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Effect of Ecological Construction Engineering on Vegetation Restoration: A Case Study of the Loess Plateau

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Abstract: Since the 1980s, with rapid economic development and increased attention given to ecological protection, China has launched a series of ecological-restoration programs to restore the local environment through afforestation and natural forest protection. The evaluation of vegetation restoration is an important part of evaluating the effectiveness of ecological restoration. The Loess Plateau is an area where ecological problems are concentrated, and it is a key area of ecological construction in China. This paper takes the Loess Plateau as the research area, using remote sensing and geographic information technology combined with ecosystem structural changes and an improved residual model to study vegetation restoration. The following main conclusions were drawn: (1) From 1990 to 2000, the farmland area increased by 3084.81 km^2, resulting in the encroachment of a large area of grassland and shrubland. (2) With the implementation of ecological engineering, the area of returning farmland to forest and grassland reached 18,001.88 km^2; in this period, the NDVI of vegetation increased rapidly, and the area that increased comprised 91.90% of the total area, of which the area of significant increase reached 65.78%. The quality of vegetation was restored to a great extent, and ecological engineering played a major role in this stage. (3) Under the background of large-scale implementation of ecological restoration, the urban area of the Loess Plateau continues to expand.

Keywords: ecosystem; vegetation quality; climatic factors; improved residual model

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1. Introduction

In recent decades, due to the rapid development of urbanization, farmland expansion, deforestation, reclamation and other human activities, China has suffered serious ecological and environmental problems, including wetland degradation, soil erosion, sandstorms, desertification, wildlife-habitat loss and other ecological problems [1]. Since the 1980s, with rapid economic development and increased attention toward ecological and environmental protection, China has launched a series of ecological-restoration programs to mitigate these increasingly devastating environmental problems. These projects include the "Three-North" Shelterbelt Development Program (TNSDP), the Grain for Green Program (GFGP), the Natural Forests Conservation Program (NFCP), the Beijing-Tianjin Sand Source Control Program (BSSCP) and others [2,3]. These projects have been implemented with the primary goal of restoring the local environment by planting trees and protecting natural forests in semiarid and arid areas [4–9]. However, the effect of the implementation of these ecological projects needs to be further explored.

As an important part of terrestrial ecosystems, vegetation plays a critical role in the process of land-surface energy exchange, the water cycle and the biogeochemical cycle [10–13]. The improvement of vegetation growth can reduce runoff erosion, wind

erosion and soil and water conservation by changing the surface reflectance and underlying surface roughness, and promote the regional ecological environment [14]. Ecological environment restoration and management is a long-term and arduous task in China; monitoring vegetation change is an effective indicator to reflect regional ecological change, and its spatiotemporal variation characteristics can be used as the evaluation basis for ecological-restoration projects [15–17]. Using remote-sensing data sources and methods to analyze global or regional vegetation-quality change has unique advantages [18]. The normalized difference vegetation index (NDVI) is the best indicator of vegetation growth status and vegetation coverage, and it is an effective indicator used to monitor global or regional vegetation change [19–23]. In the application of vegetation-restoration assessment, the NDVI is mainly used to reflect the vegetation quality of an area to realize research on the effect of vegetation restoration [24–27].

As one of the regions with earlier development and greater artificial transformation in the history of China, the Loess Plateau is deeply affected by the interference of human activities, especially in recent decades, and deforestation and overgrazing have seriously damaged the local ecological environment. In addition, the Loess Plateau is located in a semiarid and semihumid climate zone, with serious wind and water erosion, resulting in a series of ecological and environmental problems such as soil erosion and desertification [27,28]. The Loess Plateau is an area where ecological problems are concentrated, and it is a key area of ecological construction in China [29]. Therefore, the evaluation of vegetation restoration in the Loess Plateau is an important part of the effectiveness evaluation of ecological restoration, and this information can reveal the effectiveness of ecological restoration projects in the region and provide theoretical reference and scientific support for the smooth implementation of the projects.

Vegetation growth is affected by environmental driving factors (such as climate change) and human activities [30]. To date, many scholars have performed much work using the NDVI to study the vegetation status of the Loess Plateau [27,31,32], and at the present stage are mainly focused on the determination of the influencing factors of climate factors and human factors in NDVI changes. There are three methods to distinguish these factors in existing studies: (1) using the correlation between climate and the NDVI and assisting the corresponding statistical data to indirectly distinguish the impact of climate factors and human activities on the NDVI change [33]; (2) using a water-use efficiency change model to extract human impacts, which is suitable only for arid and semiarid regions where vegetation change is mainly affected by precipitation [34]; and (3) using a residual model to better distinguish the impact of climate factors and human activities on vegetation, a method that is widely used at present [34–36]. However, these methods obtain only the positive or negative effects of human activities on the NDVI, and provide no clear conclusion for the areas affected by humans and the climate. In addition, these studies usually use a single data set to evaluate the vegetation dynamics in a relatively short period of time or with a coarse resolution, resulting in a lack of long-term and high spatial-resolution monitoring of vegetation change on the Loess Plateau, which limits the representativeness of previous studies on vegetation-quality restoration on the Loess Plateau.

Therefore, through monitoring and analyzing the ecosystem changes on the Loess Plateau from 1990 to 2015, we hope to obtain data on the ecosystem changes in the region before and after the implementation of ecological projects to provide basic data support for the implementation of the projects. On the basis of the above research, combined with the constructed long-term series of the NDVI data, the vegetation quality on the Loess Plateau before and after the implementation of ecological engineering was compared and analyzed. We used the improved residual model to determine the factors that caused the change in vegetation quality, and we evaluated the vegetation restoration of the ecological project on the Loess Plateau from the two aspects of "quantity" and "quality", so that the implementation effect of the ecological project in the study area could be quantitatively analyzed and displayed in a more intuitive way. The purpose of this study was to provide

a theoretical basis for the formulation of eco-environmental protection-related policies and regional sustainable developments.

2. Study Area

The Loess Plateau is located in northern-central China, in the middle of the Yellow River basin. Its geographical location is 33°41′–41°07′N, 100°54′–114°07′E (Figure 1) The Loess Plateau spans Shanxi, Ningxia, Shaanxi, Gansu, Inner Mongolia, Henan and Qinghai Provinces, with a total area of 62.36 × 104 km^2, accounting for 6.44% of the total land area in China. The terrain in the region is high in the northwest and low in the southeast, with thousands of gullies and broken terrain. The climate is a continental monsoon climate; i.e., it is cold and dry in winter, windy and sandy in summer, and hot and rainy in summer. From southeast to northwest, the vegetation can be divided into forest zones, forest steppe zones, typical steppe zones, desert steppe zones and grassland desertification zones. The main types of soil are loessial soil and chernozem.

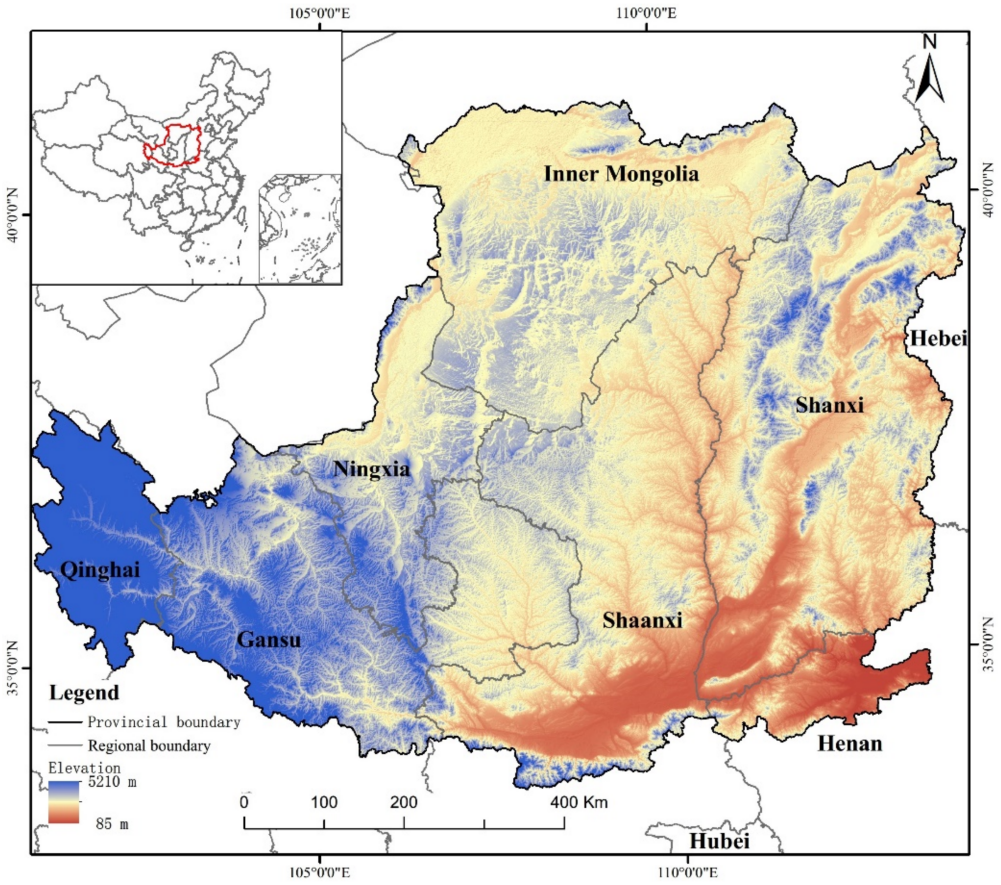


Figure 1. The location map of the Loess Plateau.

3. Materials and Methods

3.1. Ecosystem Classification

The satellite images used for ecosystem analysis in the study area included cloud-free Landsat TM images from 1990/2000/2005/2010 and OLI images from 2015, which were downloaded from the USGS website (http://glovis.usgs.gov/, accessed on 1 April 2021). Most of the selected images were obtained from June to September, and missing images or images of poor quality were replaced with images from the closest month or year during this period. Before we extracted the ecosystem information, the images were preprocessed by geometric correction, radiometric correction and atmospheric correction. In this study, the object-oriented classification method and human–computer interactive-interpretation method were combined to extract the status and dynamic information of the ecosystem on

the Loess Plateau [37–39]. In detail, the 2010 ecosystem data set adopts the classification method based on the combination of object-oriented automatic classification and ground survey for image classification (Figure 2); the ecosystem data sets of 1990, 2000, 2005 and 2015 were extracted based on the data of 2010 through human–computer interaction. Seven different ecosystem types were identified (Table 1): forest, shrub, grassland, farmland, wetland, urban and desert [40]. Using random verification points obtained from the field and Google Earth high-resolution images, the accuracy of the interpretation results of the Loess Plateau ecosystem in 2010 was verified. Specifically, 10% of the spots in each operation area were randomly selected for inspection; in order to ensure the quality of inspection, it was necessary to use a random sampler to sample the ecosystem patches in the ArcGIS environment. With the support of ArcGIS and Google Earth synchronization software, the high-resolution image on Google Earth was used as reference for verification; at the same time, the actual landscape photo library could be used as a reference for verification of the areas that had completed the field investigation. The results showed that the accuracy of the data was 94% in the first level and 86% in the second level [41,42]. Finally, five periods of ecosystem data for the Loess Plateau were established: 1990, 2000, 2005, 2010 and 2015.

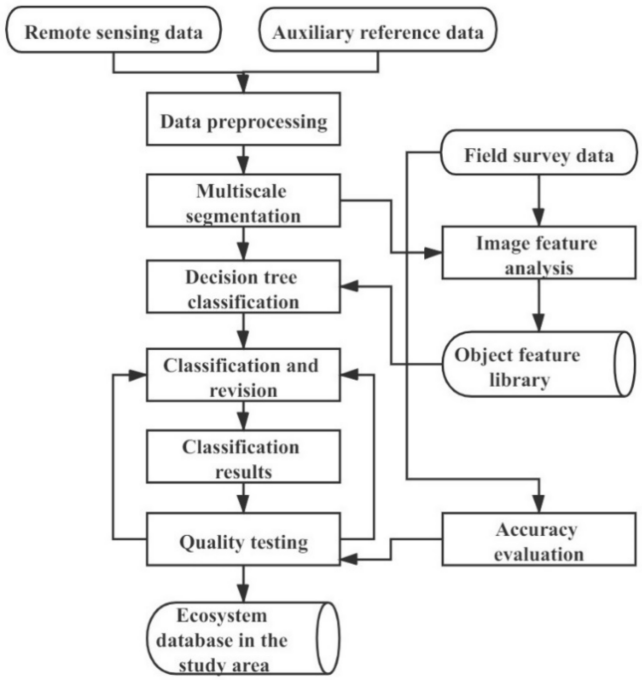


Figure 2. Flowchart of ecosystem information extraction in Loess Plateau.

Table 1. The six ecosystem types with detailed descriptions.

Ecosystem Types	Description
Forest	Land mainly covered by arbor plants (height > 5 m)
Shrub	Land mainly covered by shrub plants (height < 5 m)
Grassland	Land mainly covered by herbaceous plants
Farmland	Land mainly covered by crop vegetation
Wetland	Natural or artificial marshes and other shallow-water areas with static or flowing water bodies
Urban	Artificial surface of human living land
Desert	Land distributed in arid and semiarid areas with vegetation coverage of less than 4%

3.2. NDVI Data Sources and Preprocessing

The remote sensing datasets used in this study included the NDVI datasets from NOAA/AVHRR and TERRA/AQUA MODIS. The NOAA/AVHRR NDVI dataset was generated from the Global Inventory Modeling and Mapping Studies (GIMMS) of the Goddard Space Flight Center (GSFC) with a spatial resolution of 8 km × 8 km, a 15-day temporal resolution and an Albers conic projection in 32-bit GeoTIFF format from January 1990 to December 2006 (ftp.glcf.umiacs.umd.edu, accessed on 1 April 2021). The data were preprocessed for geometric correction, radiometric correction and atmospheric correction; additionally, the maximum value composite (MVC) was used to reduce the effects of clouds, atmosphere and solar elevation angles [43]. MOD13A3 is the monthly vegetation index product developed by the MODIS Terrestrial Product Group. It includes the MVC NDVI and enhanced vegetation index (EVI); additionally, it has a spatial resolution of 1 km × 1 km and can be accessed through the NASA Earth Observation System Data Sharing platform (https://earthdata.nasa.gov/, accessed on 1 April 2021). For this study, the data from 2000 to 2015 were downloaded.

A previous study found a large difference between the GIMMS and GIMMS 3g data sets for the Northern Hemisphere, and suggested that GIMMS and MODIS could be used in conjunction with each other [44]. The time series of the NDVI data can be extended using the correlation between the GIMMS NDVI and the MODIS NDVI. Here, monthly GIMMS NDVI data were generated using the MVC method via the 15-day NDVI data set, and then the monthly NDVI data set of GIMMS was resampled based on the MODIS 1 km grid. This study used the NDVI as an indicator to study the status of vegetation. In general, areas where the NDVI ≤ 0 are nonvegetated regions. To eliminate the effects of no vegetation, the grid values with NDVI > 0 in each month were selected to calculate the linear correlation coefficient (Table 2) between the GIMMS NDVI and the MODIS NDVI in China from 2000 to 2006. Finally, based on this relationship, the time series of the MODIS NDVI was extended by using the GIMMS monthly NDVI from 1982 to 1999 [45–47].

Table 2. The correlation between the GIMMS NDVI and the MODIS NDVI.

Month	N	Parameter Estimation		Regression Results	
		a	b	r^2	RMSE
January	226,985	0.727	0.033	0.845	0.051
February	222,175	0.749	0.023	0.873	0.042
March	335,459	0.709	0.030	0.838	0.045
April	370,184	0.781	0.020	0.875	0.048
May	376,391	0.824	0.013	0.873	0.064
June	391,512	0.849	0.010	0.852	0.083
July	421,885	0.888	0.007	0.881	0.087
August	424,014	0.883	0.010	0.877	0.089
September	413,307	0.855	0.019	0.872	0.080
October	373,024	0.792	0.024	0.879	0.056
November	322,274	0.792	0.017	0.915	0.042
December	307,161	0.752	0.020	0.874	0.047

3.3. Meteorological Data Sources and Preprocessing

The meteorological data were derived from the China Meteorological Science Data Sharing Service Network (http://cdc.cma.gov.cn/home.do, accessed on 1 April 2021), and included the daily mean temperature and precipitation for the Loess Plateau region and its surrounding areas from 1990 to 2015. We used the ANUSPLIN software package version 4.3 [48], which implements the thin-plate smoothing splines procedure described by Hutchinson [49,50]. We chose this method because it has been widely used in spatial-interpolation analyses of climate elements [51,52] and performs well in comparison with other methods, such as inverse distance weighting (IDW) and kriging [53]. The applicability of this method in China has also been proved in relevant studies [54,55].

3.4. Specific Research Methods

3.4.1. Net Change Rate and Transfer Matrix of Ecosystem Type

The average annual net change rate of ecosystem types quantitatively reflects the rate of change in the area of that ecosystem type, and it plays an important role in comparing the regional differences in changes in ecosystem types [56]. The calculation formula is as follows:

$$K = \frac{U_b - U_a}{U_a} \times \frac{1}{T} \times 100\% \quad (1)$$

where K is the average annual net change rate of a certain ecosystem type; U_a and U_b are the areas of a certain ecosystem type at the beginning and end of the study period, respectively; and T is the length of the study period, and the time period is set as one year.

A transition matrix can describe the structural characteristics of regional ecosystem change and the change direction of each ecosystem comprehensively and concretely [57,58]. The area of the ecosystem type was used as the vector in the state transition matrix of the ecosystem type, and the transition matrices were counted for the five periods of 1990–2000, 2000–2005, 2005–2010, 2010–2015 and 2000–2015:

$$A_{\mathrm{ij}} = \begin{bmatrix} A_{11} & A_{12} & \cdots & A_{1n} \\ A_{21} & A_{22} & \cdots & A_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ A_{n1} & A_{n2} & \cdots & A_{nn} \end{bmatrix} \quad (2)$$

where A is the area, i, $j(i, j = 1,2, \ldots, n)$ are the ecosystem types before and after the transfer, A_{ij} is the area where the ecosystem type changes from type i to j, and n is the number of ecosystem types before and after the transfer.

3.4.2. Mean and Difference of the NDVI

To study the basic characteristics of the overall change in vegetation, the mean method uses the average NDVI of all the pixels in a statistical area. More specifically, the average of the NDVI accumulated in the study period is taken as the annual average $\overline{NDVI_y}$ (Equation (3)). To study the characteristics of vegetation during the year, the average monthly $\overline{NDVI_i}$ is the sum of the i-month averages used to represent the annual variation in vegetation (Equation (4)). The difference method is used to calculate the change in the $NDVI$ value between two periods to measure the relative change:

$$\overline{NDVI_y} = (\sum_{j=1}^{N}\sum_{i=1}^{M} NDVI_{ij})/N, i = 1,2.....12; j = 1,2.....N \quad (3)$$

$$\overline{NDVI_i} = (\sum_{j=1}^{N} NDVI_{ij})/N, i = 1,2.....12; j = 1,2.....N \quad (4)$$

where N is the number of years, and $NDVI_{ij}$ is the $NDVI$ of the j-th year and i-th months (where i = 1 for January, i = 2 for February, and so on to December; where j = 1 for the first year and j = 26 for the last year).

3.4.3. Linear Regression Method

A linear regression analysis can simulate the trend of each pixel over the past 25 years. Stow et al. [59] used this method to calculate the greenness rate of change (GRC) of vegetation. The GRC is defined as the slope of the minimum sublinear regression equation of the normalized difference index (e.g., the $NDVI$) for a given period of time [60]. In this

study, the method was used to simulate the *NDVI* trend in the study area. The formula was as follows:

$$\theta_{slope} = \frac{n \times \sum_{i=1}^{n} i \times NDVI_i - \sum_{i=1}^{n} i \sum_{i=1}^{n} NDVI_i}{n \times \sum_{i=1}^{n} i^2 - (\sum_{i=1}^{n} i)^2} \quad (5)$$

where n is the time-series length of the simulation (n = 26), the variable i is the sequence number of the time series, and $NDVI_i$ is the average value of the *NDVI* in the i-th year. The numerical trend reflects the trend of annual *NDVI* during the study period. The trend line of a given point represents the general trend of the average *NDVI* value during the 25 years. $\theta_{slope} > 0$ indicates an increasing *NDVI* trend, and $\theta_{slope} < 0$ indicates a decreasing *NDVI* trend.

3.4.4. Multiple Regression Analysis

Climate factors (temperature and precipitation) usually interact with each other, and the impact on vegetation is not antagonistic. In this study, multiple regression analysis was used to study the common effects of temperature and precipitation on the *NDVI* [61]. The study of temperature and precipitation by multivariate regression analysis is to prepare for the subsequent use of improved residual model to quantitatively determine the degree of climate and human impact.

$$\frac{NDVI - \overline{NDVI}}{\sigma_{NDVI}} = \beta_0 + \beta_1 \frac{CLM_1 - \overline{CLM_1}}{\sigma_1} + \ldots + \beta_n \frac{CLM_n - \overline{CLM_n}}{\sigma_n} \quad (6)$$

where $\overline{NDVI}$ is the average value of the multiyear *NDVI*, σ_{NDVI} is the standard deviation of the multiyear *NDVI*, $\overline{CLMi}$ is the multiyear average value of the ith climate factor, and σ_i is the standard deviation of the ith climate factor. The F test was used to test the significance of the above multiple linear regression equation.

3.4.5. Improved Residual Trend Analysis

The residual trend method uses the annual *NDVI* and precipitation data for each pixel in the whole time series to establish the response relationship, and obtains the residual between the actual *NDVI* and the predicted *NDVI* of each pixel in the whole time series to judge the impact of human factors on vegetation growth [34,62,63]:

$$\Delta NDVI = NDVI_{actual\ value} - NDVI_{analog\ value} = \begin{cases} < 0, \text{ Negative impact} \\ = 0, \text{ Less interference} \\ > 0, \text{ Positive impact} \end{cases} \quad (7)$$

To further study the impact of climate and human activities on vegetation change, based on the above model, the annual *NDVI* change trend corresponds to the regions where the correlation between climate change and the *NDVI* is not significant [64]. Specifically, significant restoration of vegetation caused by climate change refers to a significant increase in the trend of the *NDVI* over time, a significant correlation between the *NDVI* and climatic factors and an insignificant change in the residual trend of the *NDVI*. Significant vegetation degradation caused by climate change refers to a significant decline in the *NDVI* trend over time, a significant correlation between the *NDVI* and climatic factors and an insignificant change in the residual trend of the *NDVI*. Significant vegetation restoration caused by humans refers to a significant increase in the *NDVI* trend over time, an *NDVI* not significantly related to climatic factors, and a significant increase in the trend of the *NDVI* residuals. A significant degradation of vegetation caused by humans means that the trend of the *NDVI* changes significantly over time, the *NDVI* is not significantly correlated with climatic factors and the trend of the *NDVI* residuals decreases significantly. The significant restoration of vegetation caused by climatic factors and human activities means that the change trend of the *NDVI* over time has significantly increased, the *NDVI* is

significantly related to climatic factors and the trend of the *NDVI* residual changes has increased significantly. The significant degradation of vegetation caused by climatic factors and human activities means that the change trends of the *NDVI* over time have increased significantly, the *NDVI* is significantly related to climatic factors and the trend of the *NDVI* residuals has significantly increased.

4. Results

4.1. Ecosystem Changes Before and After the Implementation of Ecological Projects

4.1.1. Overall Change in Ecosystem Pattern from 1990 to 2015

Since 1990, the area of forest ecosystems on the Loess Plateau has been increasing continuously, and the rate of increase after 2000 was obviously faster than that before, in which the net increasing rate reached 0.09% from 2000 to 2005 and then began to slow down. The shrub ecosystem has been increasing since 1990, reaching the fastest net increase rate of 0.45% from 2000 to 2005, and then continuing to increase. The area of the shrub ecosystem began to decrease in 2010, and the net decrease rate was greater than the net increase rate before 2000, which was 0.07%. The grassland ecosystem decreased before 2000, with a net decrease rate of 0.10%. Since then, grassland ecosystems on the Loess Plateau began to increase, and the rate of increase was greater than that of forests and shrubs. However, the area of grassland ecosystems decreased during 2010 to 2015, with a decrease rate of 0.03%. From 1990 to 2000, the farmland ecosystem increased at a rate of 0.14% and then began to decrease. From 2000 to 2005, the decrease rate reached 0.86% and then slowed, but it was still greater than the increase rates for forest, grassland and shrub. Compared with before, the area of wetland ecosystems has been increasing since 2000, with a larger increase from 2000 to 2005, and then it slowed, but the increase rate increased again from 2010 to 2015. It is worth noting that the area of urban ecosystems increased from 1990 to 2015, and its growth rate has been increasing. Contrary to the urban ecosystem, the area of desert ecosystems on the Loess Plateau has been decreasing (Table 3, Figure 3). From the above analysis, we can see that although some ecological projects, such as the TNSDP, had been implemented in some areas of the Loess Plateau before 2000, they had little effect. Therefore, the follow-up analysis of this study will distinguish before and after the implementation of ecological projects by the year 2000.

Table 3. Changes in ecosystem areas in different periods on the Loess Plateau.

Type	Area (km^2)					Net Rate of Change (%)			
	1990	2000	2005	2010	2015	90–00	00–05	05–10	10–15
Forest	48,840.57	48,897.66	49,151.33	49,260.01	49,345.61	0.01	0.09	0.04	0.03
Shrub	77,199.21	77,387.99	79,462.53	80,610.79	80,291.49	0.02	0.45	0.24	−0.07
Grassland	23,0887.19	228,391.86	235,166.71	239,083.15	238,644.53	−0.10	0.49	0.28	−0.03
Farmland	20,6118.87	209,203.68	198,396.38	190,861.18	188,217.51	0.14	−0.86	−0.63	−0.23
Wetland	5370.87	4220.19	4438.66	4500.84	4591.87	−1.95	0.86	0.23	0.34
Urban	14,497.14	16,401.55	18,293.95	21,229.60	24,644.91	1.19	1.92	2.67	2.68
Desert	39,978.76	38,326.21	37,848.96	37,249.20	37,018.42	−0.38	−0.21	−0.26	−0.10

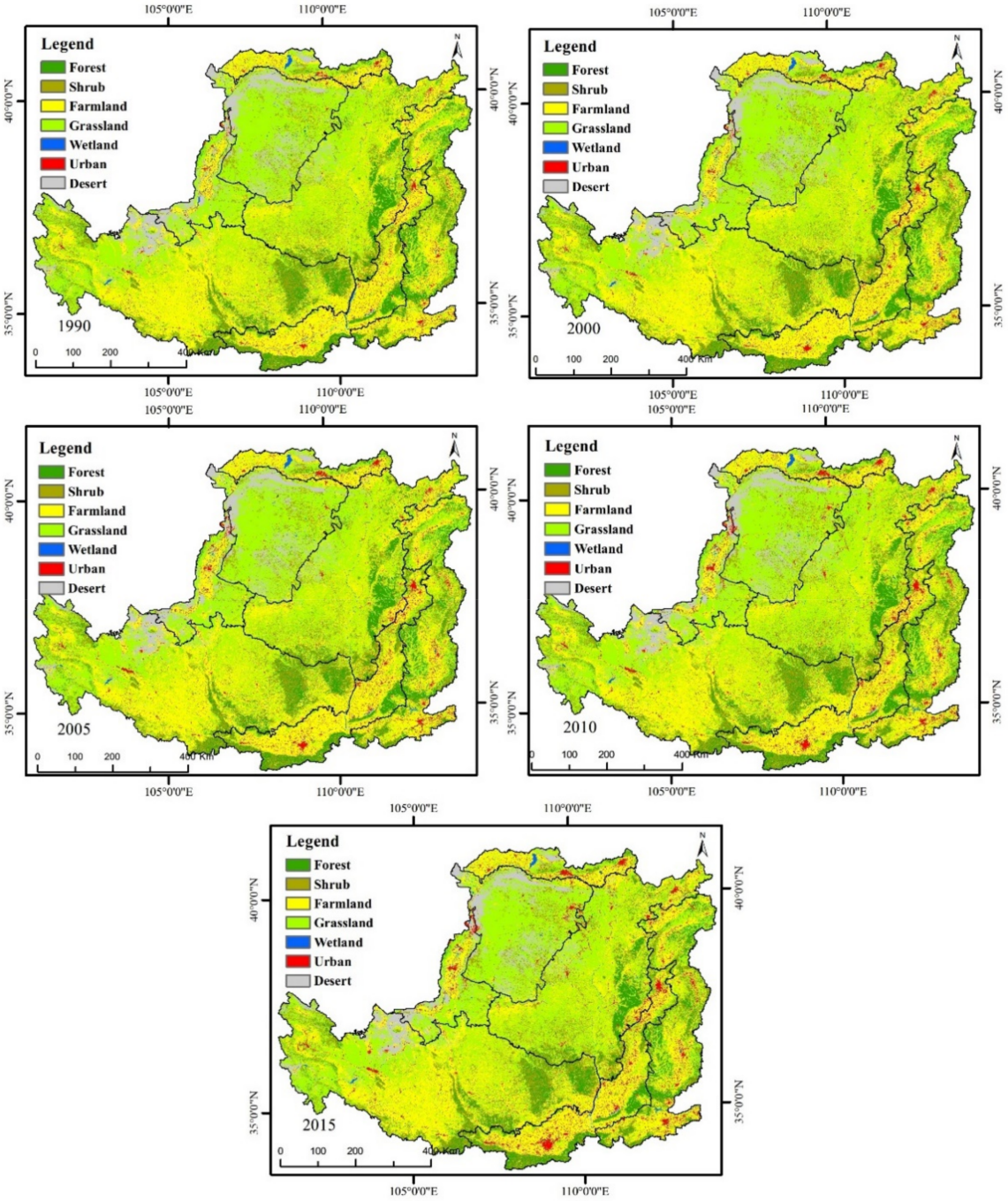


Figure 3. Spatial distribution of ecosystems in different periods of the Loess Plateau.

4.1.2. Changes in Ecosystems Before and After the Implementation of Ecological Engineering

Before the implementation of ecological engineering (1990–2000), the areas of forest, shrub, farmland and urban ecosystems on the Loess Plateau increased, while the areas of other ecosystem types decreased (Table 4). The increased area of forest mainly came from farmland, followed by grassland and wetland, while the reduced area of forest was mainly caused by land conversion to farmland and town, with areas of 27.59 km^2 and 7.80 km^2, respectively. The change in shrub ecosystems was similar to that in forests. The increased area mainly came from farmland, with an area of 385.95 km^2. In addition, the areas of grassland and desert that were converted into shrub were equivalent, with areas of 63.60 km^2 and 67.49 km^2, respectively; during this period, the reduced shrub area was

mainly converted into farmland, with an area of 241.89 km^2. The increased area of the farmland ecosystem mainly came from grassland and desert, with areas of 4104.05 km^2 and 1479.75 km^2, respectively; the decreased farmland area mainly turned into towns and grasslands (Table 4). Grassland was mainly transformed into farmland, with an area of 4104.05 km^2, followed by urban areas and deserts; the increased grassland was also mostly from farmland, but compared with the reduced area, the transferred area was smaller, at 1320.95 km^2. The reduced wetland ecosystem area mainly turned into farmland, with an area of 925.75 km^2, and some turned into grassland and desert; at the same time, a small area of grassland, farmland and desert ecosystems turned into wetland. The desert was mainly transformed into grassland, with an area of 690.11 km^2, while the increased desert area was mainly transformed into wetland, with an area of 394.82 km^2 (Table 4).

Table 4. Transfer matrix of different ecosystems from 1990 to 2000 (unit: km^2).

Type	Forest	Grassland	Farmland	Wetland	Urban	Desert	Shrub
Forest	48,800.53	2.82	27.59	1.30	7.80	0.22	0.31
Grassland	4.86	226,100.37	4104.05	108.09	270.87	235.36	63.60
Farmland	84.78	1320.95	203,212.10	189.34	1492.86	156.89	385.95
Wetland	4.89	228.58	925.75	3772.63	23.56	394.82	20.64
Urban	1.13	0.12	0.00	0.24	14,495.65	0.00	0.00
Desert	1.36	690.11	1479.75	142.60	90.63	37,506.82	67.49
Shrub	0.10	48.91	241.89	6.01	20.18	32.10	76,850.00

After the implementation of ecological engineering (2000–2015), the area of forest mainly increased, and the transfer of farmland was the main reason for the increase; similarly, the transfer of farmland was an important factor for the increase in grassland area, with an area of 14,278.59 km^2, and the reduced grassland area was mainly transformed into farmland and towns, with areas of 1930.85 km^2 and 2563.69 km^2, respectively. During this period, the shrub area increased, and the transferred area from farmland reached 3215.45 km^2, which was second only to grassland in vegetation types. Although some of the wetlands were converted into farmland (316.92 km^2) or desert (266.22 km^2), the total number of wetlands still increased, and the increased areas mainly came from farmland, grassland and desert. During the study period, the urban area increased, mainly from farmland and grassland, with areas of 4838.25 km^2 and 2563.69 km^2, respectively. At the same time, the area of farmland was reduced, and the urban area was mainly transformed into the ecosystem types described above; the reduced desert area was mainly converted into grassland, with an area of 1197.67 km^2 (Table 5).

In the early stage of the implementation of ecological engineering (2000–2005), the increased area of forest ecosystems mainly came from farmland transfer, with an area of 255.35 km^2. The area of other ecosystem types converted to forest was less than that of farmland transfer. The area of forest ecosystems decreased mainly by the conversion to shrubs and urban areas, with areas of 11.19 km^2 and 6.00 km^2, respectively (Table 5). During this period, the area of forest increased. The increase in grassland area was mainly from farmland, with an area of 7829.17 km^2, followed by that of desert, with an area of 421.59 km^2; at the same time, there was still a part of grassland that was converted to farmland, but the area was only 700.22 km^2, and the area converted to urban land was 432.75 km^2. Thus, the overall performance of grassland ecosystem area was increasing. The increase in shrub area was mainly from farmland area, with an area of 2006.08 km^2, followed by that of grassland area, with an area of 130.83 km^2; the decrease in shrub area was not much, mainly from grassland and town, with areas of 46.81 km^2 and 22.55 km^2, respectively. In this period, the total change in shrub area was the same as that of the forest and grassland ecosystems; the area was increasing, and it was mainly from farmland ecosystems. The above results were mainly due to the full implementation of the policy of returning farmland to forest (grassland). Wetlands were mainly transformed to farmland, desert and grassland to varying degrees, and the overall performance was increasing. From

2000 to 2005, the urban area still showed an increase that mainly came from the transfer of farmland area, with an area of 1316.00 km^2. The main trend of desert was reduction: the reduced area was mainly transformed into grassland, farmland and wetland, of which the area transformed into grassland was 421.59 km^2. The increased area was also mainly from grassland, farmland and wetland, of which the largest area transferred was farmland, with an area of 242.93 km^2.

Table 5. Transfer matrix of different ecosystems from 2000 to 2015 (unit: km^2).

Period	Type	Forest	Grassland	Farmland	Wetland	Urban	Desert	Shrub
2000–2015	Forest	48,793.92	8.23	19.13	2.20	47.49	14.99	11.69
	Grassland	24.47	222,833.81	1930.85	300.52	2563.69	522.55	215.96
	Farmland	507.84	14,278.59	186,047.50	621.99	4838.25	481.51	3215.45
	Wetland	2.73	228.15	316.92	3299.38	74.44	266.22	32.36
	Urban	4.75	6.26	1.76	1.69	16,382.39	4.26	0.44
	Desert	6.24	1197.67	498.64	347.31	486.48	35,676.69	113.20
	Shrub	5.66	91.83	264.97	18.77	252.17	52.21	76,702.39
2000–2005	Forest	48,872.42	2.74	3.54	1.51	6.00	0.26	11.19
	Grassland	11.83	226,738.83	700.22	169.68	432.75	207.71	130.83
	Farmland	255.35	7829.17	198,081.38	260.21	1316.00	242.93	2006.08
	Wetland	1.83	122.27	180.67	3730.38	23.92	151.19	9.94
	Urban	2.61	5.31	1.66	1.11	16,389.80	0.62	0.44
	Desert	2.72	421.59	273.35	272.10	102.93	37,235.61	17.91
	Shrub	4.56	46.81	13.64	3.67	22.55	10.63	77,286.13
2005–2010	Forest	49,134.21	2.62	3.00	0.76	7.55	2.59	0.61
	Grassland	13.85	233,110.28	447.44	150.83	1114.90	225.71	103.70
	Farmland	104.64	5240.07	190,793.94	363.39	1480.77	173.96	1097.70
	Wetland	2.14	150.63	211.37	3800.82	40.65	215.73	17.33
	Urban	0.00	0.25	0.07	0.27	18,293.35	0.01	0.00
	Desert	4.43	558.19	206.75	178.20	219.54	36,622.03	59.82
	Shrub	0.75	21.12	20.43	6.57	72.85	9.17	79,331.64
2010–2015	Forest	49,187.21	3.74	18.73	0.47	36.84	12.59	0.42
	Grassland	6.81	236,441.71	1146.82	137.67	1087.77	233.86	28.51
	Farmland	144.23	1666.39	187,369.86	231.31	1959.52	208.23	103.46
	Wetland	0.53	136.48	123.98	4031.29	9.06	186.70	12.81
	Urban	1.90	1.24	0.03	1.61	21,216.09	8.72	0.00
	Desert	3.32	360.56	176.05	177.77	172.21	36,328.46	30.83
	Shrub	1.62	34.42	244.29	11.75	163.40	39.85	80,115.47

In the later stage of the implementation of ecological engineering (2005–2010), the areas of forest, grassland and shrub in the Loess Plateau increased continuously, and the increasing areas were mainly from the transfer of farmland, with values of 104.64 km^2, 5240.07 km^2 and 1097.70 km^2, respectively; additionally, their reduced areas were mainly converted into urban areas, with areas of 7.55 km^2, 1114.90 km^2 and 72.85 km^2, respectively (Table 5). In addition to the above three types of ecosystems, most of the reduced farmland ecosystems were transformed into towns, covering an area of 1480.77 km^2. The wetland ecosystem was mainly transformed with farmland and desert, but the area of wetland generally increased, although compared with other types of area increases, the increase in wetland area was smaller.

In the suspended period of ecological-engineering implementation (2010–2015), the increasing area of forest area was mainly transferred from farmland, with an area of 144.23 km^2, while the decreasing area was mainly urban area, with an area of 36.84 km^2. The areas of grassland and shrub land decreased, and the reduced area was mainly transformed into farmland and urban areas. The above results showed that with the intensification of urbanization, the Loess Plateau region experienced recultivation during 2010–2015 (Table 5).

4.2. Spatiotemporal Variation in Vegetation Quality

4.2.1. Distribution Characteristics of the NDVI

The Chinese government has approved the "outline of comprehensive management plan for the Loess Plateau Region", which divides the Loess Plateau into six zones according to the characteristics of topography and soil erosion, combined with the regional natural conditions and management approaches, and carries out comprehensive management according to local conditions [65]. This study is mainly combined with the analysis of governance zoning. The annual average NDVI distribution map of the Loess Plateau from 1990 to 2015 (Figure 4) reflected the basic characteristics of the vegetation NDVI in the past 25 years. Macroscopically, the NDVI values of vegetation in the eastern and southern regions were significantly higher than those in the western and northern regions, and showed a gradual decreasing trend. The maximum value of the NDVI was 0.72, and the minimum value was 0.04. Grassland was mainly distributed in most areas of the Loess Plateau, and the average annual NDVI of grassland ecosystem was 0.35. Shrub and forest ecosystems were mainly distributed in the south and east of the Loess Plateau, in which the average annual NDVI of shrub ecosystem was 0.43 and that of forest ecosystem was 0.46.

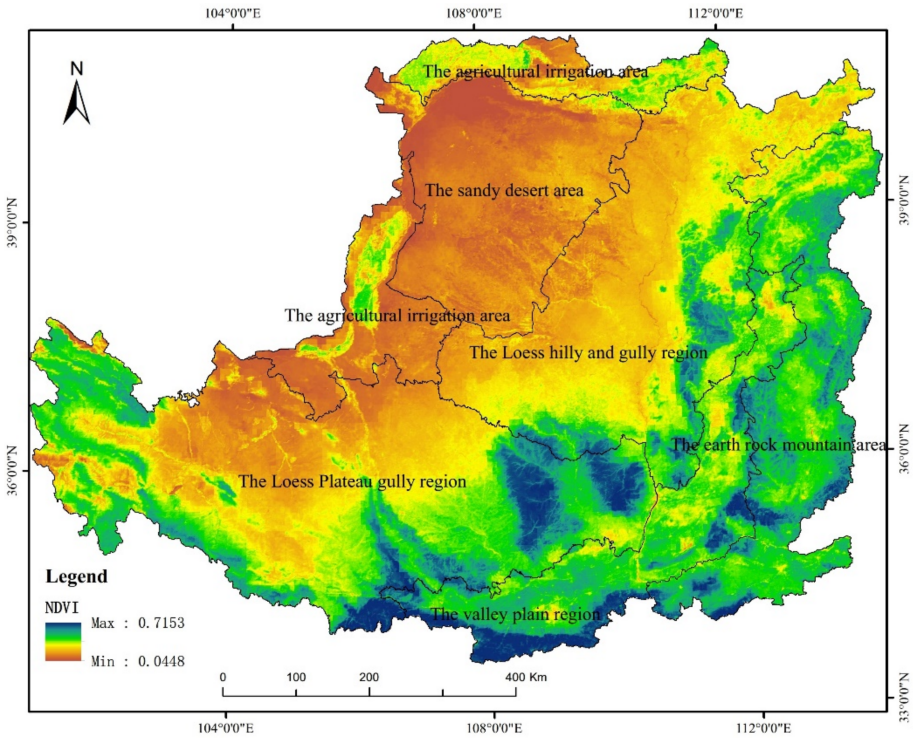


Figure 4. Average NDVI distribution on the Loess Plateau from 1990 to 2015.

4.2.2. Interannual Variation in the NDVI

To study the interannual variation characteristics of the NDVI, the average value of the NDVI in the growing season (April–October) was used to characterize vegetation growth. From 1990 to 2015, the NDVI of vegetation in the Loess Plateau showed an overall upward trend, and the change trend was obvious and could be divided into two periods (Figure 5a): from 1990 to 1999, the NDVI value in the Loess Plateau fluctuated greatly, ranging from 0.3304 to 0.3670, with a slight decreasing trend, especially in 1998 and 1999. After 2000, the NDVI value in the region showed an increasing trend of 0.2864–0.3723, and the maximum value appeared in 2012. The average annual NDVI of forests and shrubs in the growing season showed an increasing trend from 1990 to 2015 (Figure 5b,c). The average annual NDVI value of grassland ecosystems in the growing season was generally lower than that of the above two types, but the overall change trend was consistent, showing an increasing trend (Figure 5d).

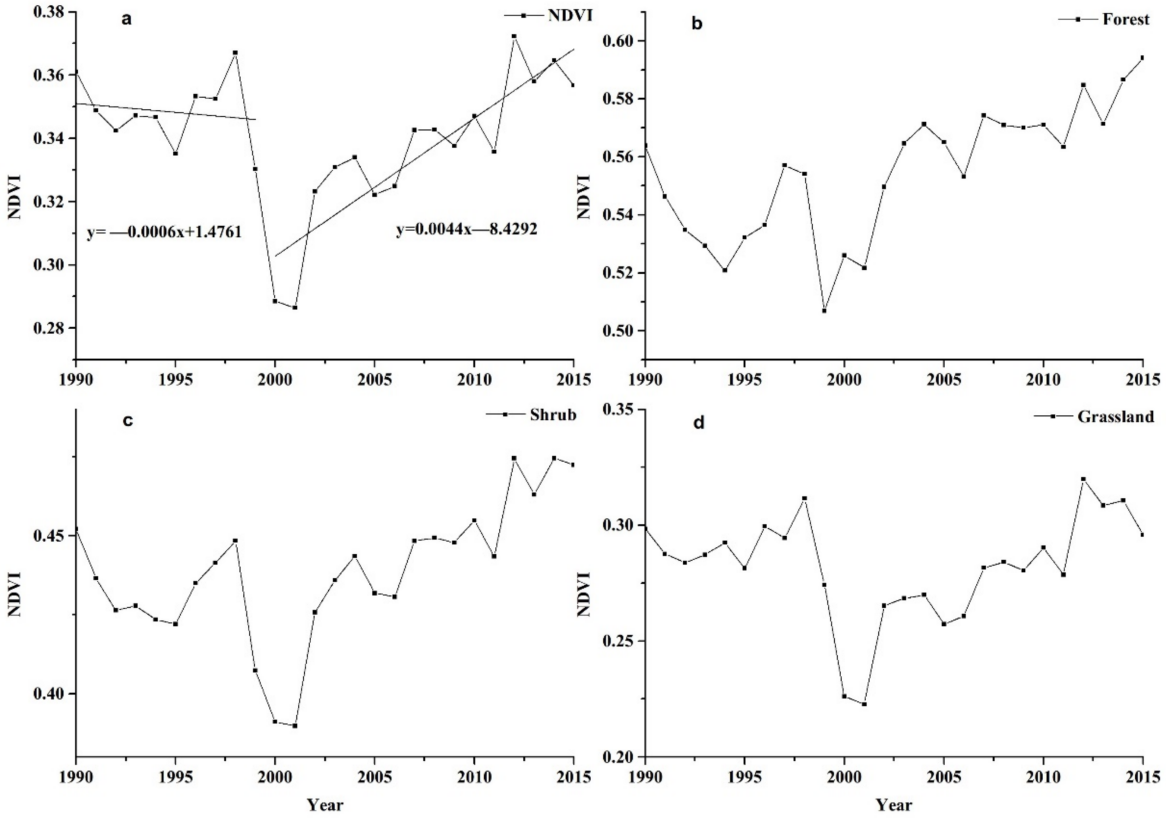


Figure 5. Interannual trend of the NDVI in the growing season from 1990 to 2015.

4.2.3. Spatial Variation in the NDVI

From 1990 to 2015, the NDVI of vegetation on the Loess Plateau showed an overall upward trend, and the areas with significant increases were mainly concentrated in the central and eastern regions (Figure 6). The statistical results showed that in the past 25 years, the NDVI of vegetation in 53.45% of the Loess Plateau showed an upward trend, and that in 33.05% showed a significant increase (Table 6). The areas where the NDVI decreased were mainly distributed in the northern parts of Gansu and Ningxia, the southern part of Shaanxi and the eastern part of Shanxi. The NDVI decreased in 46.55% of the area and decreased significantly in 24.61% of the area. From 1990 to 1999, the vegetation NDVI of the Loess Plateau showed a decreasing trend, and the rising area accounted for 44.92% of the total area, of which the significant increase accounted for only 6.45%; after 2000, compared with before, the vegetation NDVI of the Loess Plateau increased rapidly, and the rising area reached 91.90% of the total area, with a significant increase of 65.78%.

Table 6. Number and percentage of NDVI change types of pixels in the growing season of the Loess Plateau in each time period.

Change	1990–2015		1990–1999		2000–2015	
	Number of Pixels	Percentage/%	Number of Pixels	Percentage/%	Number of Pixels	Percentage/%
Significant increase	20,6129	33.05	40,202	6.45	410,252	65.78
Significant decrease	15,3485	24.61	31,067	4.98	10,302	1.65
Increase	12,7219	20.40	239,937	38.47	162,891	26.12
Decrease	13,6822	21.94	312,449	50.10	40,210	6.45

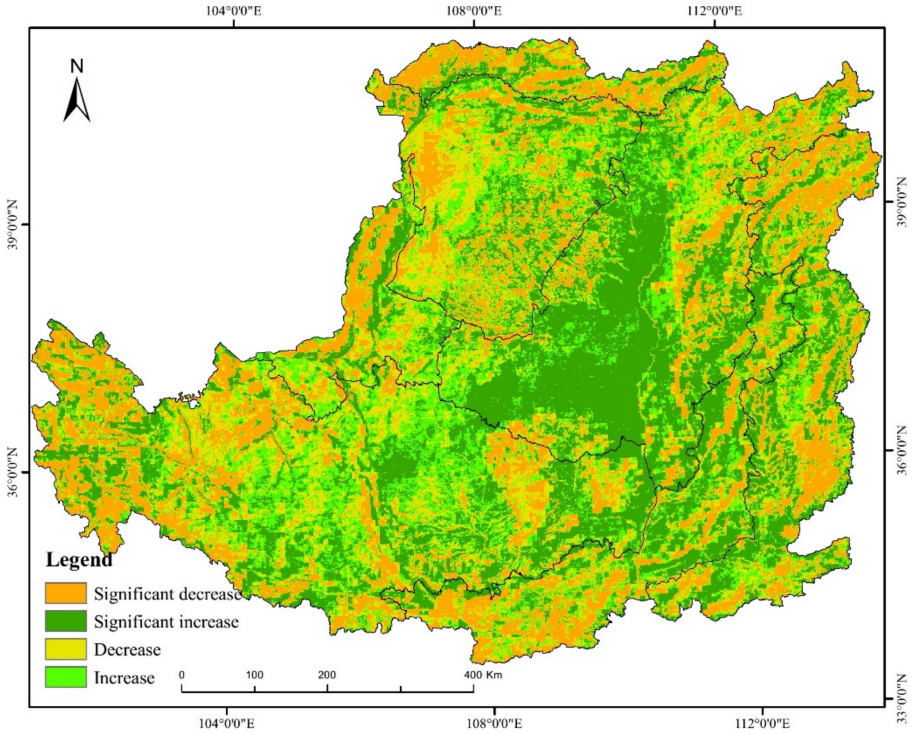


Figure 6. Distribution of significant NDVI changes in the growing season from 1990 to 2015.

4.2.4. Changes in the NDVI in Different Periods of Ecological-Engineering Implementation

In the early stage of ecological engineering (2000–2005), the NDVI value of vegetation in the Loess Plateau increased in many areas, including the west and south of the Loess hilly and gully region, the middle of the Loess Plateau gully region, the north and middle of the valley plain region and the middle and south of the earth rock mountain area (Figures 7 and 8). There were also a few areas in the agricultural irrigation area and sandy desert area in which the NDVI value of vegetation in the Loess Plateau gully region increased. The NDVI value in the middle part of the Loess Plateau and its junction with the Loess hilly and gully region increased greatly. In the northwest of the Loess Plateau gully region, the NDVI decreased in a small area. The main ecosystem type in this area was grassland. There were sporadic areas in the agricultural irrigation area and the valley plain region where the NDVI decreased seriously. In the early stage of ecological-engineering implementation, the area with a slight increase in the NDVI value accounted for 27.06%, the area with a large increase accounted for 5.15% and the area with a decrease accounted for only 1.16% (Table 7).

Compared with the early stage, the increase in the NDVI in the late stage of ecological engineering (2005–2010) was smaller. The Loess hilly and gully region was the largest area with an increasing NDVI value, which was distributed in the middle and south of the region, in the southwest of the sandy desert area, in the east of the agricultural irrigation area, in the north of the Loess Plateau gully region and in the northwest of the valley plain region. The NDVI values decreased in the west of the Loess Plateau gully region, the southwest of the valley plain region and the middle and southeast of the earth rock mountain area (Figures 7 and 8). After the implementation of ecological engineering, the area of vegetation NDVI increased, accounting for 22.51% of the study area, of which the area with an obvious increase accounted for approximately 2.26%, and the area with a decrease accounted for approximately 1.82% (Table 7).

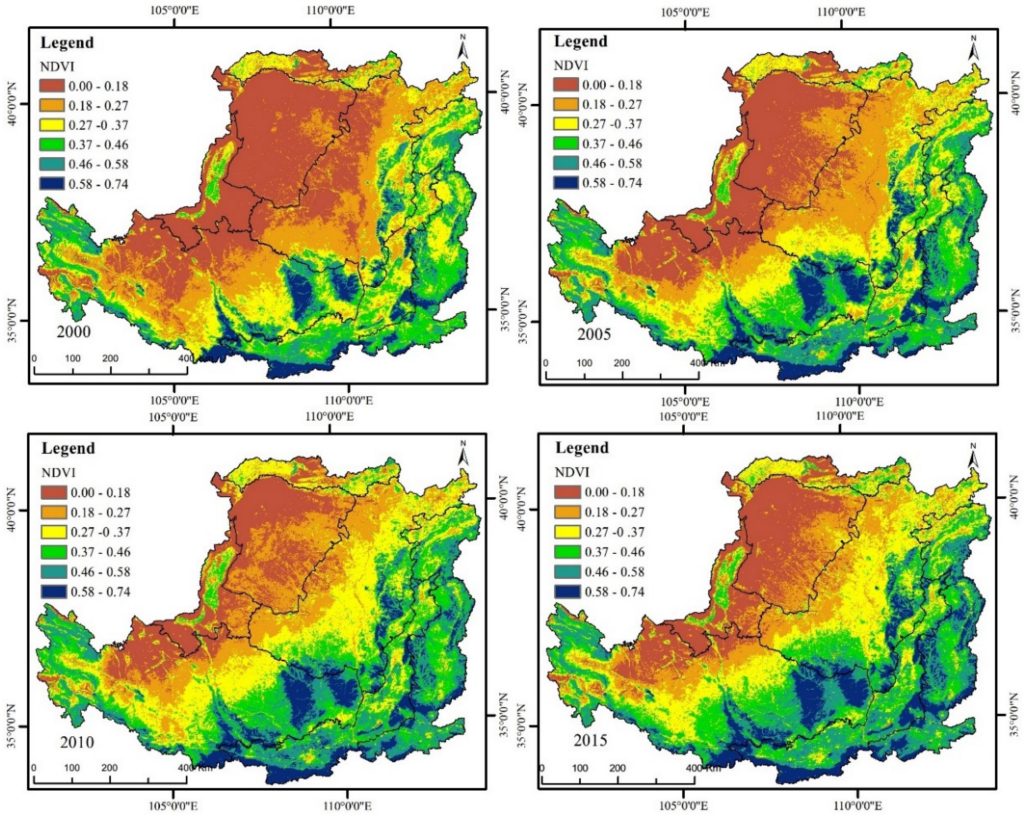


Figure 7. Spatial distribution of the NDVI on the Loess Plateau in different periods of ecological engineering.

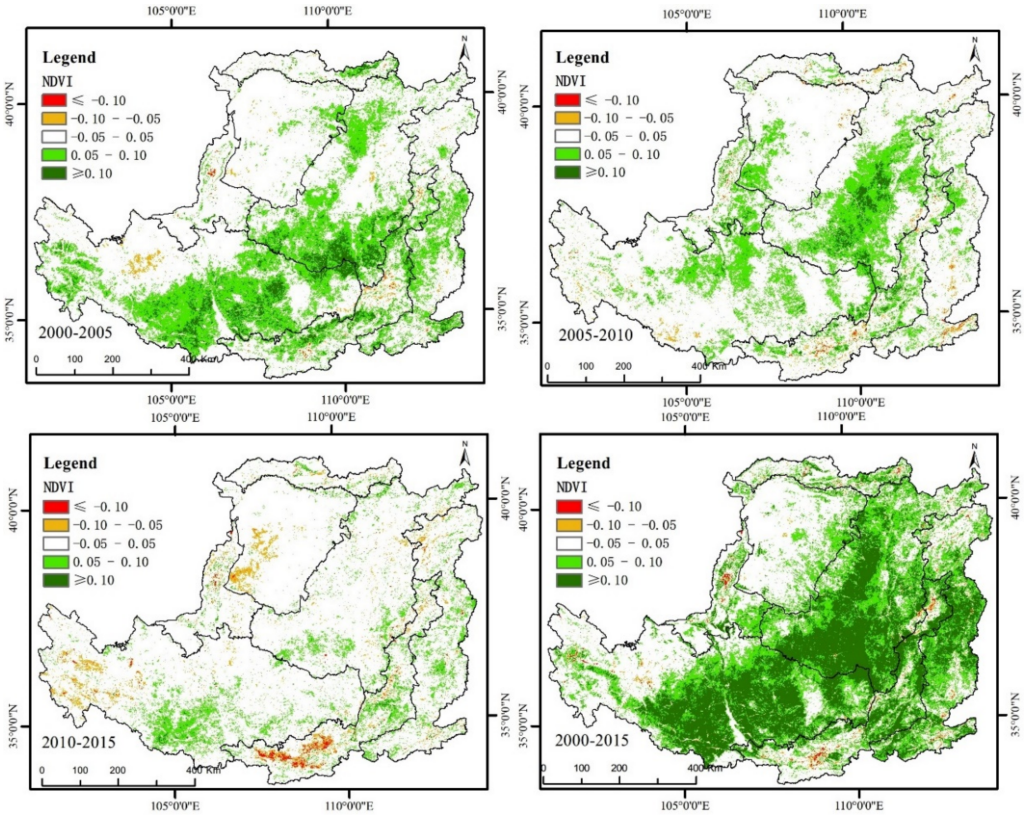


Figure 8. NDVI difference map of vegetation on the Loess Plateau in different periods of ecological engineering.

Table 7. Changes in the NDVI in different periods of ecological engineering on the Loess Plateau.

Rank		2000–2005		2005–2010		2010–2015		2000–2015	
Change	**Change Rank**	**Number of Pixels**	**%**	**Number of Pixels**	**%**	**Number of Pixels**	**%**	**Number of Pixels**	**%**
≤−0.10	Decreased severely	689	0.11	1554	0.25	3681	0.59	2580	0.41
−0.10~−0.05	Decreased slightly	6550	1.05	9789	1.57	22,327	3.58	6424	1.03
−0.05~0.05	unchanged	415,527	66.63	471,964	75.68	537,672	86.21	257,144	41.23
0.05~0.10	Increased slightly	168,784	27.06	126,267	20.25	57,256	9.18	176,583	28.31
≥0.1	Increase greatly	32,105	5.15	14,081	2.26	2719	0.44	180,924	29.01

During the suspended period of ecological-engineering implementation (2010–2015), there were few areas where the NDVI value of vegetation increased on the Loess Plateau. Specifically, the NDVI increased slightly in the middle part of the Loess Plateau gully region, the southern and eastern parts of the Loess hilly and gully region, and the northern and middle parts of the valley plain region and the earth rock mountain area. In the southwestern sandy desert area and the western Loess Plateau gully region, the NDVI value of a small amount of regional vegetation decreased slightly, while in the southwestern valley plain region, the NDVI value decreased seriously (Figures 7 and 8). During this period, the overall change in the NDVI in the Loess Plateau was small, the area with slight change accounted for 86.21% of the total area, the area with an increase accounted for 9.62% and the area with an obvious increase was only 0.44%. It is worth noting that the area with a slight decrease in NDVI accounted for 3.58%, the area with a serious decrease accounted for 0.59% during this period and the area with a decrease was greater than that during the implementation of the project (Table 7).

4.2.5. Comparison of the NDVI Changes Before and After the Implementation of Ecological Engineering

Before the implementation of ecological engineering (1990–1999), the NDVI values of vegetation on the Loess Plateau decreased in many areas, mainly in the eastern and southern Loess hilly and gully region and most of the earth rock mountainous area, and the NDVI values in some areas decreased seriously. The NDVI values also decreased in some areas of the north of the valley plain region and the middle and northeast of the Loess Plateau gully region; additionally, the increase in the NDVI value was mainly distributed in the northwestern Loess Plateau gully region (Figure 9a). In contrast, after the implementation of ecological engineering (2000–2010), the NDVI values in most areas of the Loess Plateau increased, including most areas of the Loess hilly and gully region, the valley plain region, the Loess Plateau gully region except in the northwest and southwest, and the middle and south of the earth rock mountain area. The NDVI values also increased in some areas at the junction of the sandy desert area and the agricultural irrigation area; the areas with decreased NDVI values were mainly scattered in the agricultural irrigation area, the valley plain region and the earth rock mountain area (Figure 9b). Combined with the analysis of the change in ecosystem structure in the Loess Plateau in the previous section, although the implementation scope of the Three-North Shelterbelt System project was involved in the Loess Plateau before 2000, the implementation intensity and coverage were not large. From the perspective of vegetation quality, the area where the vegetation NDVI value decreased accounted for 33.42% of the total area, of which the area of serious decrease accounted for 6.34%, and the area of increase accounted for only 3.38%. With the full implementation of returning farmland to forest (grassland) and other projects, the area of vegetation NDVI increased on the Loess Plateau, accounting for 53.79% of the total area, of which 20.49% increased significantly and only 1.13% decreased (Table 8).

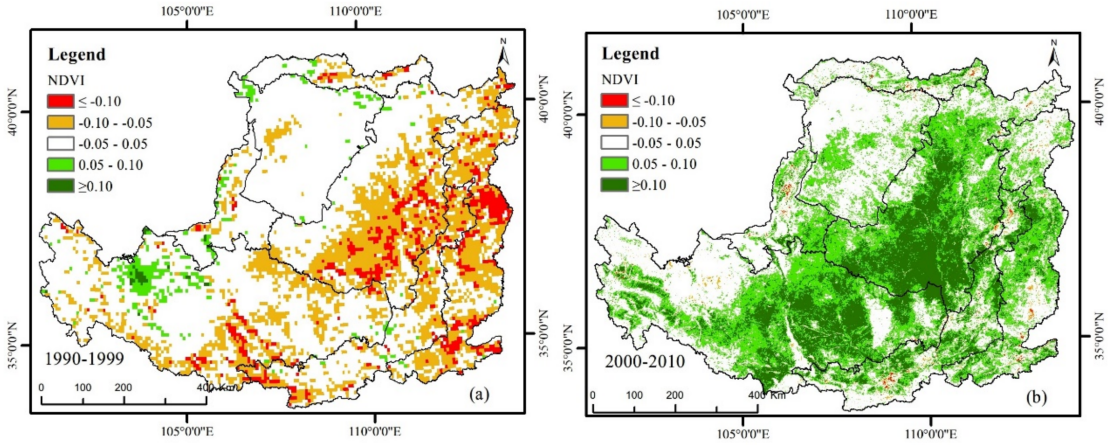


Figure 9. NDVI difference map on the Loess Plateau before (**a**) and after the implementation of ecological engineering (**b**).

Table 8. Changes in the NDVI before and after ecological engineering on the Loess Plateau.

Rank		1990–1999		2000–2010	
Change	**Change Rank**	**Number of Pixels**	**Percentage/%**	**Number of Pixels**	**Percentage/%**
≤−0.10	Decreased severely	39,553	6.34	1510	0.24
−0.10~−0.05	Decreased slightly	168,866	27.08	5523	0.89
−0.05~0.05	unchanged	394,201	63.21	281,124	45.08
0.05~0.10	Increased slightly	19,256	3.09	207,708	33.30
≥0.1	Increase greatly	1779	0.29	127,790	20.49

4.3. Determination of Influencing Factors of Vegetation Quality Change

4.3.1. Changes in Temperature and Precipitation on the Loess Plateau from 1960 to 2015

The annual average temperature variation trend of the Loess Plateau during 1960–2015 was mainly divided into two stages, namely, 1960–1999 and 2000–2015 (Figure 10a). Compared with the first stage, the annual average temperature of the Loess Plateau increased slowly from 2000 to 2015, but the average annual average temperature of this stage was greater than that of the first stage. The annual precipitation changes from 1960 to 2015 could also be divided into two stages, namely, 1960–1999 and 2000–2015 (Figure 10b). Different from the variation trend of the annual mean temperature, the annual precipitation decreased in the first stage and increased in the second stage.

4.3.2. Identification of Dominant Factors of Vegetation Quality Change from 1990 to 2015

Through the improved residual trend analysis (Figure 11, Table 9), the vegetation restoration areas caused by humans and climate were mainly distributed in the middle of the Loess Plateau and mainly concentrated in northern Shaanxi, accounting for 9.41% of the total area. Human-induced vegetation restoration was mainly distributed in the eastern and northern parts of Inner Mongolia, the southern part of Gansu and Ningxia and the central parts of Shaanxi and Shanxi, accounting for 21.74% of the total area. The vegetation-restoration area caused by climate only accounted for 1.91% of the total area and was mainly distributed in Qinghai Province. The vegetation degradation caused by humans and climate was mainly distributed in northern Inner Mongolia, Shanxi and Ningxia, accounting for 4.71% of the total area. The human-induced vegetation-degradation area accounted for 11.99% and was mainly distributed in northwestern Inner Mongolia, Shanxi and some areas of Shaanxi. The main reason for this phenomenon was the expansion of urbanization. Climate-induced vegetation degradation was mainly distributed in Qinghai and Gansu, mainly due to the rapid temperature rise, but the precipitation increase was not obvious, which accelerated the corresponding regional climate warming and drying, and was one of the reasons for the inhibited vegetation growth.

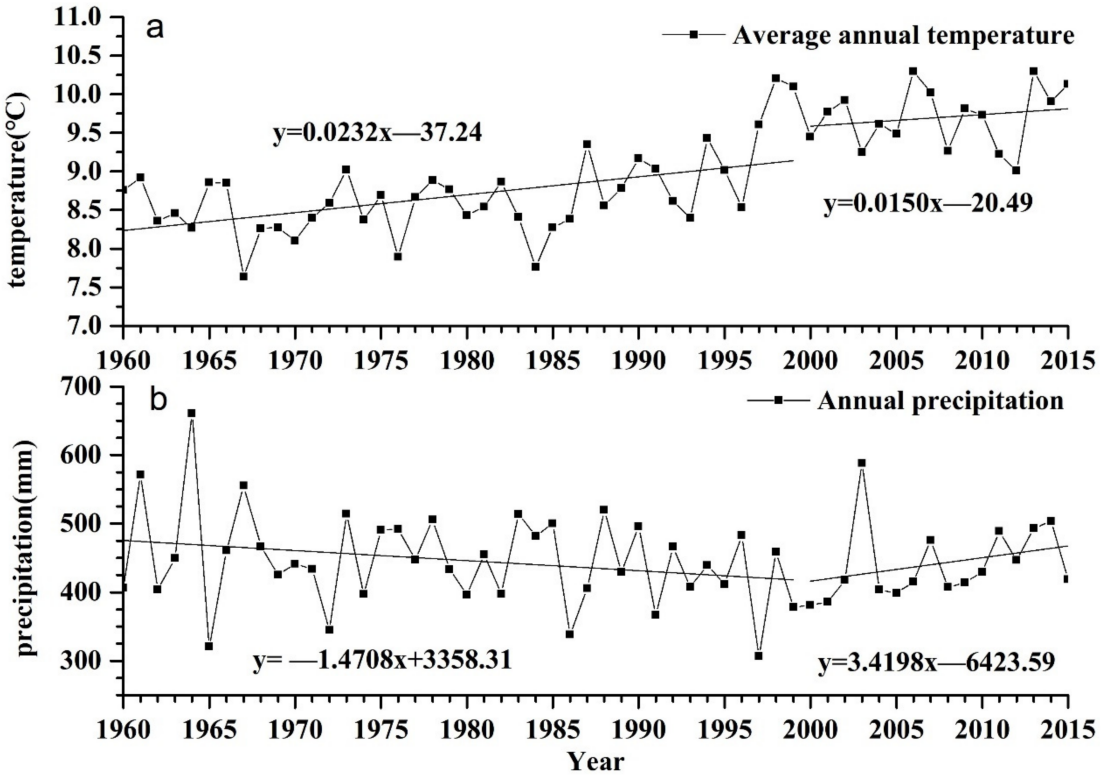


Figure 10. Annual precipitation (**b**) and average temperature (**a**) changes on the Loess Plateau from 1960 to 2015.

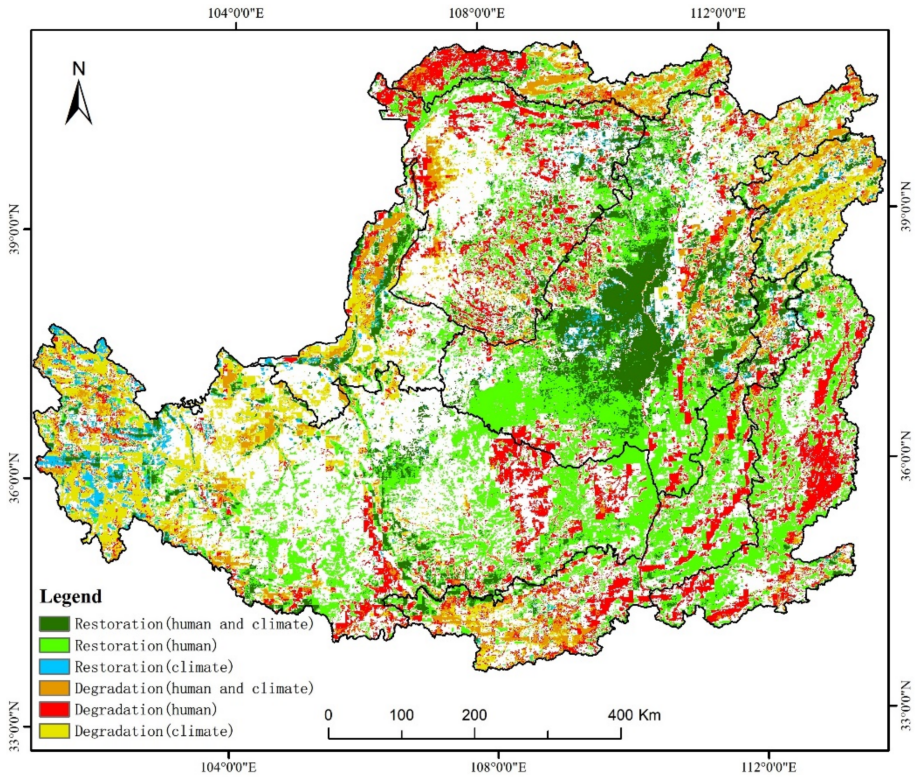


Figure 11. Distribution of driving factors of the significant restoration and significant degradation of vegetation quality on the Loess Plateau from 1990 to 2015.

Table 9. Analysis of driving factors of vegetation quality changes on the Loess Plateau from 1990 to 2015.

Driving Factors	Number of Pixels	Percentage/%
Human and climate cause vegetation restoration together	58,667	9.41
Human-induced vegetation restoration	135,569	21.74
Climate-induced vegetation restoration	11,893	1.91
Human and climate cause vegetation degradation together	29,346	4.71
Human-induced vegetation degradation	74,758	11.99
Climate-induced vegetation degradation	49,381	7.92

Further analysis was performed on the areas where the vegetation on the Loess Plateau was mainly affected by climate. The temperature and precipitation in the area of vegetation change caused by climate had the same trend, showing an upward trend (Figure 12). From 1990 to 2015, the temperature increased significantly, and the temperature increased faster in the vegetation degradation area than in the restoration area. The trend of precipitation showed a slight increase, and the vegetation restoration area was more obvious than the degradation area.

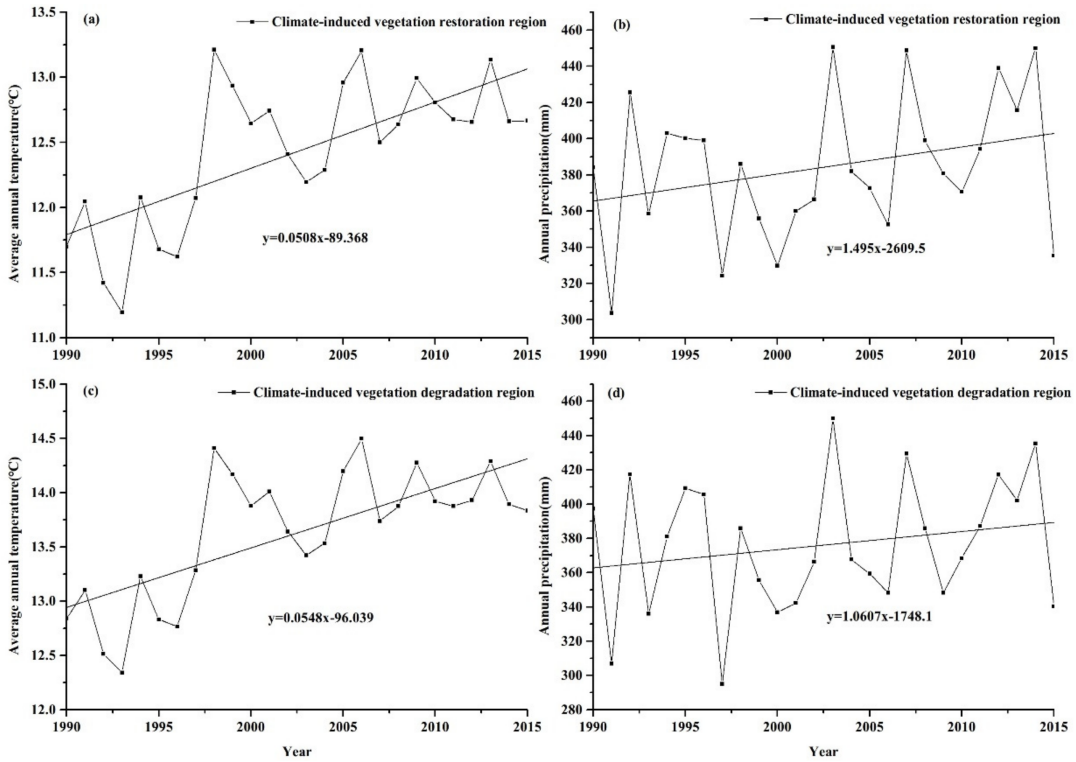


Figure 12. Annual average temperature and annual precipitation trends in climate-induced vegetation restoration (**a**,**b**) and degradation from 1990 to 2015 (**c**,**d**).

4.3.3. Identification of Dominant Factors of Vegetation Quality Change Before and After the Implementation of Ecological Engineering

Before the implementation of ecological engineering (1990–1999), the areas of significant restoration and significant degradation of vegetation quality on the Loess Plateau were lower, and the change trend of vegetation quality in most areas was not obvious from 1990 to 1999. The vegetation restoration area caused by humans and climate was mainly concentrated in the northwestern Loess Plateau, accounting for approximately 1.30% of the total area of the study area, and the main type was grassland; the areas of vegetation restoration caused by human activities were mainly distributed in the northern and northwestern regions of the Loess Plateau, accounting for approximately 3.83% of

the total area, and these areas were mainly distributed in grassland and shrubland. The area of vegetation restoration caused by climate was mostly concentrated in the area of vegetation restoration caused by the interaction of climate and human beings or by human beings alone, accounting for approximately 1.32% of the total area. The area of vegetation degradation was mainly distributed in the northern agricultural irrigation area, the southern Loess Plateau gully region and the Loess hilly and gully region. The main type of ecosystem in the degraded area of agricultural irrigation areas was farmland. In addition to farmland, grassland and forest were the main types of degraded area in the Loess Plateau gully region, while grassland, shrub and forest were the main types of degraded area in the loess hilly gully region. Among the regions with vegetation degradation, human activities caused the largest area of vegetation degradation, accounting for 2.69% of the total area, followed by climate factors, accounting for 1.75% of the total area (Figure 13, Table 10).

During the period of 2000 to 2015, the vegetation quality of the Loess Plateau was restored to a great extent, which was mainly due to the full implementation of ecological engineering. The area of vegetation-quality restoration caused by ecological engineering accounted for 46.12% of the total area, and the main distribution types of these areas were grassland, forest and shrubland. Climate- and human-induced vegetation restoration areas were mainly distributed in the northern and middle Loess hilly and gully region and the northern Loess Plateau gully region. The main types of these areas were grassland and shrubland, and the vegetation-restoration area accounted for approximately 17.27% of the total area. The area of vegetation restoration caused by climate was in the northeastern Loess Plateau, as well as in the agricultural irrigation area and the Loess Plateau gully region, accounting for approximately 2.4% of the total area. Most of the distribution types were grassland and shrubland. The vegetation-degradation areas affected by climate or human activities were mainly distributed in the distribution areas of farmland ecosystems on the Loess Plateau, and the area of human-induced degradation accounted for approximately 1.01% of the total area (Figure 13, Table 10).

Table 10. Analysis of driving factors of vegetation-quality changes on the Loess Plateau before and after the implementation of ecological engineering.

Period	Driving factors	Number of Pixels	Percentage/%
1990–1999	Human and climate cause vegetation restoration together	8103	1.30
	Human-induced vegetation restoration	23,893	3.83
	Climate-induced vegetation restoration	8206	1.32
	Human and climate cause vegetation degradation together	3384	0.54
	Human-induced vegetation degradation	16,768	2.69
	Climate-induced vegetation degradation	10,915	1.75
2000–2015	Human and climate cause vegetation restoration together	107,693	17.27
	Human-induced vegetation restoration	287,599	46.12
	Climate-induced vegetation restoration	14,960	2.40
	Human and climate cause vegetation degradation together	2068	0.33
	Human-induced vegetation degradation	6282	1.01
	Climate-induced vegetation degradation	1952	0.31

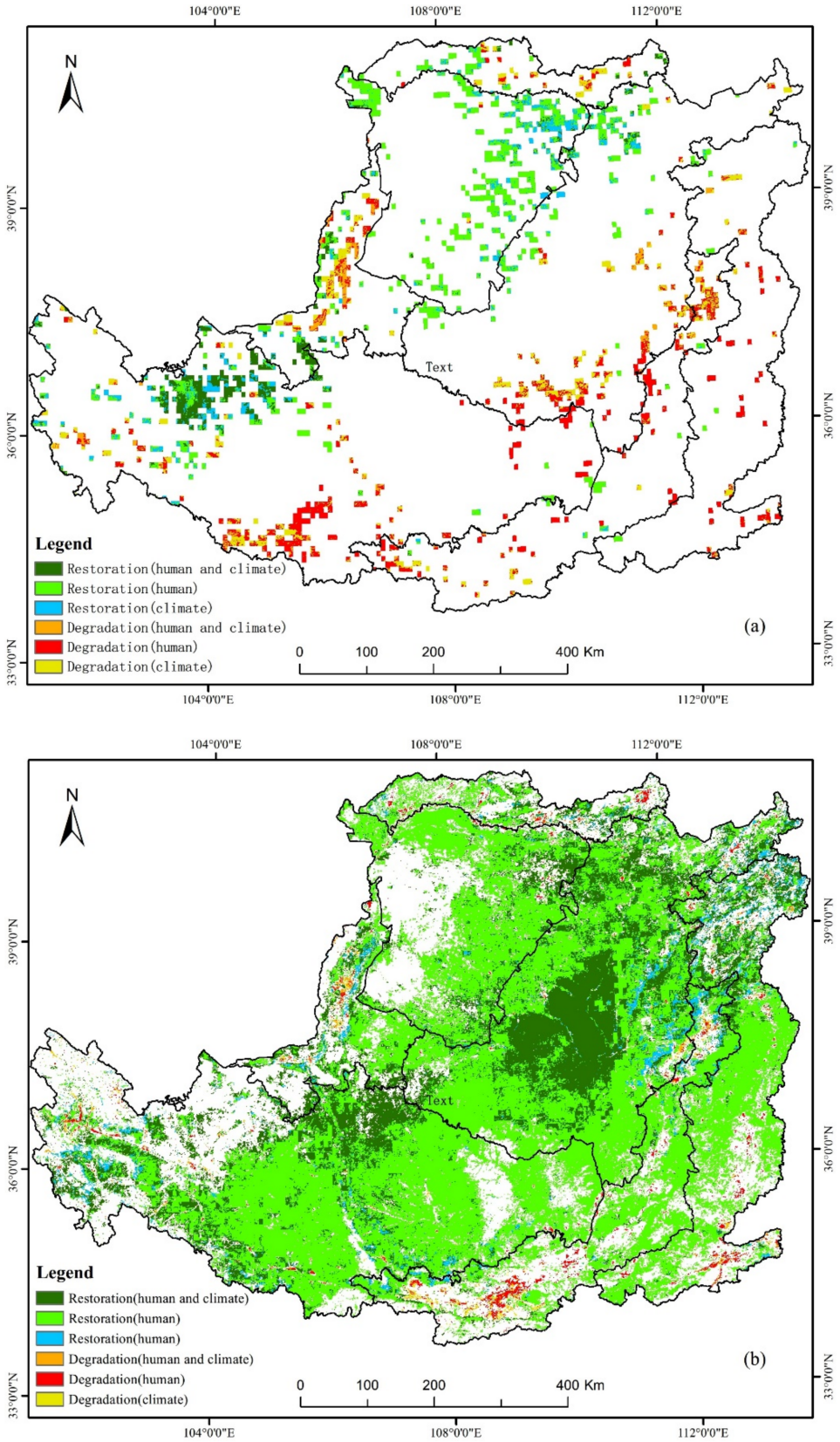


Figure 13. Distribution of driving factors of significant restoration and significant degradation of vegetation quality on the Loess Plateau before ((**a**): 1990–1999) and after ((**b**): 2000–2015) the implementation of ecological engineering.

5. Discussion

Over the past 20 years, the ecosystem structure of the Loess Plateau has changed greatly. During the period of 1990 to 2000, the rapid expansion of farmland and urban ecosystem in the Loess Plateau directly led to the decrease of grassland area, and the decrease of forest and shrub areas in varying degrees [65]. In the early stage of ecological engineering implementation (2000–2005), with the full implementation of a series of ecological projects such as GFGP, the area of forest, shrub and grassland has increased rapidly, which shows that the implementation of ecological projects in the Loess Plateau has achieved initial results [66]. In the late stage of ecological-engineering implementation (2005–2010), although part of the grassland and shrub ecosystem distribution area was occupied with the accelerating process of urbanization, the ecological restoration project in the Loess Plateau area was still continuing [67].

The regions of vegetation restoration caused by humans and climate are mainly distributed in the middle of the Loess Plateau, mainly in the north of Shaanxi; the regions of vegetation restoration caused by humans are mainly distributed in eastern and northern Inner Mongolia, southern Gansu and Ningxia, western Shaanxi and the middle of Shanxi. The above research results obtained by the model are also confirmed by the existing research results [33]. Vegetation degradation caused by humans and climate has been mainly distributed in northern Inner Mongolia, Shanxi and Ningxia; vegetation degradation caused by humans has been mainly distributed in northwestern Inner Mongolia, Shanxi and part of Shaanxi, which was mainly due to the expansion of urbanization. Similar findings have been reported previously [68–70]. Compared with the land-use distribution map of the Loess Plateau, it can also be seen that some human-induced vegetation degradation areas are distributed in the areas with cultivated land. Due to the limited resolution of remote-sensing data used in this study, it is inevitable to integrate the changes in the NDVI values of cultivated land into the model. With the implementation of the policy, the amount of cultivated land was reduced, which affected the final simulation results. In this study, the temporal and spatial pattern changes of the Loess Plateau ecosystem were monitored based on Landsat data with a spatial resolution of 30 m and a time span of 25 years. The advantage of this data set lies in the long time series and higher spatial resolution, which can allow for a more detailed and in-depth analysis of the spatial and temporal changes of ecosystem types before and after the implementation of ecological engineering on the Loess Plateau, such as the area of returning farmland to forest and grassland. However, due to the rapid increase in population on the Loess Plateau, before the implementation of ecological engineering, we insisted on "taking grain as the core" for a long time and engaged in deforestation and grassland reclamation. In addition to its special topography, it is common to cultivate grain on steep slopes on the Loess Plateau. The key work of the GFGP in regional implementation includes the conversion of sloping farmland. However, due to the spatial resolution of remote-sensing data used for ecosystem interpretation in this study, there will be some errors in monitoring the conversion of sloping farmland in some areas of the Loess Plateau, resulting in limited interpretation accuracy. Therefore, future research should use higher-resolution images for ecosystem interpretation in these areas.

Although the NDVI used in this study had a higher resolution than that of other long time series NDVI products, the spatial resolution of 1 km is still relatively low for the Loess Plateau. In some complex terrain, slope and other terrain factors have a certain impact on the reflectance of vegetation, thus affecting the NDVI observed value. In addition, the geographical location of the Loess Plateau makes the vegetation change tend to be degraded when the vegetation in a certain area is sparse. These degraded or exposed spots may affect the reflectance of remote-sensing monitoring and then the NDVI value monitoring.

The residual method is widely used to separate the effects of climate and human factors on vegetation change [71]. The residual method takes pixels as the analysis unit and proposes an analysis method that fully considers the influence of slope, soil and vegetation spatial variability on temperature–precipitation–NDVI. However, this method also has some disadvantages [35]. The trend analysis of the potential precipitation–temperature–

NDVI relationship is based on the same time series. Due to the limitation of remote-sensing data, the residual trend method can detect only degradation in the time series of such data. Considering that there are many factors that affect the change in the NDVI, such as evapotranspiration and soil moisture, these factors need to be carefully considered in future research to improve the model. In addition, there are some differences in the NDVI changes in different ecosystem types, and the implementation dynamics and specific measures of ecological engineering in different regions of the Loess Plateau are not the same. Therefore, the residual model should be used in future research to establish models for forests, shrubs, grasslands and farmlands.

6. Conclusions

From 1990 to 2015, the forest area was increasing, especially after the full implementation of ecological engineering. Before 2000, land reclamation on the Loess Plateau led to a significant increase in farmland area and then occupied a large amount of grassland and shrubland. After the implementation of ecological engineering, although the urbanization process was still expanding, the overall vegetation area on the Loess Plateau continued to increase, wetlands could be restored, and the increased areas mainly came from farmland, grassland and desert. The measures of returning farmland to ecological engineering directly led to an increase in wetland area, promoted the total wetland area of the Loess Plateau to recover to a certain extent at this stage and explained the improvement of the overall ecological environment of the region. It should be noted that after 2010, the phenomenon of returning to farming appeared in some areas.

Although the TNSDP was implemented on the Loess Plateau from 1990 to 2000, the impact of the project was small, and even the forest area in Gansu and Inner Mongolia decreased; after the full implementation of the ecological project, a large amount of farmland was converted into forest, shrubland or grassland. During this period, the area of afforestation continued to increase, especially in Shaanxi, Gansu and Ningxia.

From 1990 to 2015, the NDVI of vegetation in the Loess Plateau showed an upward trend, and the quality of vegetation tended to improve. The areas where the quality of vegetation improved significantly were mainly distributed in the central and eastern regions. Climate factors and human activities played important roles in the improvement of vegetation quality in this period. Especially after 2000, the vegetation quality on the Loess Plateau increased rapidly, and the increasing area reached 91.90% of the total area, of which the significant increasing area reached 65.78%. The vegetation quality of the study area was restored to a great extent, which was mainly due to the full implementation of ecological engineering. During the implementation of ecological engineering on the Loess Plateau, the change in vegetation quality was not the same. In the early stage of the implementation of ecological engineering, there were more areas where the vegetation quality value increased, while in the later stage, the increase was smaller. During the suspension period, the area where the NDVI value had decreased then increased.

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Abbreviations

TNSDP	"Three-North" Shelterbelt Development Program
GFGP	Grain for Green Program
NFCP	Natural Forests Conservation Program
BSSCP	Beijing-Tianjin Sand Source Control Program
NDVI	Normalized Difference Vegetation Index
GIMMS	Global Inventory Modeling and Mapping Studies
GSFC	Goddard Space Flight Center
MVC	Maximum Value Composite
EVI	Enhanced Vegetation Index
IDW	Inverse Distance Weighting

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