Vegetation Restoration and Its Environmental Effects on the Loess Plateau

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Abstract: An analysis of land use/cover change (LUCC) on the Loess Plateau over the past 30 years and its environmental effects was performed to provide scientific guidance for a sustainable development policy for the regional ecological environment and social economy. Geostatistical and trend analyses are used to study the LUCC characteristics, driving forces and environmental effects, and the relationship between LUCC and regional sustainable development is explored. The following results were obtained: (1) Overall, the land use structure has not changed, with grassland, farmland, and forest land remaining dominant; however, the vegetation coverage has significantly increased, especially in the central area. (2) LUCC is affected by climate change and human activities, with greater climate change impacts in the northwest than the southeast and greater among which human-induced impacts on the hilly/gully region in the central part. (3) LUCC will produce long-term ecological and environmental processes, such as surface runoff, soil erosion, soil moisture and carbon cycling. Vegetation restoration has both negative and positive effects on the regional ecological environment. Vegetation productivity on the Loess Plateau has approached the water resource carrying capacity threshold. Therefore, improving artificial vegetation stability and promoting the water resources balance have become the main strategies for promoting sustainable development on the Loess Plateau.

Keywords: vegetation restoration; LUCC; Loess Plateau; sustainable development

1. Introduction

LUCC, a direct reflection of the interaction between humans and nature, is a complex process of the combined effects of natural, social and economic factors and is a basic problem for population, resource and environmentally sustainable developments [1–4]. The spatial and temporal characteristics, driving forces and environmental effects of LUCC are three focuses of LUCC research [5]. These aspects are prerequisites for understanding the interaction mechanism between human-driven land use change and the environment, which can reflect the direct interactions between natural patterns, processes and human society. Understanding LUCC is of great significance for promoting regional ecological and socioeconomic sustainable development [6–8].

The Loess Plateau is susceptible to environmental changes resulting from LUCC because the region is located in a semiarid and semi-humid climatic zone, and the ecological environment is
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fragile [9]. The Loess Plateau is a hotspot for studying ecological processes due to the fragility and importance of ecosystems in the region [10]. Over the past few decades, land use/cover has changed significantly on the Loess Plateau due to reforestation in large scale [11]. Based on remote sensing imagery interpretation and GIS (Geographic Information System) spatial analysis techniques, researchers have studied the temporal and spatial characteristics of LUCC at the regional and watershed scales [12]. The basic features of LUCC were that the area of sloping farmland decreased and forest and grassland increased, and vegetation coverage increased [12,13].

However, as global warming progresses, will undoubtedly impact the vegetation restoration and increase the surface water and soil moisture stress in the region in the worldwide [4,14,15]. To quantitatively attribute LUCC, the relationships between climate change, human activities and vegetation should be determined to reconstruct the vegetation series under natural condition [4,6,12,16]. In recent years, many scholars have used models, principal component analysis, grey system analysis, regression analysis and other methods to study the driving mechanisms of LUCC at different spatial scales [12,17–20]. Some studies show that human activities have had a strong impact on LUCC in the Loess Plateau in recent decades, especially the large-scale policy of “Grain for Green” that began in 1999, which has transformed a large number of sloping farmland area into forest or grassland and improved vegetation coverage [13]. However, our understanding of the main driving factors is still controversial because some scholars have suggested that the Loess Plateau has been characterized by a warmer and more humid climate in recent years, and these changes represents the main driving factor of LUCC [18,21]. Additionally, to which extent has the land use/land cover been influenced by human activities or climate change?

LUCC, a complex system, has an important impact on ecosystems at different spatial scales through interactions with environmental factors, and although LUCC impacts the natural geographical environment by affecting the elements of the atmosphere, soil, plants and hydrology, it also affects the material circulation, energy flow, landscape structures and ecological service functions of the ecosystem [22]. LUCC on the Loess Plateau is particularly important in controlling soil erosion, improving soil quality, and maintaining carbon stability [23,24]. Simultaneously, environmental problems such as sharp declines in river runoff, water shortages, soil moisture desiccation, and degradation of plantation ecosystems are emerging, which threaten the sustainable development of society [22,25–29]. The maintenance of the water balance and ecological and social sustainable developments on the Loess Plateau have become the most important issues for the government and researchers [22,25,30–32]. However, the current assessment was not comprehensive, and there were still trade-offs among multiple ecosystem services [33]. Therefore, it is important to evaluate characteristics, driving force and environment effects of LUCC comprehensively.

Previous studies are mostly based on single-sided research or research focusing on the impact of a single environmental factor. Comprehensive research is still rare, and our understanding of LUCC processes in terms of land use and environmental factor interactions and the maintenance regional sustainable development remains restricted. Based on ecological restoration projects (“Grain for Green”) implemented since the 1980s and climate change observed in recent years, we analyzed the spatial and temporal characteristics, driving forces and environmental effects, especially ecological hydrology process of LUCC and discussed strategies for maintaining regional ecological, economical and socially sustainable development. The paper is structured as follow (Figure 1): the spatial and temporal characteristics of LUCC from 1980 to 2015; LUCC driving forces, (including climate change and human activities); environmental effects (like ecological hydrology, soil moisture, soil erosion and carbon cycle); and sustainable development of regional ecology (economic and social). The objective of this research is to provide a scientific basis for regional ecological environments and water resources management.
2. Materials and Methods

2.1. Study Area

The Loess Plateau (35°–41° N, 102°–114° E) is located in the upper and middle reaches of the Yellow River in China and has an area of 640,000 km² (Figure 2). This region is the largest loess unit in the world, has a large population and a fragile ecological environment [11]. The population increase has accelerated regional development, which has led to serious damage to the surface vegetation and steep slope reclamation, resulting in strong soil erosion [11]. Statistical analyses have indicated that the proportions of cultivated land, forest land, grassland, water bodies, construction land and unused land in the total area in 1980 were 32.9%, 14.7%, 42.2%, 1.4%, 1.8% and 6.9%, respectively. To curb soil erosion, the region has implemented a series of soil and water conservation measures since the 1980s, especially the policy of “Grain for Green” that began in 1999. Human management has transformed large-scale sloping farmland into forest land or grassland, and the vegetation coverage has been significantly improved [34]. The central part of the Loess Plateau is the key management area. The main river basins are the Huangfuchuan River, Wuding River, Yan River, Beiluo River, Jing River, Wei River and Fen River. Land use change significantly impacts ecological and hydrological processes such as hydrology, soil erosion and carbon cycling [34].

2.2. Data Resource

In this paper, the following data were used (Figure 1):

(1) Land use data were obtained from the Chinese Academy of Sciences Resource and Environmental Science Data Centre [35], with the resolution of 1 km for the years 1980, 1990, 2000, 2010 and 2015. The land use types were divided into six categories: cultivated land, forest land, grassland, water body, construction land and unused land.

(2) MODIS NDVI (Normalized Difference Vegetation Index) data were sourced from the TERRA/MOD13Q1 NDVI obtained from the NASA Earth Observation data [36]. Studies have shown that the vegetation coverage or NDVI did not change significantly before 2000 but rapidly increased after 2000 [12,37]; thus, we focused on the spatial-temporal characteristics of change after 2000. The time range was from 2000 to 2016, and the spatial and temporal resolutions were 250 m and 16 days, respectively. Images were decoded, re-projected, reformatted, and stitched using the Modis Reprojection Tool. Data in the wet season from June (Day of Year 178) to August (Day of Year 225) were...
processed using the max synthesis method, which is widely used to avoid the influences of clouds and solar altitude angle [12,19].

(3) Climate data from 129 stations and 86 stations in the Loess Plateau (Figure 2) were collected from National Climate Center of the China Meteorological Administration [38], including the daily precipitation and temperature of the Loess Plateau from 2000 to 2016. Daily climate data used to calculate annual temperature and precipitation that converted to surface data using Kriging interpolation method.

(4) Human activities data mainly including the area of farmland returning to forests or grassland on the Loess Plateau were collected from the statistical data [34].

(5) The water and sediment data from hydrological stations were obtained from the Yellow River Conservancy Commission, and the time range is from 1980 to 2015.

(6) Other data, including soil erosion, soil moisture and soil organic carbon associated with typical land use types were derived from the published literature, which is noted in the text.

2.3. Methods

2.3.1. Calculation of Land Use Cover Change

The paper employs statistical methods to determine land use trends, the ArcGIS grid calculator was used to calculate the spatial variation characteristics of land use, and the spatial transfer matrix was calculated using the ArcGIS overlay analysis function [39,40].
2.3.2. Variation Trends

The univariate linear regression formula was used to detect the variation trends. Spatial differences were observed in the series of NDVI change trends in recent few decades on the Loess Plateau, and the trend of each pixel NDVI can be simulated using the univariate linear regression [12,19,41,42]. This gradient is calculated as follows:

$$slope = \frac{n \times \sum_{i=1}^{n} i \times NDVi - \left( \frac{n}{i} \sum_{i=1}^{n} i \right) \left( \frac{n}{i} \sum_{i=1}^{n} NDVi \right)}{n \times \sum_{i=1}^{n} i^2 - \left( \frac{n}{i} \sum_{i=1}^{n} i \right)^2}$$

(1)

where, \(i\), is the number of the year and extends from 1 to \(n\) (\(n = 17, 2000–2016\)); and \(NDVi\) represents the max synthesis NDVI in the wet season of the \(i\)-th year. A slope value >0 indicates an increasing trend, while a slope value <0 represents a decreasing trend during the 17-year period. This method was also used for detecting the spatial-temporal trends of climate factors.

2.3.3. Partial Correlation Analysis

A linear regression analysis and partial correlation analysis were used to identify spatial-temporal changes of the NDVI and its response to climate factors. The relationship between the NDVI and different climatic factors (precipitation and temperature) was evaluated to detect possible correlations between meteorological factors [19,41]. The partial correlation coefficients are calculated as follows:

$$r_{12 \cdot 3} = \frac{r_{12} - r_{13} \times r_{23}}{\sqrt{(1 - r_{13}^2) \times (1 - r_{23}^2)}}$$

(2)

$$r_{13 \cdot 2} = \frac{r_{13} - r_{12} \times r_{23}}{\sqrt{(1 - r_{12}^2) \times (1 - r_{23}^2)}}$$

(3)

where \(r_{12}, r_{13},\) and \(r_{23}\) are the correlation coefficients between the NDVI and temperature, between the NDVI to precipitation, and between temperature and precipitation, respectively, and they were determined using the method of univariate linear regression formula. \(r_{12 \cdot 3}\) and \(r_{13 \cdot 2}\) represent the partial correlation coefficients between the NDVI and temperature and precipitation respectively. The t-test was used to assess the significance of the partial correlation coefficient.

2.3.4. Ecohydrology Analysis

To further explore cause–effect mechanism of LUCC, we carried out ecohydrology analysis through water balance model in addressing relationship between hydrological processes in ecosystem and climate change, LUCC, human activities. A water balance states that the amount water entering the soil must be equal to the amount of water leaving the soil plus the change in the amount of water stored in the soil [43]. The model can be described as follows:

$$nZr \frac{ds(t)}{dt} = R(t) - I(t) - Q[s(t), t] - E[s(t)] - L[s(t)]$$

(4)

This water has a volume equal to the porosity of the soil \((n)\) multiplied by its saturation \((s)\) and the depth of the plant’s roots \((Zr)\). The differential equation \(\frac{ds(t)}{dt}\) describes how the soil saturation changes over time. The terms on the right-hand side describe the rates of rainfall \((R)\), interception\((I)\), runoff \((Q)\), evapotranspiration \((E)\), and leakage \((L)\). The depth of loess more than 50 m, and rainfall only affects the soil moisture in the surface layers at a depth of 40 cm. So, we assumed the leakage was negligible.
3. Results

3.1. Temporal and Spatial Distribution Patterns of LUCC on the Loess Plateau

The overall change characteristics of land use showed decrease in the areas of cultivated land, grassland, water bodies and unused land and an increase in the area of forest land and construction land over the past 35 years (Figure 3). The area of cultivated land, grassland, water bodies and unused land decreased from 205,764 km$^2$, 264,402 km$^2$, 9024 km$^2$ and 43,475 km$^2$ in 1980 to 202,134 km$^2$, 261,064 km$^2$, 8505 km$^2$ and 41,847 km$^2$ in 2015, respectively. Additionally, the area of forest land and construction land increased from 92,340 km$^2$ and 11,238 km$^2$ in 1980 to 94,814 km$^2$ and 17,878 km$^2$ in 2015, respectively. The proportion of cultivated land, forest land, grassland, water bodies, construction land and unused land to the total area changed from 32.9%, 14.7%, 42.2%, 1.4%, 1.8% and 6.9% in 1980 to 32.3%, 15.1%, 41.7%, 1.4%, 2.9% and 6.7% in 2015, respectively. For more than 30 years, the land use structure of the Loess Plateau has not changed significantly.

Figure 3. Structural changes of land use in the Loess Plateau from 1980 to 2015.
The middle part of the Loess Plateau was the key region for soil and water conservation and represented the most significant area of land use change in the past few decades. According to the basin statistics, the Yan River, Jing River and Wei River basins were the most obvious areas of cultivated land reduction from 1980 to 2015. From 1980 to 2015, the cultivated land area decreased from 3257 km$^2$, 26,070 km$^2$ and 23,113 km$^2$ to 3062 km$^2$, 25,187 km$^2$ and 22,351 km$^2$, which represented reduction rates of 5.9%, 3.4% and 3.3%, respectively. In addition, the Wuding River and the Yan River basins were the most obvious areas of increasing forestland from 1980 to 2015. The area increased from 1588 km$^2$ and 840 km$^2$ to 2107 km$^2$ and 1063 km$^2$, which represented total increases of 32.7% and 26.6%, respectively. All construction land in the basin increased significantly at a rate of more than 50%. Other types of land use were not obviously changed.

The land use type of the Loess Plateau experienced a phase change in the year 2000. We analyzed the characteristics of change before and after 2000. The main changes from 1980–2000 were an increase of cultivated land area (increase of 1928 km$^2$) and decrease of grassland area (reduction of 1770 km$^2$). The main change from 2000 to 2015 was a reduction of cultivated land and grassland area (reduced by 5558 km$^2$ and 1568 km$^2$, respectively) and an increase in the area of forest land (increase by 2593 km$^2$). According to the land use transfer matrix, we analyzed the dynamic changes in land use types on the Loess Plateau. From 1980 to 2015, the area presented dynamic land use type changes in the Loess Plateau was 77,000 km$^2$, accounting for 11.5% of the total area. According to the statistics of land use types, the cultivated land, grassland and unused land areas changed strongly, with 12,573 km$^2$, 14,436 km$^2$ and 6379 km$^2$ converted into other land use types, respectively, with change rates of 6.1%, 5.4% and 14.7%, respectively. According to the river basin statistics, the dynamic changes of land use types in the Huangfuchuan River, Wuding River and Yan River basins were the most significant, and the proportions of changed area to the total area were 33.19%, 20.89% and 12.34%, respectively.

Over the past 35 years, the vegetation coverage (NDVI) has changed significantly on the Loess Plateau. Significant changes in vegetation coverage, which reflects the vegetation conditions, were not observed before 2000, and a rapid increase were observed after 2000 [12,37]. We focused on the characteristics of change after 2000. The value of max NDVI in summer increased from 0.49 in 2000 to 0.61 in 2016, for an average increased rate of 0.006 per year. The change in the central part of the Loess Plateau was more obvious (Figure 4a). The max NDVI in summer of the Huangfuchuan River, Wuding River, Yan River, Beiluo River, Jing River, Wei River and Fen River basins increased by 47.3%, 35.0%, 44.9%, 19.3%, 30.6%, 23.8% and 23.0% from 2000 to 2016, respectively (Figure 4b). The most obvious change region of NDVI was Huangfuchuan River and Yan River basins, the central part of the Loess Plateau. The area of NDVI decreased at 8.5% of total area, and it was mainly concentrated in Xi’an and surrounding regions.

Figure 4. NDVI change on the Loess Plateau from 2000–2016: (a) Spatial patterns of change rates; (b) Temporal change on the Loess Plateau and seven catchments.
3.2. Driving Factors of LUCC on the Loess Plateau

3.2.1. Natural Environmental Factors

LUCC on the Loess Plateau is mainly affected by anthropogenic factors, such as climate change and socioeconomic development [11,12,30]. We considered that changes in land use type would mainly be caused by human activities, and partial correlation coefficients were used to detect the relationship between the NDVI and climate change from 2000 to 2016. Temperature and precipitation have become the most important climatic factors affecting the NDVI. The overall climate change of the Loess Plateau from 2000 to 2016 was characterized by warming and humidification. The increased rate of annual temperature and precipitation were 0.02 °C/year and 3.58 mm/year respectively, and these changes were observed over a great majority of the region. However, the temperature decreased in the central part of the Loess Plateau over an area of 40,592 km², which accounted for 6.3% of the total area. The correlation between the NDVI and precipitation trends was higher than that between the NDVI and temperature, and variations were observed (Figure 5). The correlation coefficients between the NDVI and temperature were from −0.90–0.92, with an average of 0.06, and the values were less than zero in the western and central part of the Loess Plateau (39.3% of the total area). The correlation coefficients in the northern and southern were greater than zero, indicated that warmer climate promotes vegetation restoration in this region. However, the correlation coefficients between the NDVI and precipitation were different with temperature, as shown in Figure 5b, were from −0.9–1.0, with an average of 0.34, which indicated a significantly positive correlation. The correlation coefficients were greater than zero in a majority of the region (86.4% of the total area), except in the southern Loess Plateau. Therefore, the impact of precipitation on vegetation was greater than that of temperature. According to the climate change analysis, the degree of warming and humidification in recent decades is greater in arid and semiarid areas than in the semi-humid areas in the southeastern part of the Loess Plateau. In arid and semiarid areas, water condition is the restricted factor, increased precipitation will promote vegetation growth. So, the influence of climate change, mainly increased precipitation on LUCC on the Loess Plateau is greater in the northwest than in the southeast.

**Figure 5.** Relationship (partial correlation coefficient) between NDVI and different climatic factors: (a) NDVI and temperature; (b) NDVI and precipitation.

3.2.2. Human Activities

Human activities such as returning farmland to forest and social and economic developments have an important impact on LUCC. To control soil erosion since the 1980s, various projects have been implemented on the Loess Plateau, such as the “Comprehensive Management of Small Watersheds”, “Natural Forest Protection” and “Grain for Green”, and these projects have played a significant role in ecological construction (Figure 6). Before 1999, the governance in this period was weak, and the total administrative area was 145,000 km², which did not have a significant effect on LUCC. After
1999, large-scale sloping farmland was converted into forest land or grassland. From 2000 to 2012, the areas of artificial forest and grassland were 75,000 km² and 26,000 km², respectively, on the Loess Plateau, and the area of closed treatment was 100,000 km². Some of the grasslands became forest through succession and reforestation, and the proportion enlarged dramatically after 2000 as result of artificial revegetation. We also found that the decrease in farmlands was more at higher elevations and steeper slopes. Among these areas, the Wuding River and Yan River in the central part of the Loess Plateau, were the key management regions (Figure 4a) [34]. According to the above information, the Loess Plateau, especially in Wuding River and Yan River basins were the most significant areas for land use change and vegetation restoration, indicating that human activities play a more important role in vegetation change than climate variability in this region (Figures 3 and 4a).

Figure 6. The main measures of soil and water conservation on the Loess Plateau (photographed in the Wuding River Basin in 2017): (a) terrace; (b) check dam; (c) grain for forest; (d) closed treatment.

3.3. Environmental Effects of LUCC on the Loess Plateau

3.3.1. Ecological Hydrology

The change in the underlying surface of the Loess Plateau has an impact on ecological and hydrological processes, water balance and water conversion. After vegetation restoration, vegetation will increase rainfall interception, vegetation transpiration and soil infiltration and reduce surface runoff (Figure 7) [44]. According to the plot experiment, the interception efficiency of vegetation on surface runoff increases with increases in the recovery time. The interception efficiency is related to the vegetation type and vegetation coverage. For example, the runoff coefficient ($R_c$) is closely related to the vegetation cover ($R_c = -9.12NDVI^2 + 6.65NDVI - 1.06$, $R^2 = 0.30$) [45,46]. With the increase of vegetation coverage, the regional actual evapotranspiration was showing a significant increasing trend, the increasing rate of actual evapotranspiration of 1.34 mm/a [47]. At the same time, vegetation changes led to a decline in runoff in the middle reaches of the Yellow River. The annual average runoff (Huayuankou hydrological station, the Yellow River inlet of the Loess Plateau) decreased from 3.3 billion m³ in 1980–1999 to 2.6 billion m³ in 2000–2015. Simultaneously, the hydrological process changed when the peak discharge of 500–1000 m³/s dropped to less than 300 m³/s after 1999, and
LUCC contributed more than 70% to the Yellow River runoff reduction [48]. We also noted that since 2000, the observed river flow at Huayuankou Station tended to be lower than at Lanzhou Station (Figure 7b(b4)), emphasizing that water consumption had already exceeded the water yield within the Loess Plateau.

![Diagram of terrestrial ecosystems](image)

**Figure 7.** Ecological hydrology and vegetation restoration: (a) Schematic of terrestrial ecosystems water cycle after vegetation restoration; (b) Precipitation (b1), NDVI (b2), actual evapotranspiration (b3, data from the literature [47]) and difference of river discharge at the Huayuankou station (outlet) and Lanzhou station (the Yellow River inlet of the Loess Plateau) (water discharge = water discharge in Huayuankou − water discharge in Lanzhou) (b4).

### 3.3.2. Soil Moisture

The water supply factor is the most important limiting factor in the Loess Plateau for vegetation recovery. The water balance indicator of the difference between evapotranspiration and precipitation was introduced to demonstrate the sustainability of vegetation water use in the Loess Plateau. Precipitation is the main source of water input while evapotranspiration and runoff are the main sources of water output in the Loess Plateau. From above, we know that water consumption had already exceeded the water yield within the Loess Plateau from 2000. So, vegetation restoration will reduce soil moisture, especially in the regions of vegetation improved significantly or forest planted exotic species [26]. Soil is an important part of terrestrial ecosystems, and LUCC causes soil water to be redistributed in the soil system. After vegetation restoration, soil water absorption was increased by plant roots and plant transpiration increased, resulting in a lower soil moisture content than the field stable water holding capacity (Figure 8a). Soil moisture is related to land use types, vegetation restoration years, and vegetation types. According to the analysis of a large amount of monitoring data, the average soil water content decreased after the conversion of cultivated land on the Loess Plateau, and the soil water content on cultivated land was highest, followed by shrub and arbor forest land [30]. The soil moisture decreased with increasing years of fallowing. The soil moisture in the land after cultivated land was returned to forests after 10, 20 and 32 years showed decreases of 10%, 17% and 8%, respectively. Differences in soil moisture were observed under different tree species types. For example, the soil moisture was significantly lower in *Pinus tabulaeformis* and *Robinia pseudoacacia* forests than in *Caragana korshinskii*, and *Pinus tabulaeformis* and *Robinia pseudoacacia* were the main species involved when farmland was returned to forest on the Loess Plateau [26].
At the regional scale, after the implementation of the “Grain for Green” project, soil moisture decreased in most areas of the Loess Plateau, and matched the vegetation improved well. Rainfall is the main method of recharging of soil moisture in the Loess Plateau, which only affects the soil moisture in the surface layers at a depth of 40 cm. Therefore, replenishing deep soil moisture through rainfall is difficult. In this study, the vegetation restoration on the Loess Plateau was found to be close to the vegetation carrying capacity threshold of water resources in the region, and problems are observed in the ecological construction of the Loess Plateau due to insufficient water resources, unreasonable vegetation allocation and reduced ecological service functions. Soil desiccation is one of the key factors that influences the sustainable development of crop production on the Loess Plateau. Maintenance of the balance of water consumption and effective precipitation in different land use types and finding a reasonable spatial allocation of land use to prevent the occurrence of dry soil layers are still problems that need to be studied in depth.

### 3.3.3. Soil Erosion

LUCC on the Loess Plateau plays an important role in controlling strong soil erosion by reducing rainfall kinetic energy, slowing slope runoff, and changing surface hydrological processes. According to the runoff plot experiment, soil erosion is closely related to land use type, coverage and composition. The soil erosion intensity is much larger in cultivated land than in other land use types. The soil erosion intensity of sloped farmland is dozens of times that of forest land or grassland under the same conditions. After the conversion of cultivated land to grassland and forest land, the soil erosion intensity decreases by more than 90% [28,46,51]. From 1999 to 2011, the area of farmland being returned to forests on the Loess Plateau totaled 7.52 million hm², were mainly distributed in the central part of the Loess Plateau, and strong erosion was effectively curbed [52].

Using the revised universal soil loss equation (RUSLE) model, the soil erosion changes on the Loess Plateau since the 1980s were studied. The soil erosion intensity showed a significant decreasing trend. The average erosion modulus decreased from 5555 t km² a⁻¹ before 1999 to 4616 t km² a⁻¹...
after 1999, and the rate of decline was 67 t km$^2$ a$^{-1}$ per year. The current erosion intensity is close to the level of agricultural civilization (before 700 AD) and has reached a relatively stable state [22,24]. Over the past 35 years, more than 20% of the low vegetation cover areas on the Loess Plateau have been transformed into a high vegetation coverage area. The increase in vegetation coverage and land use change are the main reasons for the weakening of soil erosion intensity on the Loess Plateau [12]. According to the above information, the area of cultivated land reduction in the past 35 years is 3630 km$^2$. In 2015, more than 200,000 km$^2$ of cultivated land remained, and soil erosion was strong in these areas, and the average soil erosion intensity was still higher than the allowable erosion intensity (1000 t km$^2$ a$^{-1}$). Therefore, the implementation of a new round of policies for returning farmland to forests still requires soil and water conservation.

3.3.4. Carbon Cycle

Vegetation and soil land ecosystems are two carbon pools. After vegetation restoration, biological carbon sequestration as well as soil carbon sequestration increases [53]. The carbon sink capacity is related to the period of returning farmland as well as vegetation type, soil moisture, etc. The vegetation type and return of farmland are the main factors affecting carbon storage in the Loess Plateau. Ecosystem NPP (net primary productivity) has a clear relationship with land use types. The NPP is significantly higher in forest land than in cultivated land and grassland, and increased with vegetation restoration. The NPP of the Loess Plateau increased from 280 g C m$^{-2}$ a$^{-1}$ in 2000 to 370 g C m$^{-2}$ a$^{-1}$ in 2015, with an average annual increase of 4.3 g C m$^{-2}$ a$^{-1}$ per year [37]. At the regional scale, ecosystem NPP is related to water resources, and the production potential of the Loess Plateau is close to the carrying capacity threshold of water resources [27].

The soil carbon pool is the largest carbon storage system with the longest residence time in the terrestrial ecosystem. LUCC affects the soil carbon cycle and reserves. The soil carbon sequestration capacity was significantly enhanced after vegetation restoration. The soil organic carbon storage increased with the extension of the return period of farmland. According to the study of the soil carbon change in the artificial forest of the Zhifanggou watershed in the hilly and gully region of the Loess Plateau, the soil organic carbon storage is 3.1 times that of the former tillage after 35 years of farmland return, and the organic carbon storage in the abandoned land and grassland continues to increase with returning farmland. After 35 years, the organic carbon storage was 2.9 times and 2.0 times higher than that before the farmland was returned [25]. After the farmland had been returned for more than a certain period of time, the carbon sink had stabilized and gradually turned into a carbon source. According to the study of vegetation succession in Ziwuling, after the vegetation was destroyed, the natural succession time was more than 150 years; thus land use change would affect the spatial distribution pattern of soil carbon for a long period of time [54].

4. Discussion

The basic characterizes of LUCC was decreased of cultivated land and increased of forest land and grassland, increased of vegetation coverage on the Loess Plateau. Both natural and anthropic factors result in vegetation changes. We found that the influence of climate change, mainly increased precipitation on LUCC on the Loess Plateau is greater in the northwest than in the southeast, and human activities play a more important role in vegetation change than climate variability in the central part regions. Driving factors of LUCC is complex because of environmental heterogeneity [22,45]. According to the comparative analysis, the proportion of land use change and vegetation coverage in the main areas returning farmland to forests or grassland (Wuding River and Yan River) was significantly higher than that in other regions, indicating that human activities play an important role in LUCC. At the same time, more than 60% of the vegetation on the Loess Plateau had been significantly restored, and the vegetation area is larger than the area in which the ecological restoration project was implemented. Therefore, climate change, especially precipitation increased has a significant effect on LUCC. In fact, interactions are observed between land use/cover and regional socioeconomics
and climate [12]. For example, LUCC will improve the regional economic structure and increase the regional economic income. Simultaneously, regional economic and social development levels have a profound impact on land use patterns. After economic and social development, the land reclamation rate is significantly reduced, and areas of forest land or grassland are increased [18]. Further, the data of high resolution society economic and the method of system model are required to quality the interaction between climate change, human activities and vegetation.

Vegetation restoration played important role in improving ecosystem service, such as controlling soil erosion and increasing carbon sequestration. However, the land use structure has not changed significantly, cultivated land and grassland was the main type on the Loess Plateau. More than 200,000 km² was cultivated land in 2015, caused severe soil erosion on the Loess Plateau. The reason of average soil erosion modules decreased not only vegetation restoration, but also the implication of soil and water conservation projects, such as terrace and check dam [55,56]. Additionally, LUCC has an important negative impact on ecosystems at different spatial scales, caused service problem on the Loess Plateau, such as vegetation degradation, declining ecological stability and an imbalance of water resources [22,27]. After the implementation of the “Grain for Green” project on the Loess Plateau, 6847 km² of sloping farmland was converted into forest land or grassland, and after the vegetation was restored, a dried soil layer was formed, which restricted sustainable ecological development. We found that dry soil layer at 2 m in the 20-year-old forest land and exceeding 5 m from the ground, especially in the place planted exotic species. More importantly, the species involved when returning farmland to forests in this area were mainly exotic species (such as Pinus tabulaeformis, Robinia pseudoacacia, etc.), which will decline ecological stability [26]. The Loess Plateau is fragile ecological zone, especially in arid and sub arid regions, and water shortages are the main reasons for the ecological fragility. The stability of artificial vegetation is low, and a large number of “little old trees” appeared in the northern part of the Loess Plateau [22]. Vegetation restoration exacerbates the contradiction between water supply and demand. From previous study, the vegetation productivity of the Loess Plateau is close to the carrying capacity threshold of water resources, and this threshold tends to be stable under natural conditions [27]. Therefore, we can confirm that the stress of water resources will increase with the vegetation restoration in this tendency. Previous study shown that the water use efficiency and the degree of water stress showed appreciable differences among the various zones, forest, forest steppe, steppe and desert from southeast to northwest in the Loess Plateau [26,57]. We found that in the central part, especially Wuding River and Yan River basins, the NDVI value was high in recent years, but the precipitation is low in this region, will causes serious water stress. Changes in the type of vegetation restoration by humans similar to be an efficient way to promote water balance. In the future, vegetation restoration should improve the quality of forest and grass areas and the stability of artificial vegetation under the principles of zonality and local conditions. How to make water resources effective utilization and management is the main concern of regional sustainability development.

From previous analysis, human activities played an important role in vegetation restoration. Meanwhile, ecological projects have an obvious effect on economic and social developments. The Grain-for-Green ecological restoration project has been proved to be an important measure to mitigate human pressures on natural ecosystems and to improve ecosystem services. Starting from 1999, the Grain-for-Green Project was regarded as the largest ecological restoration program in developing countries around the world, with an ambitions to curb the degrading and disturbed ecosystems in China. The Chinese government has invested over $US 40 billion on the Grain-for-Green Project by 2050, and over the past decade approximately $US 28.8 billion has already been invested on the conversion of cultivated land on steep slopes (≥25°) to perennial vegetation. After the implementation of “Grain for Green Project”, the output value of the tertiary industry in the Loess Plateau increased significantly. The average annual growth rate from 1995 to 2010 was 17.6%, and the economic benefits of ecological environmental construction were gradually reflected. However, the growth rate of agricultural industry was slowly, and the proportion in economy decreased in past 20 years. Currently, there are 98 million people in the region. After the conversion of sloping land to forest land or
grassland, food production in the region was difficult to meet the needs of the population, which will create food security problems. The incomes generally balanced expenditures and the major items in expenditure were living expenses, investment in agriculture, and educational and medical expenses. However, the Loess Plateau still has problems with unsustainable economic and social developments, because the main reason for the smooth implementation of the policy of the “Grain for Green” is reliance on government financial subsidies. In addition, the region has a large population, a fragile ecological environment, and uneven regional development. Most of the population in rural area, which increased the press of vegetation restoration. According to previous analyzes, more than 200,000 km² land was cultivated land, and development and construction destroyed and will further damage ecology. Urbanization is the way to reduce the population in rural area that could promote the natural ability of vegetation restoration. Most importantly, a continuable mechanism is necessary for ecological construction. According to the latest policy, the state of the ecological forestry subsidy has been extended for 8 years on the basis of the original 8-year subsidy. The unilateral investment method has exerted pressure on regional sustainable development [1,58]. Implement of the compensation mechanism for ecological public welfare forests could be an approach to promote social and ecology sustainability. In the future, the economic and social benefits of forest and grassland must be further improved, the proportion of the tertiary industry in the region must be increased, and rural population transfer and regional social development must be promoted.

Our findings in this research prove that ecological hydrological process after vegetation restoration in the Loess Plateau. We connected precipitation, evapotranspiration, runoff, soil erosion and carbon sequence to evaluated LUCC in past 35 years. However, due to lack of high-resolution data and efficient method, it is difficult to reveal the role and feedback mechanism. The future research needs to strengthen the application of system dynamics and other cross-disciplinary disciplines, and collect or monitor more data used to analysis comprehensively.

5. Conclusions

Climate change and human activities have led to considerable LUCC in the Loess Plateau, which has had an important impact on ecological and environmental systems. We analyzed the temporal and spatial characteristics, driving forces and environmental effects of LUCC on the Loess Plateau since 1980. The main conclusions are as follows: (1) Land use types show regional variation characteristics. The Wuding River and Yan River basins in the central part of the Loess Plateau are the most obvious regions of change, although the land use structure has not changed overall. (2) LUCC is affected by climate change and human activities. The influence of climate change on LUCC on the Loess Plateau is greater in the northwest than in the southeast. Regional differences are observed in the contribution rates of climate change and human activities, and changes in the central part of the Loess Plateau are mainly caused by human activities. (3) LUCC on the Loess Plateau will have a long-term impact on reducing surface runoff, controlling soil erosion, reducing soil moisture and increasing carbon sequestration. LUCC will also exert negative effects on regional ecological restoration. Due to the regional and natural differences on the Loess Plateau and the complexity of the interactions among land use types and environmental factors, it is difficult to reveal the role and feedback mechanisms between LUCC and environmental factors by analyzing single environmental factors.

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