erosion leads to the deterioration of the ecological environment, low level of agricultural production, and personal poverty, which is the fundamental cause of social and economic development. To mitigate the impacts of erosion, the Natural Forest Protection Project (NFPP) and Green for Grain Project (GCP, also known as the Conversion of Cropland to Forest and Grassland Program), both of which incorporate Inner Mongolia, were launched in 1998 and 1999, respectively [5, 6]. These programs aimed to prevent soil erosion by converting farmland on steep slopes into forests. An assessment of soil erosion hazards before and after the implementation of measures can help to assess the extent of effectiveness of these recovery strategies and thus aids decision makers in determining appropriate practices and formulating conservation plans.

A number of models have proven to be effective in estimating soil erosion at different scales in previous studies. One of the most commonly used models is the universal soil loss equation (USLE) developed by Wischmeier and Smith [7]. Although the model was later modified to a new version known as RUSLE [8, 9], USLE is still widely used for its simplicity [10–12]. USLE and its revised models have been used increasingly more widely with the development and integration of RS (remote sensing) and GIS (geographical information systems) technologies because they solve the problem in which the input data of models are difficult to obtain [10–18]. The models can be successfully used to estimate soil erosion because they consider climate, topography, soil, and management practices. However, they cannot assess the impact of a single factor on soil erosion, such as LUCC (land use and land cover change) or rainfall-runoff erosivity change.

Land cover is considered to be one of the most important factors affecting soil erosion and the investigation of soil losses due to differences or changes in land cover types is a popular research topic [19–26]. Therefore, field experiments are an ideal method for observing the differences in hydrological characteristics (e.g., runoff) between one experimental area treated with vegetation cover and other experimental areas to assess the effect of vegetation on soil erosion [22, 26, 27]. However, field experiments are time-consuming and costly. The scenario design proves to be a useful tool in investigating soil erosion under different hypothesized climate scenarios [28]. This method can also serve as a constructive method in evaluating the effect of LUCC on soil erosion. In this study, the USLE model is used to obtain the spatial and temporal patterns of soil erosion in Liangcheng County, Inner Mongolia, from 2001 to 2010, and the scenarios are constructed to evaluate the impact of LUCC on soil erosion.

2. Study Area and Data

2.1. Study Area. Liangcheng County is located in southern Ulanqab, in the Inner Mongolia Autonomous Region, North China, between 112°28′ and 112°30′ east longitude and 40°29′ and 40°32′ north latitude, with an area of 3456.12 km^2 (Figure 1). Because it is located in the transition zone between the Loess Plateau and Mongolia Plateau, there are many gullies throughout this area. As shown in Figure 1, the study area is surrounded by mountains, and the middle part is a trough basin. Located in the north and south of the study area are the Manhan Mountain and the Matou Mountain Range, and the middle of the study area is the Daihai Basin. The mountainous area covers 47.83% of the study area, comprised an approximately equal proportion (25%) of hills and basins. The elevation of the study area is between 1100 and 2300 m (Figure 1). According to the sequence from old to new, the strata in the working area include middle Archean, Mesozoic, Cenozoic, Pleistocene, and Holocene. The main part of the area is the late Archean acid intrusive area. The late K-feldspar granite has an obvious gneissic texture and few phenocrysts [29].

The area belongs to the semiarid temperate continental monsoon climate. The annual average temperature is 6.1°C, and the average annual rainfall (1989–2018) is 409.6 mm [30]. Forest covers approximately 51.7% of the study area [31] in which various trees (such as poplar, birch, and aspen) and shrubs (such as Caragana, Ostryopsis, and sea buckthorn) predominate.

2.2. Research Data. The materials used in this study are as follows: (1) monthly precipitation data of 20 years (1992–2011) from the China Meteorological Administration (CMA), used for calculating R factor in 2001 and 2010; (2) ASTER GDEM data with a resolution of 30 meters downloaded from http://reverb.echo.nasa.gov used to calculate slope gradient and slope length; (3) two Landsat5/TM scenes with a resolution of 30 meters dated August 20, 2001, and August 10, 2010, that were obtained from the USGS Glovis data archive, and terrain-corrected Level 1T scenes with geodetic accuracies of one-quarter to less than half a pixel (Figure 2), used to extract land use/cover and vegetation information; (4) available 1 : 1,000,000 soil map from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences, used to calculate soil erodibility factor; and (5) woodland survey data in 2001 and 2010 from China's Liangcheng County government, auxiliary data used to extract land use/cover information.

3. Methodology

3.1. USLE Model and Parameters Estimation. The USLE model was used to assess soil erosion of the study area:

$$A = R^* K^* L^* S^* C^* P, \quad (1)$$

where A is the mean annual soil loss (t ha^{-1} $year^{-1}$); R is the rainfall erosivity factor (MJ mm $ha^{-1} h^{-1}$ $year^{-1}$); K is the soil erodibility factor (t ha h $ha^{-1} MJ^{-1} mm^{-1}$); L is the slope length factor (dimensionless); S is the slope factor (dimensionless); C is the cover management factor (dimensionless); P is the erosion control practice factor (dimensionless). All parameter preparation methods are included in the subsequent content, and the calculation process is mainly completed on the Arcmap platform.

3.1.1. Rainfall and Runoff Erosivity Factor (R). R is the rainfall and runoff factor by geographic location. The greater the intensity and duration of the rain storm, the higher the erosion potential. However, for most meteorological stations, the intensity and duration are difficult to obtain, and R must be estimated based on the amount of rainfall. The R factor is calculated using the equation proposed by Wischmeier and Smith [7] and developed by Arnoldus [32]:

$$R = \sum_{1}^{12} \left(1.735 \times 10^{\left(1.5 \log_{10}\left(p_i^2/p\right) - 0.08188\right)} \right), \quad (2)$$

where p represents annual precipitation (mm) and pi represents monthly precipitation (mm).

The precipitation data from CMA used to calculate R factor is estimated by the Energy and Water Balance System (EWBMS) based on two sources of information: (1) point precipitation data from meteorological stations and (2) cloud frequency data derived from the FY2c meteorological geostationary satellite [33, 34].

3.1.2. Soil Erodibility Factor (K). "K" values represent the susceptibility of soil to erosion and the amount and rate of runoff, as measured under the standard unit plot condition. K is a measure of the susceptibility of soil particles to the

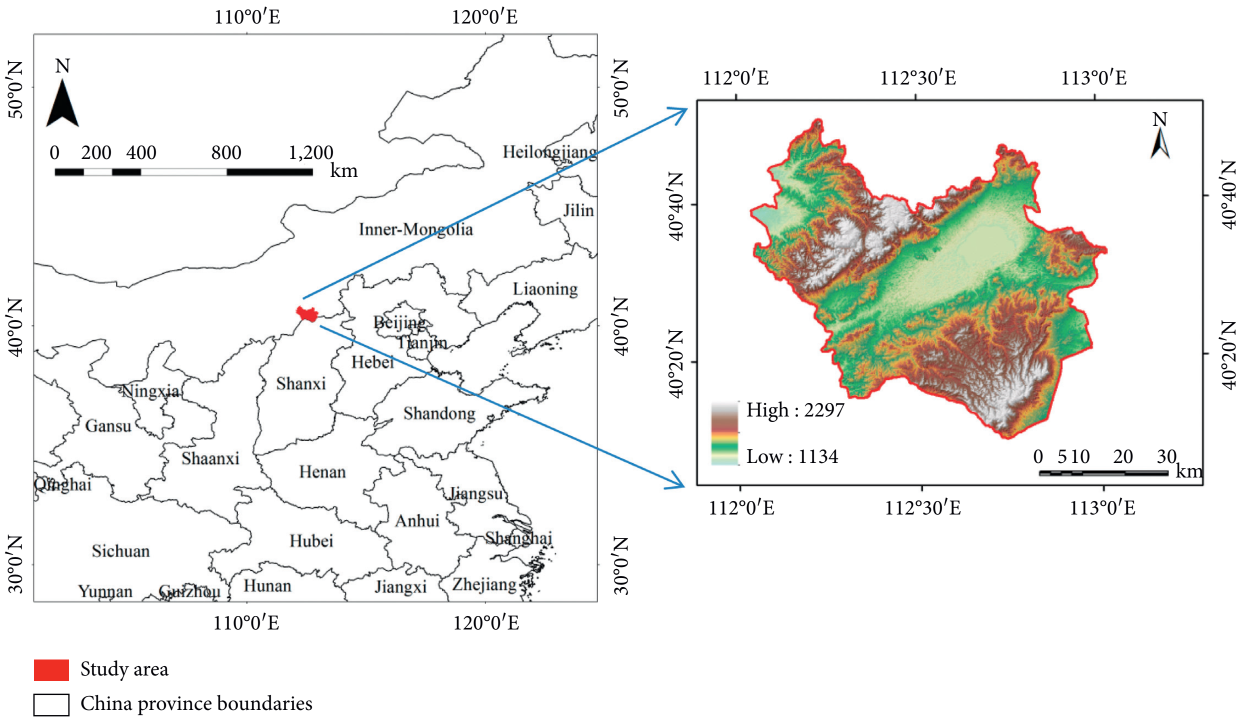

Figure 1: Location of the study area.

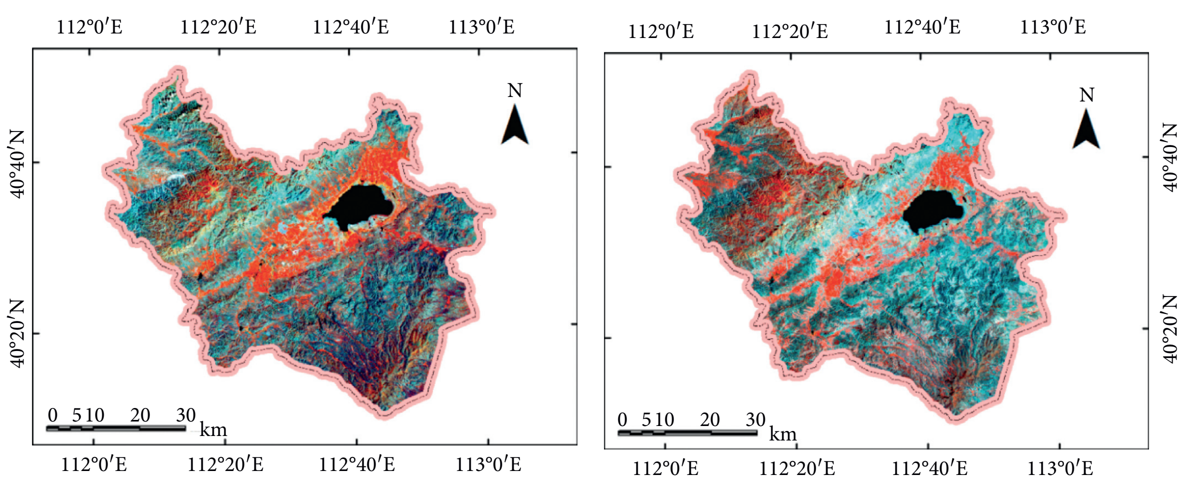

Figure 2: Landsat/TM false-color composite of the study area ((a) 2001; (b) 2010).

detachment and transport by rainfall and runoff [7]. Texture is the principal factor affecting K, but structure, organic matter, and permeability also contribute. The K factor was estimated based on the soil texture classes and organic matter content, which may be determined from the soil map with a 1 : 1,000,000 scale(Figure 3). This soil map scale is large, but it is the only available soil data in China, including soil type map and soil property data for each soil type. The K factor is calculated using the equation proposed by Williams [35]:

$$K = \left\{0.2 + 0.3 \times \exp\left[-0.0256 \times \mathrm{Sd} \times \left(\frac{1 - \mathrm{Si}}{100}\right)\right]\right\} \times \left[\frac{\mathrm{Si}}{(\mathrm{Cl} + \mathrm{Si})}\right] 0.3 \times \left\{\frac{1.0 - 0.25\mathrm{C}}{[\mathrm{C} + \exp(3.72 - 2.95\mathrm{C})]}\right\} \times \frac{[1.0 - 0.7 \times ((1 - \mathrm{Sd})/100)]}{\{((1 - \mathrm{Sd})/100) + \exp[-5.51 + 22.9 \times ((1 - \mathrm{Sd})/100)]\}}, \quad (3)$$

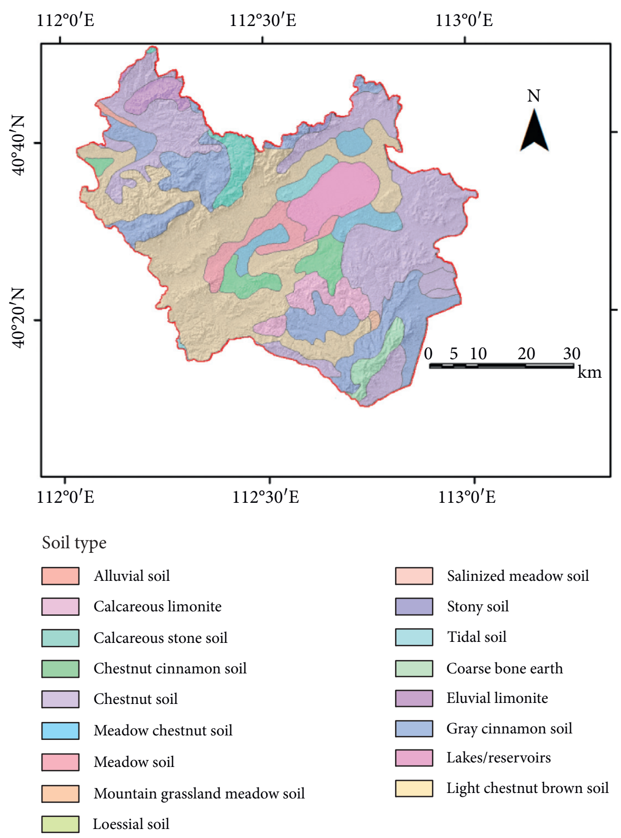

Figure 3: Soil type map.

where Sd represents the percentage of sand content; Si represents the percentage of silt content; Cl represents the percentage of clay content (%); C represents the percentage of organic matter content; the unit of k is $\mathrm{t\,ha\,h\,ha^{-1}MJ^{-1}mm^{-1}}$).

3.1.3. Slope Steepness Factor (S) and Slope Length Factor (L). The S and L factors are used to estimate the influence of topography on soil erosion in the ULSE. S and L represent the effect of slope steepness and slope length, respectively, on erosion. The computed soil erosion rates are more sensitive to slope steepness than to slope length—the steeper and longer the slope, the higher the risk for erosion.

The S factor is calculated using the equation proposed by Liu et al. [36, 37] and McCool et al. [38]:

$$S = \begin{cases} 10.8 \times \sin\theta + 0.03, & \theta < 5, \\ 16.8 \times \sin\theta - 0.5, & 5 \le \theta < 10, \\ 21.9 \times \sin\theta - 0.96, & \theta \ge 10, \end{cases} \quad (4)$$

where θ represents slope.

Slope length is the distance from the origin of overland flow along its flow path to the location of either concentrated flow or deposition, whereas L is the ratio of soil loss from the field slope length to a plot with a slope length of λ m under otherwise identical conditions.

The L factor is calculated using the equation proposed by Liu et al. [37, 39]:

$$L = \left(\frac{\lambda}{22.1}\right)^m, \quad (5)$$

where λ is the slope length and m is the slope index. λ is estimated by the equation [40, 41]: $\lambda = \text{Flowacc} * \text{constant grid size}$. Flowacc is runoff accumulation number obtained by using ArcGIS hydrological analysis module based on DEM. The m value can be assigned 0.2, 0.3, 0.4, and 0.5 for slope gradients <1%; 1%–3%; 3%–5%; and ≥5%.

3.1.4. Crop/Vegetation Management Factor (C). Soil and water conservation may be effectively improved by increasing vegetation cover. The crop/vegetation management factor represents the effect of plants, soil cover, soil biomass, and soil disturbance activities on soil erosion. It is used to determine the relative effectiveness of soil and crop management systems in terms of preventing soil loss. The C factor is a ratio that compares the soil loss from the land under a specific crop and management system to the corresponding loss from continuously fallow and tilled land. Therefore, it is dimensionless and its value is between 0 and 1.

The C factor is calculated using the equation proposed by Cai et al. [42]:

$$C = \begin{cases} 1, & \text{fc} = 0, \\ 0.6508 - 0.3436 \times \lg(\text{fc}), & 0 < \text{fc} < 78.3\%, \\ 0, & \text{fc} > 78.3\%, \end{cases} \quad (6)$$

where fc represents vegetation coverage, calculated based on NDVI derived from remotely sensed TM data, using a pixel dichotomy model [43].

3.1.5. Support Practice Factor (P). P represents the impact of support practices on erosion rates. In this study, the P factor value is assigned based on land use types derived from the land use map according to Liu et al. [44]. It is also dimensionless and its value is between 0 and 1. A 0.35 and 1.0 P factors are assigned to cultivated land and forested land, respectively, and the remaining land cover was assigned a P factor of 0.

3.2. Scenarios Construction. Land use and rainfall are the most important factors affecting soil erosion. Sometimes when studying the causes of soil and water loss, it is necessary to distinguish the effects of these two factors, that is, to study their effects separately. To do this, two scenarios (S1 and S2) are constructed according to different combinations of rainfall and land use factor:

S1: rainfall-runoff erosivity in 2001 + land use in 2010

S2: rainfall-runoff erosivity in 2010 + land use in 2001

S1 and S2 are designed to clarify the effect of rain-runoff erosivity and land use change on soil loss of the study area by comparing with the actual situation. The actual situation of 2001 can be defined as the combination of rainfall-runoff erosivity in 2001 and land use in 2001, and the actual situation of 2010 can be defined as the combination of rainfall-runoff erosivity in 2010 and land use in 2010.

4. Results and Discussion

4.1. Land Use and Land Cover Change. Land use maps of the study area dated to 2001 and 2010 were derived from Landsat data, forest land protection, and utilization planning data from the Liangcheng County government. The land use and land cover results were obtained by combining visual interpretation of the standard false-color combination of Landsat data with field survey data from the local government forestry administration. Figure 4 illustrates land use and land cover in 2001 and 2010. Since this project focused on the effect of returning farmland to forest, only forest types were mapped in 2010. In the land use map of 2001, in addition to forest types, there were some farmlands that were later converted into forests. From 2001 to 2010, 8.17 square kilometres of cropland was converted to woodland, 280.42 square kilometres of cropland to shrubland and 5.72 square kilometres of cropland to sparse woodland.

Figure 5 shows the dynamic change of vegetation coverage in the study area, with the average coverage increasing from 51% to 63% between 2001 and 2010. As can be seen from the figure, the increase in vegetation coverage is obvious, especially in the northwest and southeast mountain areas of the study area.

4.2. Assessment of Factors. Figure 6 shows the spatial distribution of various USLE factors in the study area. As shown in Figures 6(a) and 6(b), there are significant differences in rainfall-runoff erosivity between 2001 and 2010. The statistical results show that the R value in 2010 is generally higher than that in 2001. The average R value in 2010 is 113.53 MJ mm ha^{-1}h^{-1}year^{-1}, compared with 98.62 MJ mm ha^{-1}h^{-1}year^{-1} in 2001. The R values between 120 and 170, 105 and 120, and 90 and 105 in 2010 are about 27%, 44%, and 29%, respectively, compared with 10%, 20%, and 40% in 2001.

Figures 6(c) and 6(d) show the K factor value and LS factor value. Because K factor and LS factor are relatively stable for a short period of time, it is assumed these values are the same for 2001 and 2010.

As depicted in Figure 6, the crop management factor (C) in 2010 changed significantly compared with that in 2001. The red and yellow areas in Figure 6(f), i.e., the region whose C value was lower than 0.72 in 2010, are much larger than those in 2001 in Figure 6(e). The C average of the study area decreased from 0.68 in 2001 to approximately 0.56 in 2010. This change should be attributed to a series of important ecological and water conservation projects, including the NFPP and GCP.

4.3. Soil Erosion Estimation in an Actual Situation. Figure 7 shows the spatial distribution of the soil erosion modulus in 2001 and 2010. According to the soil erosion grading standards established by China's Ministry of Water Resources, the soil erosion modulus of Liangcheng County in 2001 and 2010 may be divided into different grades. The mean soil erosion modulus was 14190 t/(km^2 a) in 2001 and 14012 t/(km^2 a) in 2010. Thus, compared with 2001, the mean soil erosion modulus in 2010 changed little.

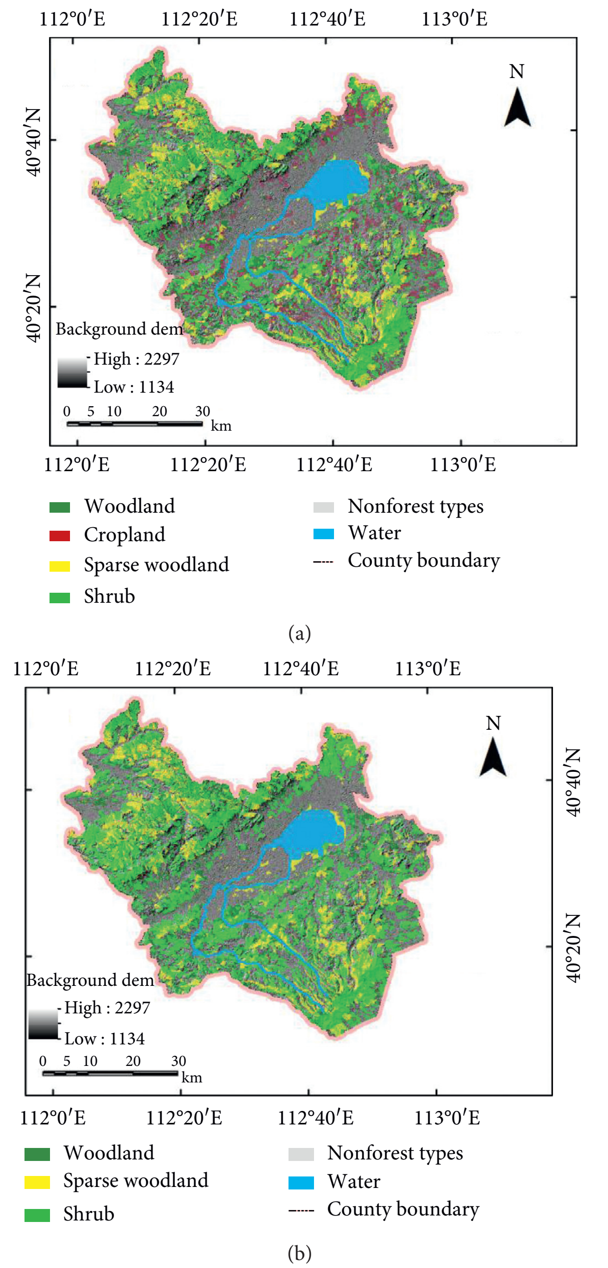

FIGURE 4: Land use map of the study area in 2001 (a) and 2010 (b).

4.4. Estimation of Soil Loss under Scenarios. The soil erosion modulus under different scenarios (S1 and S2) are calculated and presented in Figure 8. The mean soil erosion modulus under scenario 1 (S1) is 11906 t/(km^{2}a), while the mean soil erosion modulus under scenario 2 (S2) is 16270 t/(km^2 a).

For scenario 1 (S1), i.e., when the 2001 rainfall erosivity acts on the underlying surface of 2010, the simulated mean soil erosion modulus is much smaller than the actual soil

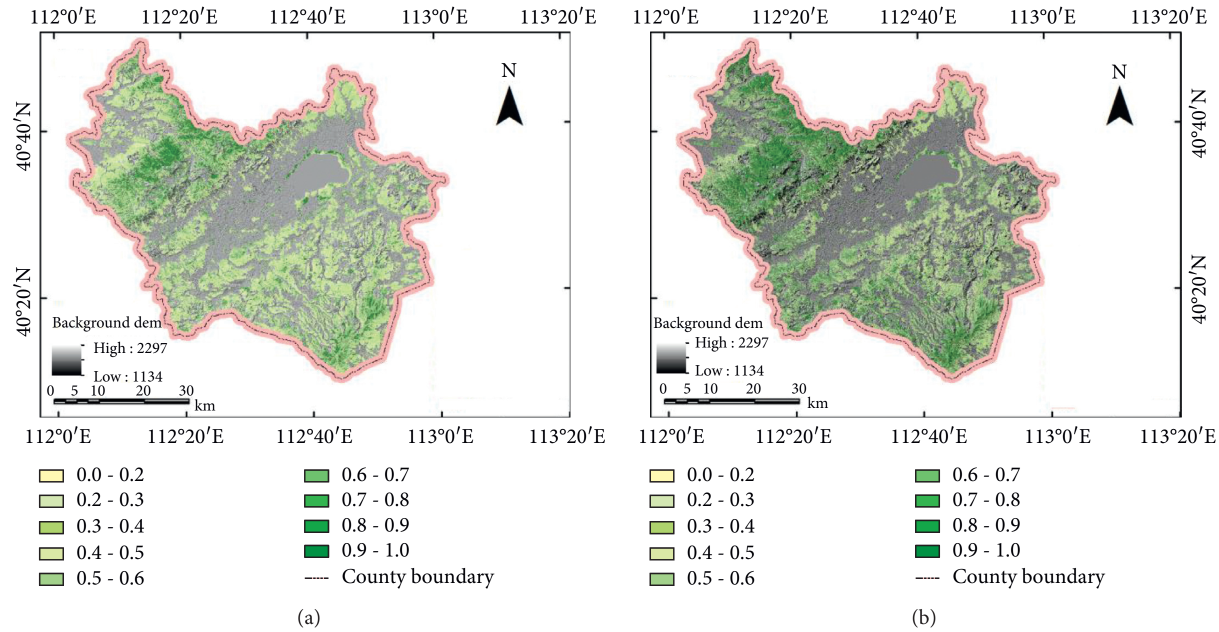

Figure 5: Vegetation coverage map in 2001 (a) and 2010 (b).

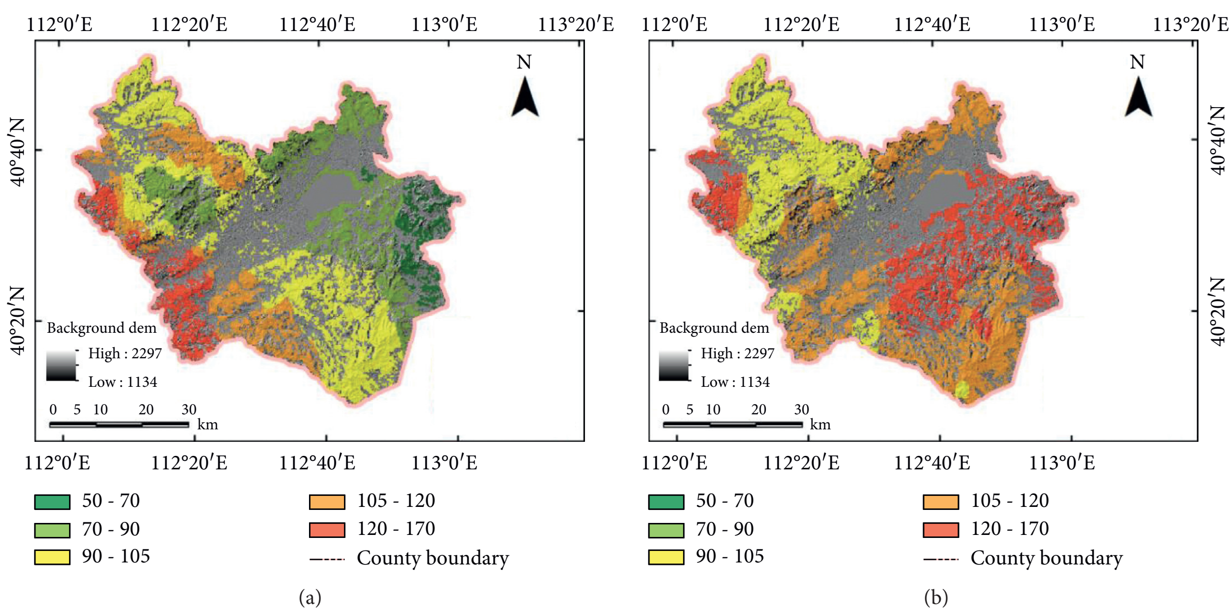

Figure 6: Continued.

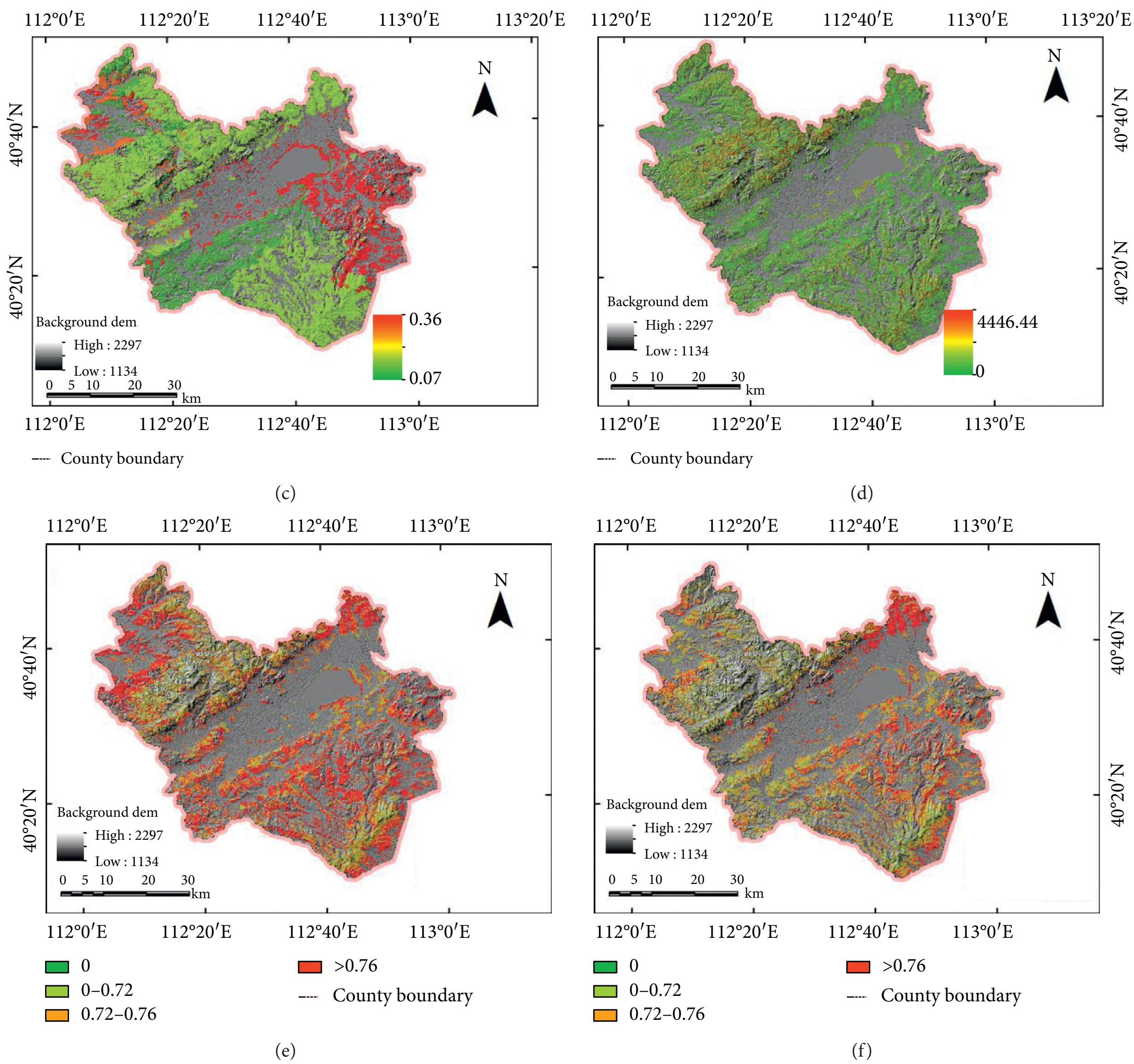

Figure 6: Factors superimposed on the elevation map of the study area. (a) R factor in 2001 (MJ mm ha^{-1}h^{-1} year^{-1}); (b) R factor in 2010 (MJ mm ha^{-1}h^{-1} year^{-1}); (c) K factor; (d) LS factor; (e) C factor in 2001; (f) C factor in 2010.

erosion modulus in 2001 and 2010 calculated above. The mean soil erosion modulus of S1 is approximately 16.10% smaller than the actual soil erosion modulus in 2001, indicating that the changes in land use and land cover between 2001 and 2010 effectively reduced soil erosion. The mean soil erosion modulus of S1 is approximately 15.67% smaller than the actual soil erosion modulus in 2010, indicating that the rainfall erosivity in 2010 is much higher than that in 2001.

The same conclusion can be obtained for the simulation of soil erosion under scenario 2 (S2). For scenario 2 (S2), i.e., when the 2010 rainfall erosivity acts on the underlying surface of 2001, the mean soil erosion modulus is as high as 16270 t/(km^2 a). Compared with the actual soil erosion modulus in 2001 and 2010, the soil erosion modulus under S2 is about 14.66% and 16.11% higher, respectively, indicating once again that the rainfall erosivity in 2010 is higher than that in 2001, and the land use and land cover change between 2001 and 2010 effectively reduced soil erosion.

The comparison presented in Table 1 illustrates the impact of rainfall erosivity and land use and land cover change more clearly. Compared with the actual situation in 2001, the percentage of area under S1 decreases by 2.87% and 4.06%, while that under S2 increases by 0.06% and 3.54%. Compared with the actual situation in 2010, the percentage of area under S1 decreases by 0.05% and 3.69%, while that under S2 increases by 2.78% and 3.91%.

Scenario construction allows us to understand that soil erosion in the region is significantly affected by rainfall erosivity in addition to land use and land cover change. This result is consistent with previous studies on the effects of rainfall erosivity on soil erosion [29, 45]. On the other hand, the conversion of cultivated land into forests will reduce soil

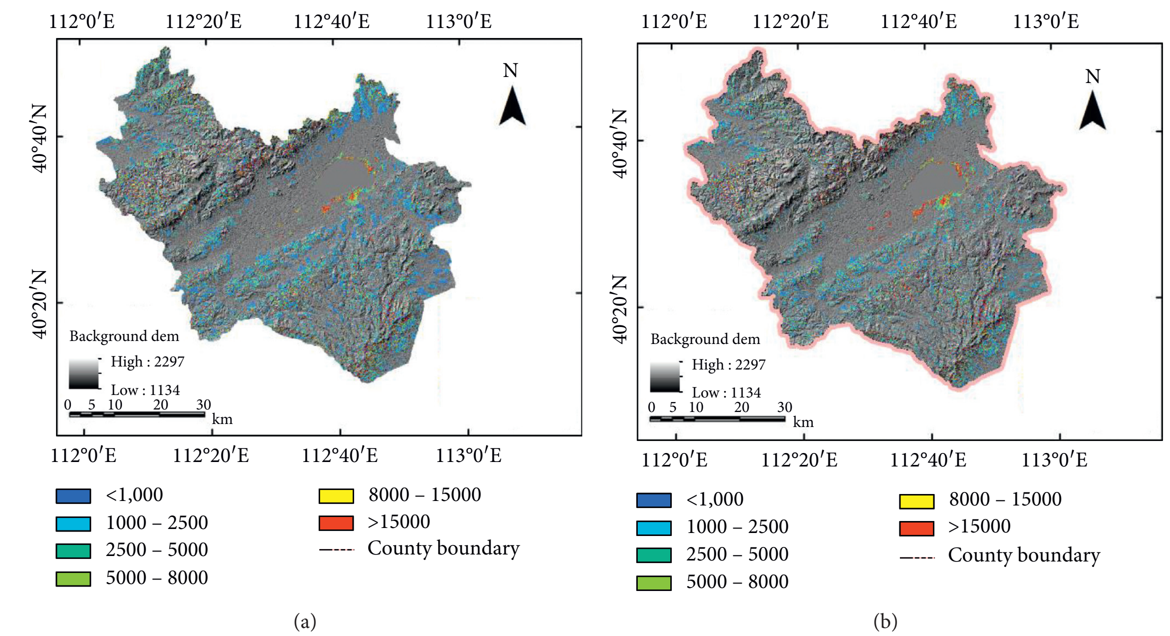

Figure 7: Soil erosion modulus map in 2001 (a) and 2010 (b).

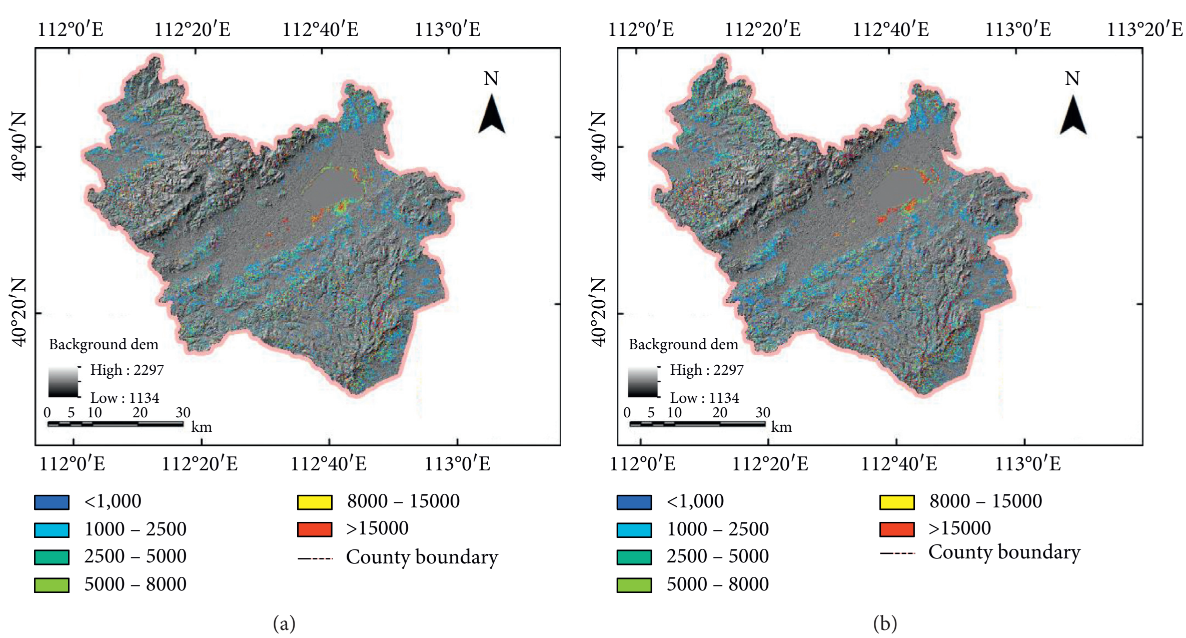

Figure 8: Soil erosion modulus under S1 (a) and S2 (b) superimposed on elevation map.

Table 1: Comparison of soil erosion intensity under different situations.

Soil erosion grades	2001 (%)	2010 (%)	S1 (%)	S2 (%)
Slight	8.48	22.16	21.61	8.6
Mild	14.43	9.64	11.93	12.69
Moderate	17.14	13.91	15.19	16.03
Strong	15.03	12.46	13.28	14.16
Intense	19.88	17.16	17.01	19.94
Severe	25.04	24.67	20.98	28.58

erosion. This is also confirmed by studies of other similar areas near the study area [46, 47], which shows that soil erosion in their study area is significantly reduced because of the large increase in forest land.

5. Conclusions

In this study, the influence of ecological restoration activities on soil erosion is assessed in the Inner Mongolia Autonomous Region, China. Due to the implementation of restoration activities, the forested area of the study region increased. The USLE model was applied to assess the soil erosion before and after the implementation of ecological projects. The scenario construction serves as a useful tool in investigating the causes of soil erosion. Actual soil erosion in the research area during the study period changed little. That is because rainfall erosivity increases soil erosion, while land use change reduces soil erosion. Measures to restore forests have significantly reduced soil erosion. The implementation of ecological projects, such as the Natural Forest Protection Project and Green for Grain Project, are constructive interventions. It is necessary to continue afforestation to offset the negative impacts of rainfall-runoff change. In the future, studying the impact of different land cover types on soil erosion will help determine the most appropriate vegetation to reduce soil erosion and maximize the benefits of environmental recovery efforts.

Data Availability

The materials used in this study are as follows: (1) monthly precipitation data of 20 years (1992–2011) from the China Meteorological Administration (CMA), used for calculating R factor in 2001 and 2010; (2) ASTER GDEM data with a resolution of 30 meters downloaded from http://reverb.echo.nasa.gov, used to calculate slope gradient and slope length; (3) two Landsat5/TM scenes with a resolution of 30 meters dated August 20, 2001, and August 10, 2010, that were obtained from the USGS Glovis data archive, and terrain-corrected Level 1T scenes with geodetic accuracies of one-quarter to less than half a pixel (Figure 2), used to extract land use/cover and vegetation information; (4) available 1 : 1,000,000 soil map from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences, used to calculate soil erodibility factor; (5) woodland survey data in 2001 and 2010 from China's Liangcheng County government, auxiliary data used to extract land use/cover information.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

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