

Evaluation of ecological policy effects from vegetation restoration potential realization perspective: A case study of China's Loess Plateau^{*}

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Abstract: 【Objective】Vegetation restoration is the prerequisite for ecological restoration. Only when vegetation is successfully restored can the goals of ecological policy be achieved. Evaluating the effects of ecological policy and past work experience facilitates more prompt adjustments of ecological policy measures. Previous research primarily explored the implementation effects of ecological policies from the perspective of vegetation coverage level. However, improvements in vegetation coverage are driven by both resource endowment conditions and policy behaviors, and it is difficult to accurately assess the implementation effects of policy alone. 【Method】This study build upon the theory of similar habitats and uses a local sliding window model to construct similar habitat units on the Loess Plateau. It proposes the index of potential realization degree as a means to evaluate the implementation effects of ecological policy. 【Result】The results show that: (1) the green territory of the Loess Plateau gradually expanded to the northwest over the study period (2000-2020), and the overall level of vegetation coverage has been effectively improved; (2) the level of vegetation coverage in the Loess Plateau has room for further improvement, especially in the central and northwest areas. Establishing future vegetation will be key for restoration in these areas; (3) compared with the use of the enhanced vegetation index, the potential realization degree can more effectively separate the influence of resource endowment conditions and accurately evaluate the vegetation restoration effect driven by ecological policies. 【Conclusion】This study is expected to provide a theoretical reference for future adjustments to ecological policy and offer new options for methods of ecological policy evaluation.

Key words: vegetation restoration; ecological policy; similar habitats; potential realization degree; Loess Plateau

1 Introduction

After the reform and opening up, with the rapid development of China's economy and urbanization level (Wang et al., 2019), ecological protection issues were once ignored, resulting in a series of environmental problems, including soil degradation, soil erosion, resource shortages, and ecological damage (Lyu et al., 2018; Xing et al., 2019). To protect the environment and counter the present situation of fragile ecosystems in many parts of the country, the Chinese government has implemented some ecological restoration and governance policies. The Grain for Green Program (GFGP) is an important one of such ecological policies (He et al., 2020).

To evaluate the implementation of ecological policies, many scholars are increasingly focused on the improvement of vegetation coverage as an important area of research (Xu & Zhang, 2021; Feng et al., 2023). This is because vegetation restoration is a prerequisite for ecological restoration; only when an ecosystem's vegetation is restored can ecological engineering goals such as soil and water conservation, carbon sequestration, and biodiversity protection be achieved (Bennett et al., 2022; Ramos et al., 2023). Academics generally recognize three methods for evaluating the degree of vegetation restoration and its effects. The first is to use site observations to obtain indicators such as vegetation coverage, biomass, and species richness (Mohseni et al., 2017). The second is to use remote sensing technology to obtain data with a high spatial and temporal resolution, and analysis of the data

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to generate indicators like vegetation coverage and biomass (Almalki et al., 2022). The third method is to use a combination of site observations and remote sensing (Lawley et al., 2016). Compared with site observation, the use of remote sensing to obtain relevant characteristics of vegetation restoration is more rapid, efficient, objective, and reliable (Yin et al., 2018). Remote sensing data is thus widely used to evaluate vegetation restoration. The remote sensing vegetation index is a simple, effective, and empirical metric of surface vegetation that can directly reflect the degree of vegetation coverage in a region. Two vegetation indices commonly used include normalized difference vegetation index (NDVI) and enhanced vegetation index (EVI) (Chen et al., 2020). Building on these foundations, an international group of scholars have jointly proposed a new vegetation index called the kernel normalized difference vegetation index (kNDVI) (Camps-Valls et al., 2021).

Although the purpose of implementing ecological policies is to restore vegetation and protect ecological systems, factors influencing vegetation coverage can include natural conditions and global climate change, as well as man-made policies. (Miyasaka et al., 2014; Chen et al., 2022). Following the first and third laws of geography (Tobler, 1970; Zhu et al., 2018), vegetation under the same habitat conditions are likely to have a similar degree of vegetation coverage. The difference between actual vegetation coverage and the average coverage for similar habitats indicates the potential for improvement of vegetation coverage, which we define as vegetation restoration potential (VRP) (Xu et al., 2020). Thus, differences in natural resource endowments are an important factor affecting efforts to improve vegetation coverage (Xiu et al., 2018). Only by eliminating the effects of natural differences can we accurately evaluate ecological policies and their effect on vegetation restoration. This requires consideration of local geographical features such as terrain and soil. Spatial sliding window technology is an important tool used to overcome spatial differentiation, and is often used to build local statistical models that solve the shortcomings of missing variables in global models by processing spatially heterogeneous data (Zhang et al., 2018).

The Loess Plateau is the cradle of ancient Chinese culture. However, population growth and economic development in the region since the 1970s have driven large-scale deforestation and land reclamation and led to serious ecological and environmental problems (Liu et al., 2013). To promote vegetation restoration and ecological improvement, the Chinese government has included the region in the first set of pilot areas in which to implement the GFGP (Zhou et al., 2012). At time of writing, the GFGP has been implemented for more than 20 years. Research on the program often assesses the vegetation restoration effect over large scales such as counties, provinces, or river basins (Liu et al., 2019; Yu et al., 2020; Li et al., 2022). However, such studies do not consider the influence of different geographical characteristics under the law of spatial differentiation. This omission makes it challenging to accurately evaluate the effects of the program implementation.

Due to NDVI's vegetation oversaturation effect, its ability to distinguish vegetation coverage decreases with dense vegetation (Qiu et al., 2013). To address this shortcoming, this study uses the EVI data set, spatial sliding window technology, and the vegetation restoration potential realization model to assess local VRP and restoration effect in the Loess Plateau from 2000 to 2020 (Xu et al., 2020). The main contributions of this study are its use of local sliding window technology to overcome the influence of existing resource conditions and its use of the vegetation restoration potential realization degree (VRPRD) indicator to more accurately evaluate the implementation effect of the GFGP in the Loess Plateau. It provides theoretical guidance for future ecological policy adjustments and offers new methods of evaluation for ecological policy implementation areas.

2 Study area

The Loess Plateau is located at the junction of northern China and northwest China in the geographical range of 33° 43'~41° 16'N and 100° 54'~114° 33'E (Fig. 1). It is the largest area of loess accumulation in the world (Zhu et al., 2019). The Loess Plateau includes seven provincial-level administrative regions including Shanxi, Shaanxi, Gansu, Qinghai, Ningxia, Henan, and Inner Mongolia. It comprises a total of 341 county-level units, a total area of approximately 640,000 km², and a total population of more than 82 million. The Loess Plateau has a typical temperate continental monsoon climate, with hot and ra

iny summers and cold and dry winters. The average annual temperature ranges from 3.6~14.3°C, and the average annual precipitation is 150~750 mm, with decreasing precipitation from the southeast to the north hwest. The average altitude is between 1,000~2,000 m.

Since the 1970s, pressure from population growth and economic development has caused large-scale deforestation in the Loess Plateau, leading to serious ecological and environmental problems. To promote more ecologically-minded development, the Chinese government began implementing the GFGP in the Loess Plateau in 1999. After more than 20 years of development, the vegetation coverage has greatly improved, and the construction of ecological civilization has yielded many positive outcomes including enhanced biodiversity, improved soil conservation, and a more sustainable environment.

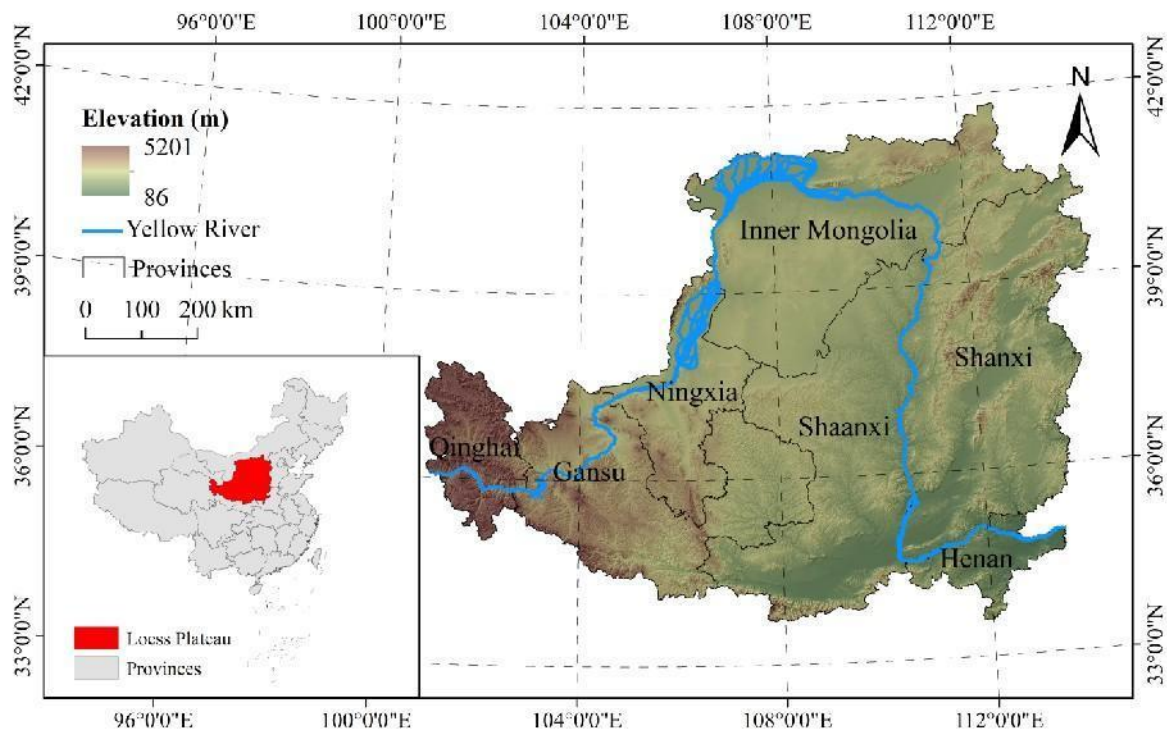


Fig. 1 Study area location

3 Data and methods

3.1 Data sources

3.1.1 Elevation and soil data

The DEM elevation data used in this study (SRTM DEM V4.1) was obtained from the Geospatial Data Cloud Platform of the Chinese Academy of Sciences (<https://www.gscloud.cn>). The data was in raster format with 90 m spatial resolution. The DEM was clipped to fit the study area (Fig. 1). The Raster Surface tool from ArcToolBox on the Arcgis10.8 platform was then used to extract the slope (Fig. 2(a)) and aspect (Fig. 2(b)) data required for this study.

The soil type data was obtained from the Resource and Environmental Science and Data Center (<https://www.resdc.cn>). The data was in raster format with spatial resolution of 1 km. Arcgis10.8 was used to resample the soil type data to 90*90 m and clip the raster data to the study area (Fig. 2(c)).

3.1.2 Meteorological data

The meteorological data used in this study comes from the 30-year average monthly/1-km climate variable dataset of China (Cheng et al., 2022). After merging and clipping to the study area, three raster

layers were obtained representing annual average temperature, annual average precipitation, and annual sunshine percentage within the study area. Finally, the spatial resolution of the meteorological grid data was unified to 90 m through resampling, as shown in Fig. 2(d)-(f).

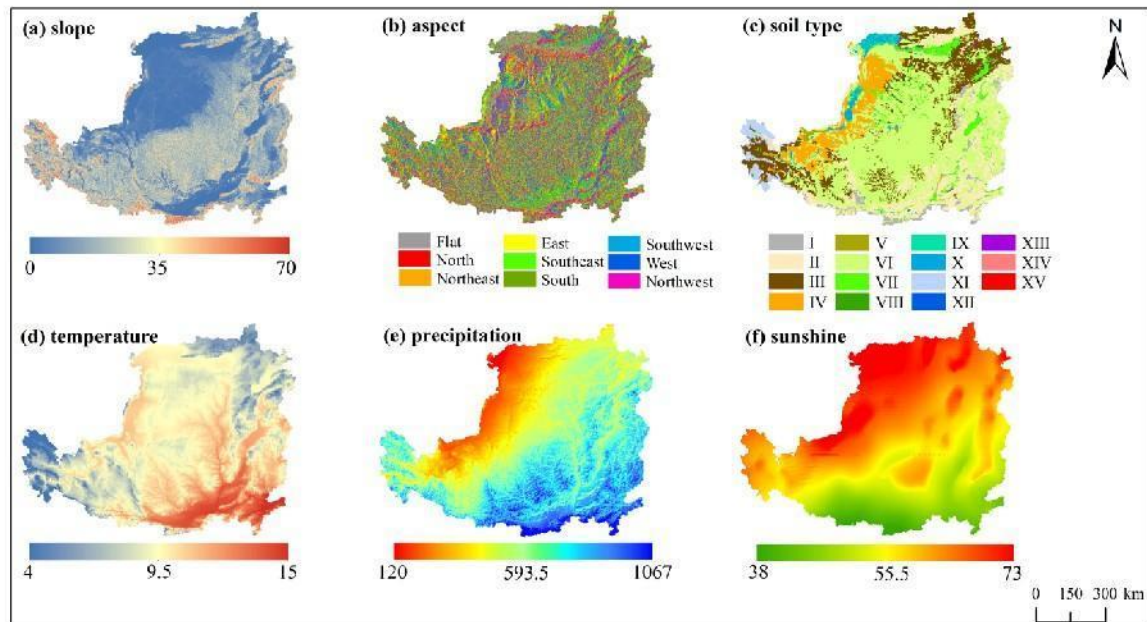


Fig. 2 Distribution of terrain, soil, and climate data on the Loess Plateau. (a) slope, unit $^{\circ}$; (b) aspect; (c) soil type, where: I represents leached soil, II represents semi-leached soil, III represents calcareous soil, IV represents dry soil, V represents desert soil, VI represents primary soil, VII represents semi-hydromorphic soil, VIII represents hydromorphic soil, IX represents saline-alkali soil, X represents anthrosols soil, XI represents alpine soil, XII represents urban area, XIII represents lake and reservoir, XIV represents river, XV represents breeding farm; (d) annual average temperature, unit $^{\circ}\text{C}$; (e) annual average precipitation, unit mm; (f) annual sunshine percentage, unit %.

3.1.3 Socioeconomic data

The road network data was obtained from the 1:1 million vector map data shared by the National Geomatics Center of China (<https://www.webmap.cn>), and the layer was clipped to fit the study area. Road density is one of the important factors driving policy effects. This study defines road density as the ratio of the length of roads in each county to the total area of the county (Bi et al., 2011).

The land use data in this study comes from the China land cover data set produced by Yang & Huang (2021) of Wuhan University. The layer was resampled and clipped to ensure consistency with the other layers' 90 m spatial resolution and scope of the study area. Using the land use data, this study calculated the intensity of the GFGP in each county as the area of cultivated land converted into forest land.

3.1.4 Vegetation coverage data

Due to the vegetation oversaturation effect associated with NDVI, dense vegetation decreases the index's ability to distinguish vegetation coverage. Therefore, this study used Google Earth Engine to obtain the annual average EVI dataset from MODIS13Q1 for 21 periods between 2000 to 2020. The temporal resolution is a 16-day synthetic product and the spatial resolution is 250 m. The data was resampled to 90 m spatial resolution to align with the other layers used in the study. To truly reflect the vegetation restoration effect after the implementation of the GFGP, this study masked out areas with terrain slopes below 6° .

3.2 Methods

3.2.1 Local-sliding-window-based similar habitat potential model

The first law of geography states that any geographical feature has a spatial correlation (Tobler, 1970). The third law of geography states that the more similar the geographical environment is, the more similar the geographical features will be (Zhu et al., 2018). Following this logic, the EVI of a given location should be equivalent to that of surrounding areas under similar growing conditions. Therefore, this study uses classification layers to construct similar habitats, with the difference between the maximum and actual EVI for a specific location defined as VRP.

The local window is a theoretically smaller spatial unit. Some macro-environmental variables, such as meteorological variables, exhibit less change across a local window, have negligible impacts on vegetation recovery, and can be regarded as having the same or similar values across geographic space (Bisson et al., 2008). Therefore, in constructing similar habitat units, this study only considered variables that change at the local window scale such as elevation, slope, aspect, and soil type, and classified and coded each control variable. To ensure the robustness of statistics, the classification of each control variable should be minimized. The specific coding mode for this study is as follows:

$$Code = a * 10^3 + b * 10^2 + c * 10^1 + d = abcd \quad (1)$$

With a , b , c , and d as the number of categories associated with each of the four variables used to construct similar habitat units, respectively. By encoding all rasters in the study area, the calculation can be reduced to one dimension, which is beneficial to the construction of similar habitat layers. Within the window radius R , we used a sliding window to find the same habitat unit as $abcd$, obtained the maximum EVI under similar habitat conditions, and calculated the VRP. The formula for the local-sliding-window-based similar habitat potential model is as follows:

$$VRP_{ij}(V_1, V_2, V_3, \dots, V_N) = \underset{\substack{1 \leq k \leq m \\ 1 \leq l \leq n}}{\text{MAX}} (u_{ij-t}, R) EVI_{kl}(V_1, V_2, V_3, \dots, V_N) - EVI_{ij}(V_1, V_2, V_3, \dots, V_N)$$

(2)

In the formula, V_N represents the N th similar habitat control variable; u_{ij-t} represents the actual EVI value of the raster located in the i^{th} row and j^{th} column in t years; t represents the time period from 2020 to 2020; $\text{MAX}(u_{ij-t}, R) EVI_{kl}(V_1, V_2, V_3, \dots, V_N)$ refers to taking the i^{th} row and j^{th} column raster as the benchmark and R as the window radius to find the theoretical maximum EVI with similar habitat conditions during the study period; and k and l are the row and column of the maximum EVI raster, respectively. Assuming m rows and n columns within the window radius R , $1 \leq k \leq m$, $1 \leq l \leq n$. $VRP_{ij}(V_1, V_2, V_3, \dots, V_N)$ is the maximum VRP of the i^{th} row and j^{th} column of the raster, which is expressed as the difference between the theoretical maximum EVI and the actual EVI of the i^{th} row and j^{th} column of the raster.

3.2.2 Potential realization degree model

At the regional scale, scholars generally regard the EVI growth rate as the vegetation restoration effect (He et al., 2018; Qu et al., 2020). Based on the VRP calculated in Section 3.2.1, this study defines VRPRD as the ratio of the actual EVI to the theoretical maximum EVI of the raster, which is used to indicate the extent to which vegetation has been restored. To avoid data errors, this study used the 99% maximum quantile value when calculating the theoretical maximum EVI. As such, VRPRD may be greater than 1, thus it is mandatory to be defined as 1. The formula for VRPRD is as follows:

$$VRPRD_{ij-t} = \begin{cases} 0, & \text{if } EVI_{ij-t} \leq 0 \\ \frac{EVI_{ij-t}(V_1, V_2, V_3, \dots, V_N)}{MEVI_{ij}(V_1, V_2, V_3, \dots, V_N)}, & \text{if } 0 < EVI_{ij-t} \leq MEVI_{ij} \\ 1, & \text{if } EVI_{ij-t} \geq MEVI_{ij} \end{cases} \quad (3)$$

In the formula, EVI_{ij-t} represents the actual EVI of the raster's i^{th} row and j^{th} column in t^{th} year; $MEVI_{ij}$ represents the theoretical maximum EVI of the raster's i^{th} row and j^{th} column under similar habitat conditions; $VRPAD_{ij-t}$ represents the VRPRD of the raster's i^{th} row and j^{th} column in the t^{th} year.

3.2.3 Ordinary least squares method

Analysis based on VRP shows that conditions of resource endowment such as elevation, slope, aspect, and soil are the primary factors influencing vegetation restoration. However, improvements in the vegetation restoration effect are caused by multiple interacting factors. VRPAD can effectively overcome the influence of endowed resource conditions. Therefore, this study uses the ordinary least squares method, with the growth rate of VRPAD between 2000 and 2020 as the dependent variable, to examine the impact of other factors such as GFGP on vegetation restoration.

$$Y_i = \alpha + \sum_k \beta_k x_{ik} + \varepsilon \quad (4)$$

In the formula, x_k represents factors in addition to resource endowment conditions that affect vegetation restoration; Y represents the growth rate of VRPAD; i represents the i^{th} county in the Loess Plateau; α and β represent the coefficients to be estimated; and ε represents the error.

4 Data and methods

4.1 Spatio-temporal changes in vegetation coverage

To assess the changes in vegetation coverage on the Loess Plateau during the study period, this study produced maps of EVI distribution on the Loess Plateau for the years 2000 and 2020. Fig. 3(a) illustrates that vegetation growth was poor in the central and northwest parts of the Loess Plateau in 2000. This is especially true in northern Shaanxi, the junction of Shaanxi and Shanxi, and the junction of Shaanxi, Gansu, and Ningxia. The annual average EVI for these areas was less than 0.25. This is likely the case because residents had minimal awareness of efforts to protect the ecological environment before the GFGP was implemented. Due to resource pressure from population growth and economic development during the study period, a large amount of vegetation was cut down for production materials and domestic fuel, and a large amount of sloped land was reclaimed for farming. This resulted in serious damage to vegetation and low EVI (Liu et al., 2013). The conditions of vegetation growth are better in the southeastern parts of the Loess Plateau, and the EVI is higher. This is mainly because the Taihang and Qinling Mountains are located in the east and south of the Loess Plateau. The complex terrain of the mountains limits human activity, so the vegetation growth in this region is greater. As shown in Fig. 3(b), the EVI of the Loess Plateau increased significantly from 2000 to 2020. This shows that decision makers in the area are gradually prioritizing ecological protection; regional vegetation has been effectively restored and the green area has expanded toward the northwest. Specifically, the southeastern parts of the Loess Plateau are maintaining their advantage in vegetation growth. The EVI in the central Loess Plateau increased significantly to about 0.35, and only a few areas of in northwest have an EVI lower than 0.25. This is a key area for subsequent work in vegetation restoration. Although the GFGP was implemented in the Loess Plateau region in 2000, the current results are insufficient to conclude that the increase in EVI is attributable solely to human policy factors. Therefore, it is necessary to isolate the influence of resource e

ndowment conditions to accurately evaluate the GFGP's effect on vegetation restoration.

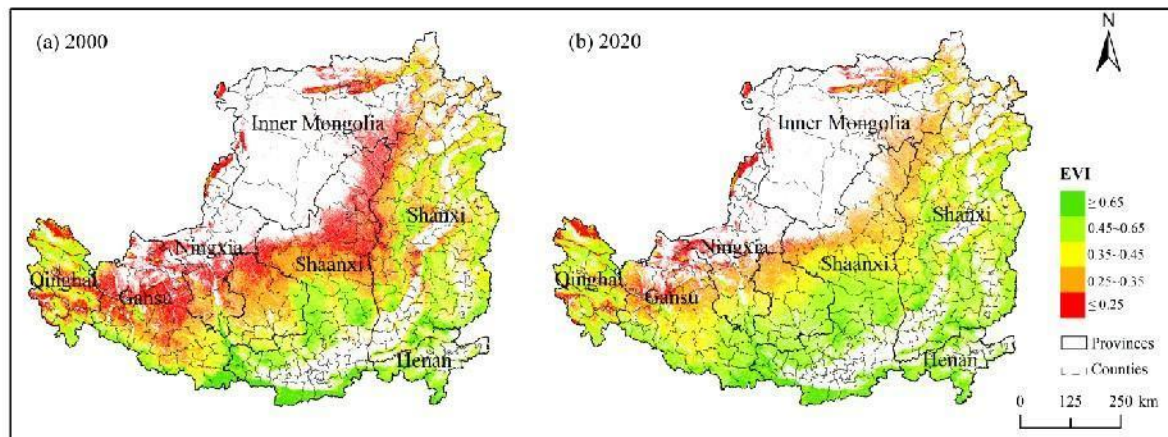


Fig. 3 Changes in enhanced vegetation index (EVI) on the Loess Plateau. (a) EVI distribution on the Loess Plateau in 2000; (b) EVI distribution on the Loess Plateau in 2020.

4.2 Vegetation restoration potential based on similar habitat units

The degree of VRP in the Loess Plateau can be better understood by constructing similar habitat units for vegetation growth in the region. This study merged the EVI layers from 2000 and 2020 using the formula (2) to calculate the VRP of each raster, and retained the maximum value to represent optimal vegetation growth. The purpose of constructing similar habitat units is to isolate the contribution of resource endowment conditions to improved vegetation coverage and to facilitate a more accurate assessment of the effects of GFGP by calculating the growth rate of VRPRD. Fig. 4 illustrates that the VRP of the Loess Plateau generally decreases from southeast to northwest. The maximum value of VRP in the southeast ranges from 0.65-1, and the number of rasters accounts for 26.7%. The minimum value of VRP in the northwest ranges from 0-0.25, and the number of rasters accounts for only 1.4%. This pattern is consistent with the water and heat distribution in the Loess Plateau. Similar habitat units were constructed using four natural conditions including elevation, slope, aspect, and soil type, which show that the resource endowment conditions in the southeast are more suitable than those in the northwest for vegetation growth. The proportion of different potential values shows the number of rasters with VRP exceeding 0.45 to account for more than 77% of the entire study area, indicating that vegetation on the Loess Plateau has high growth potential. The VRP of the Loess Plateau is also higher than the EVI in 2020 (fig. 3(b)), indicating the capacity for further improvement in vegetation restoration in the region.

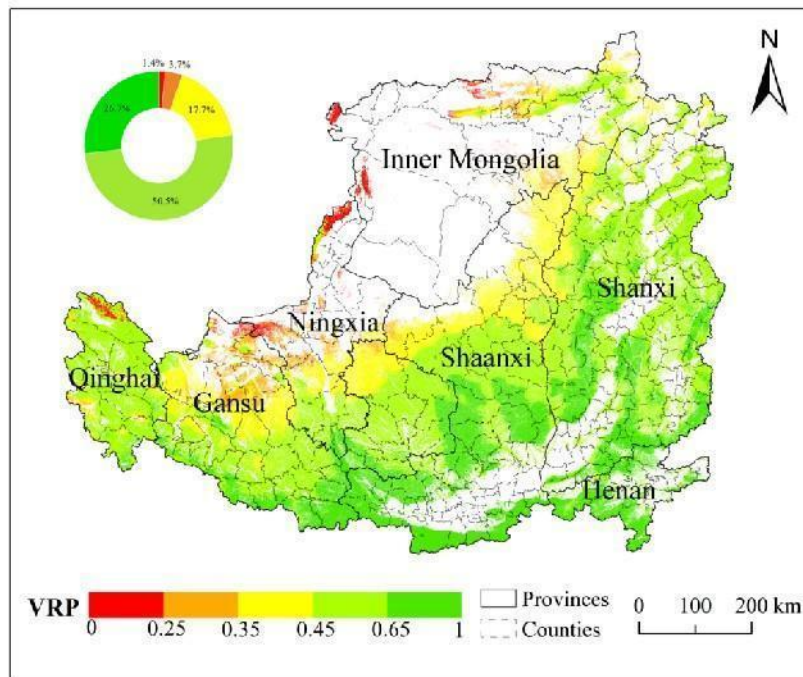


Fig. 4 Distribution of vegetation restoration potential (VRP) on the Loess Plateau.

4.3 Assessment of vegetation restoration potential realization degree

To better understand the VRPAD in the Loess Plateau at different periods, this study used formula (3) to calculate the ratio of EVI to VRP in 2000 and 2020. Fig. 5 shows that the distribution of VRPRD is consistent between the two periods and decreases from southeast to northwest. Specifically, the overall VRPRD of the Loess Plateau was low in 2000, with more than half of the rasters having a VRPRD value lower than 0.65. That is, the proportion of EVI to VRP in 2000 was less than 65% (Fig. 5(a)). This shows a capacity for improvement in EVI of at least 35%, especially in eastern Qinghai where VRPRD is lower than 0.45, indicating even greater capacity for improved vegetation coverage. The VRPRD of the region increased significantly in 2020 compared to 2000. The vast majority of the GFGP implementation area within the Loess Plateau shows VRPRD values of 0.75 and above. This is especially the case in the central part of the study area where VRPRD increased by at least 10%, exhibiting the largest improvement (Fig. 5(b)). Although the water and heat conditions in this region are relatively harsh, the central area is the epicenter of loess distribution and experiences severe soil erosion. Consequently, the GFGP was implemented here early in the program's history, which led to a substantial area under afforestation. Indeed, Wuqi County in northern Shaanxi is known as "the first county of GFGP in the country", illustrating that the vegetation restoration effect is most significant in the central Loess Plateau. In comparison, VRPRD has not changed significantly in parts of eastern Qinghai, which shows that manual management may have been neglected after the implementation of GFGP, which resulted in ineffective vegetation restoration. Comparing the VRPRD layers of the two periods, this study demonstrates that growth of VRPRD is an effective indicator of GFGP implementation, while EVI is impacted by resource endowment conditions and cannot accurately assess the effects of GFGP alone.

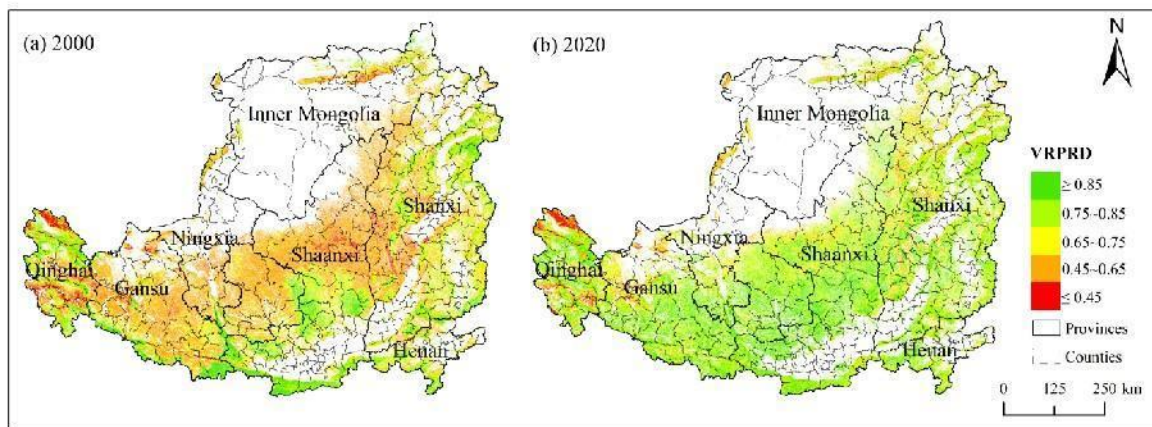


Fig. 5 Changes in vegetation restoration potential realization degree (VRPRD) of the Loess Plateau. (a) VRPRD distribution on the Loess Plateau in 2000; (b) VRPRD distribution on the Loess Plateau in 2020.

4.4 Attribution analysis of the vegetation restoration effect

The increase in vegetation coverage is the result of a combination of factors. As illustrated in Section 4.3, VRPRD is an effective metric for the vegetation restoration effect as it can effectively overcome the influence of resource endowment conditions and more accurately measure the effects of GFGP implementation. To further support the above research conclusion, this study uses formula (4) to conduct a quantitative analysis. Taking counties as sample units, we discuss the relationship between EVI growth rate and policy intensity, and other resource endowment conditions in the Loess Plateau from 2000 to 2020. Table 1 shows the magnitude and significance of the resulting correlation coefficient.

Regarding meteorological variables, there is a positive correlation between annual average temperature and EVI growth rate, with a correlation coefficient of 0.206 and significance at the 1% level. This indicates that a higher annual average temperature is more beneficial for improving vegetation restoration. The annual average temperature in the Loess Plateau decreases from southeast to northwest (Fig. 2(d)), but the EVI growth rate increases from southeast to northwest (Fig. 6(a)), which runs counter to the regression results. This is primarily because the Qinling Mountains are located in the southeast, and this area is less affected by human activities. The vegetation coverage in this region did not change much over the study period, and the EVI growth rate was low throughout. However, the central parts of the Loess Plateau are greatly affected by human activities and have significantly degraded vegetation. Moreover, this region is an important implementation area for the GFGP (Xu et al., 2020; Zhang & Zhang, 2021), and the policy response to vegetation restoration is strong, yielding a high EVI growth rate. There is a negative correlation between annual average precipitation and EVI growth rate with correlation coefficient of -0.141 and significance at the 5% level. That is, higher average annual precipitation is associated with poorer vegetation recovery, a finding which aligns with the actual situation of the Loess Plateau. Because the conditions for vegetation growth in the southeast are better and the level of vegetation coverage has been high for a long time, it is unlikely that increased precipitation will promote further improvement in the level of vegetation coverage here. There is a positive correlation between annual sunshine percentage and EVI growth rate, with a correlation coefficient of 0.061. In other words, the longer the sunshine time, the better the vegetation recovery effect. However, the correlation coefficient is not significant.

From the perspective of socioeconomic variables, there is a negative correlation between road density and EVI growth rate, with a correlation coefficient of -0.026. This is because increased road density leads to the fragmentation of regional vegetation growth plots and is not conducive to vegetation recovery. There is a positive correlation between policy intensity and EVI growth rate, with a correlation coefficient of 0.088. This shows that the implementation of GFGP is conducive to improving vegetation restoration, but the correlation coefficient is not

significant.

Overall, the positive and negative correlations between each variable and the VRPRD growth rate are consistent with those between each variable and the EVI growth rate. Except for the policy intensity variable, the absolute values of the correlation coefficients for VRPRD growth rate are smaller than those for the EVI growth rate. However, the absolute value of the correlation coefficient between policy intensity and VRPRD growth rate is greater than the absolute values of the correlation coefficients with the EVI growth rate, and it is significant at the 10% level. These results show that the EVI growth rate is more dependent on regional resource endowment conditions, while the VRPRD growth rate is less dependent on resource endowment conditions and responds more strongly to GFGP intensity. This aligns with the study's previous research hypothesis. Therefore, one can conclude that the VRPRD growth rate index effectively separates the impact of resource endowment from the vegetation restoration effect, and more accurately evaluates the effect of GFGP on vegetation restoration. Fig. 6(b) shows that the implementation of GFGP had the greatest effect in the central parts of the Loess Plateau.

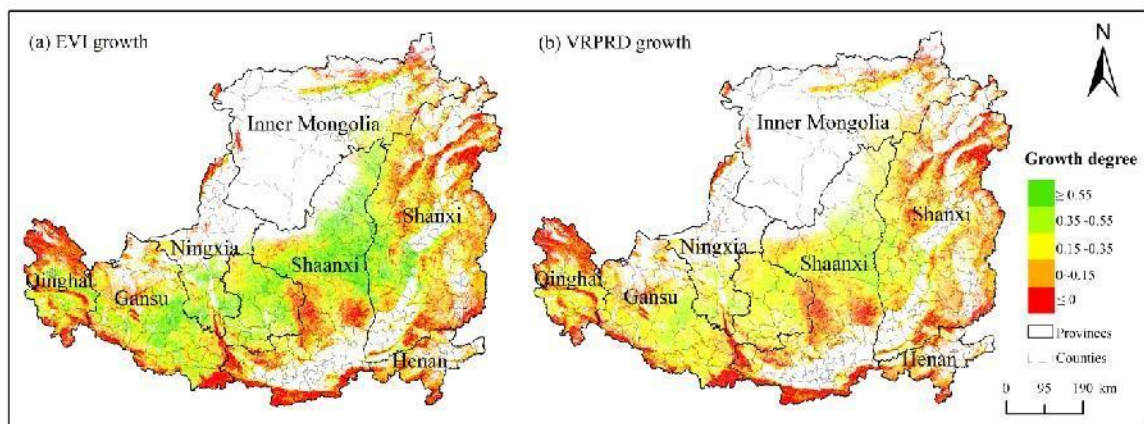


Fig. 6 Comparison of enhanced vegetation index (EVI) growth rate and vegetation restoration potential realization degree (VRPRD) growth rate in the Loess Plateau. (a) EVI growth rate distribution in the Loess Plateau; (b) VRPRD growth rate distribution in the Loess Plateau.

Table. 1 Correlation between each variable and EVI growth rate, VRPRD growth rate.

Variable type	Variable	EVI growth rate	VRPRD growth rate
Meteorological variables	Annual average temperature	0.206***	0.130***
	Average annual precipitation	-0.141**	-0.091**
	Annual sunshine percentage	0.061	0.047
Socioeconomic variables	Road density	-0.026	-0.015
	Policy intensity	0.088	0.099*

Note: * indicates significance at the 10% level, ** indicates significance at the 5% level, and *** indicates significance at the 1% level. Policy intensity refers to GFGP intensity, which represents the proportion of the area converted from farmland to forest to the total forest land area at the end of the study.

5 Discussion

5.1 The effect of the Grain for Green Program in the Loess Plateau may be overestimated

The improvement of the vegetation restoration effect is influenced jointly by human activities and re

source endowment conditions, and the essence of ecological policy is the participation of human actors. This study showed that, in the central parts of the Loess Plateau, where the GFGP has been implemented with the greatest intensity and with the largest area of grain converted to green, the average VRPRD growth rate between 2000 and 2020 was lower than the average EVI growth rate (Fig. 6). Moreover, Table 1 illustrates that EVI growth rate is more affected by natural resource endowment compared to the VRPRD growth rate. This finding is reflected in the larger absolute values of the correlation coefficients between the EVI growth rate and meteorological variables. Thus, the EVI indicator is only a simple representation of the vegetation coverage level, and includes both the impact of resource endowment conditions and the role of policy measures on vegetation restoration. Therefore, it cannot accurately represent the effect of GFGP implementation, and will likely overestimate the effect of GFGP implementation.

This study merges the first and third laws of geography, considers spatial location proximity and similar environmental variables, constructs a "potential-realization" theoretical framework for vegetation restoration, and proposes a new method of ecological policy evaluation. With this theoretical framework, the study introduces a local sliding window model to ensure that resource endowment conditions are generally consistent between similar habitat units. Given the presence of unknown variables, these are likely to be similar within a smaller window range, and thus the theoretical maximum VRP under similar habitat conditions can be estimated. The VRPRD index can reflect the effect of vegetation restoration, while the VRPRD growth rate index can overcome the impacts of resource endowment and more accurately evaluate the vegetation restoration effect brought about by GFGP. This study is expected to provide methodological support for more accurate ecological policy benefit evaluation and provide an important theoretical reference for adjusting the GFGP to local conditions in each region.

5.2 Policy implications for the Grain for Green Program in the Loess Plateau

Overall, the vegetation restoration effect across the Loess Plateau has been improved, but there remain a few areas where the vegetation restoration is poor. The VRP in some counties in southern Qinghai Province exceeds 0.45, a relatively high value. However, the VRPRD of these areas in 2020 was less than 45%, which is a low level. By considering the areas of grain for green in the previous sections, we believe that the low levels of local vegetation restoration are due to insufficient implementation intensity of GFGP. Therefore, increasing the intensity of GFGP implementation is a useful step for vegetation restoration in these parts. In the narrow northwest edge zone of the Loess Plateau consisting of northern Qinghai, northern Gansu, northern Ningxia, and western Inner Mongolia, the VRPRD maintained a low level between 2000 to 2020. However, because the VRP in these areas is also low, we believe that their resource endowment conditions are not suitable for the growth of vegetation, which results in a poor vegetation restoration effect. In future stages of the program, efforts at vegetation restoration in these parts should focus on improving the resource endowment status, adhering to the principle of suitable trees for the right site, and planting dominant tree species that are suitable for local growth conditions.

5.3 Existing inadequacies and outlook

This study uses a local-sliding-window-based similar habitat potential model, overcoming the impact of resource endowment conditions on vegetation restoration. This approach can more accurately assess the effects of ecological policies, and has great significance for vegetation restoration in arid and semi-arid areas. However, some shortcomings in our study require further exploration and research. First, this study does not incorporate information on tree species, which is crucial for improving the outcomes of ecological policies in areas with poor VRPRD. In the future, it will be important to synthesize the experience and knowledge of relevant scholars to provide policy guidance in the selection of suitable trees and reasonable species for areas with similar characteristics. In addition, water resources carrying capacity was not considered in this study's attribution analysis of the vegetation restoration effect due to limitations on data availability. Water resource carrying capacity dictates the maximum number of individuals that a u

nit area of land can carry and is an important limiting factor for vegetation restoration (Zhang et al., 2014). Therefore, future research should consider representing the variable of water resource carrying capacity with relevant data to improve the reliability of regression results.

6 Conclusions

This study analyzes EVI of the Loess Plateau between 2000 to 2020 and adopts a similar habitat theory and local sliding window model to explore the VRP of vegetation growth. The VRPRD index is calculated to evaluate the implementation effect of the Grain for Green Program (GFGP). Finally, empirical analysis is used to test the accuracy of the VRPRD index. The study draws the following conclusions: (1) the green territory of the Loess Plateau gradually expanded to the northwest between 2000 to 2020, and the central parts of the region experienced the greatest increase. In northern Shaanxi, the junction of Shaanxi and Shanxi, and the junction of Shaanxi, Gansu, and Ningxia, EVI increased by more than 40% from 0.25 to ~0.35; (2) there is room for further improvement in the vegetation restoration effect on the Loess Plateau. Both VRP and VRPRD for the region decrease from southeast to northwest. This is mainly because there are better resource endowment conditions in the southeastern parts of the study area than in the northwest which makes them more suitable for vegetation growth. Future areas of VRP growth will be concentrated in the central and northwest regions; (3) the local-sliding-window-based similar habitat potential model can effectively filter out the influence of resource endowment conditions and thus more accurately evaluate the vegetation restoration improvement effect driven by GFGP. This provides strong theoretical and methodical support for future ecological policy evaluation.

参 考 文 献

- Almalki, R., Khaki, M., Saco, P. M., Rodriguez, J. F., 2022. Monitoring and mapping vegetation cover changes in arid and semi-arid areas using remote sensing technology: A review. *Remote Sensing*, 14(20), 5143.
- Bennett, A. F., Holland, G. J., Haslem, A., Stewart, A., Radford, J. Q., Clarke, R. H., 2022. Restoration promotes recovery of woodland birds in agricultural environments: A comparison of 'revegetation' and 'remnant' landscapes. *Journal of Applied Ecology*, 59(5), 1334 - 1346.
- Bi, X., Wang, H., Zhou, R., 2011. The influence of landscape features on road development in a Loess Region, China. *Environmental Management*, 48(4), 774 - 780.
- Bisson, M., Fornaciai, A., Coli, A., Mazzarini, F., Pareschi, M. T., 2008. The vegetation resilience after fire (VRAF) index: development, implementation and an illustration from central Italy. *International Journal of Applied Earth Observation and Geoinformation*, 10(3), 312 - 329.
- Camps-Valls, G., Campos-Taberner, M., Moreno-Martínez, Á., Walther, S., Duveiller, G., Cescatti, A., Mahecha, M. D., Muñoz-Marí, J., García-Haro, F. J., Guanter, L., Jung, M., Gamon, J. A., Reichstein, M., Running, S. W., 2021. A unified vegetation index for quantifying the terrestrial biosphere. *Science Advances*, 7(9), eabc7447.
- Chen, L., Zhang, H., Zhang, X., Liu, P., Zhang, W., Ma, X., 2022. Vegetation changes in coal mining areas: Naturally or anthropogenically Driven? *CATENA*, 208, 105712.
- Chen, R., Yin, G., Liu, G., Li, J., Verger, A., 2020. Evaluation and normalization of topographic effects on vegetation indices. *Remote Sensing*, 12(14), 2290.
- Cheng, Q., Wu, X. Q., Wei, L. F., 2022. 30-year average monthly/1-km climate variable dataset of China (1951 - 1980, 1981 - 2010). *Journal of Global Change Data & Discovery*, 4, 541 - 522.
- Feng, L., Guo, M., Wang, W., Shi, Q., Guo, W., Lou, Y., Zhu, Y., Yang, H., Xu, Y., 2023. Evaluation of the effects of long-term natural and artificial restoration on vegetation characteristics, soil properties and their coupling coordinations. *Science of The Total Environment*, 884, 163828.
- He, D., Yi, G., Zhang, T., Miao, J., Li, J., Bie, X., 2018. Temporal and spatial characteristics of EVI and its response to

- climatic factors in recent 16 years based on grey relational analysis in Inner Mongolia Autonomous Region, China. *Remote Sensing*, 10(6), 961.
- He, J., Shi, X., Fu, Y., Yuan, Y., 2020. Evaluation and simulation of the impact of land use change on ecosystem services trade-offs in ecological restoration areas, China. *Land Use Policy*, 99, 105020.
- Lawley, V., Lewis, M., Clarke, K., Ostendorf, B., 2016. Site-based and remote sensing methods for monitoring indicators of vegetation condition: An Australian review. *Ecological Indicators*, 60, 1273 – 1283.
- Li, W., Wang, W., Chen, J., Zhang, Z., 2022. Assessing effects of the returning farmland to forest program on vegetation cover changes at multiple spatial scales: The case of northwest Yunnan, China. *Journal of Environmental Management*, 304, 114303.
- Liu, T., Zhang, S., Tang, J., Li, T., 2013. Comparison and analysis of agricultural and forest land changes in typical agricultural regions of northern mid-latitudes. *Chinese Geographical Science*, 23(2), 163 – 172.
- Liu, Y., Zhang, R., Huang, Z., Cheng, Z., López - Vicente, M., Ma, X., Wu, G., 2019. Solar photovoltaic panels significantly promote vegetation recovery by modifying the soil surface microhabitats in an arid sandy ecosystem. *Land Degradation & Development*, 30(18), 2177 – 2186.
- Lyu, R., Zhang, J., Xu, M., Li, J., 2018. Impacts of urbanization on ecosystem services and their temporal relations: A case study in Northern Ningxia, China. *Land Use Policy*, 77, 163 – 173.
- Miyasaka, T., Okuro, T., Miyamori, E., Zhao, X., Takeuchi, K., 2014. Effects of different restoration measures and sand dune topography on short- and long-term vegetation restoration in northeast China. *Journal of Arid Environments*, 111, 1 – 6.
- Mohseni, N., Hosseinzadeh, S. R., Sepehr, A., Golzarian, M. R., Shabani, F., 2017. Variations in spatial patterns of soil-vegetation properties and the emergence of multiple resilience thresholds within different debris flow fan positions. *Geomorphology*, 290, 365 – 375.
- Qiu, B., Zeng, C., Tang, Z., Chen, C., 2013. Characterizing spatiotemporal non-stationarity in vegetation dynamics in China using MODIS EVI dataset. *Environmental Monitoring and Assessment*, 185(11), 9019 – 9035.
- Qu, S., Wang, L., Lin, A., Yu, D., Yuan, M., Li, C., 2020. Distinguishing the impacts of climate change and anthropogenic factors on vegetation dynamics in the Yangtze River Basin, China. *Ecological Indicators*, 108, 105724.
- Ramos, R. G., Scarabello, M., Soterroni, A. C., Andrade, P. R., Simões, R., Ruivo, H. M., Kraxner, F., Ramos, F. M., 2023. Current policies are insufficient to protect or restore Brazil's cost-effective conservation priority zones. *Environmental Research Letters*, 18(6), 065006.
- Tobler, W. R., 1970. A computer movie simulating urban growth in the Detroit region. *Economic Geography*, 46(sup1), 234 – 240.
- Wang, D., Wan, K., Yang, J., 2019. Measurement and evolution of eco-efficiency of coal industry ecosystem in China. *Journal of Cleaner Production*, 209, 803 – 818.
- Xing, L., Xue, M., Hu, M., 2019. Dynamic simulation and assessment of the coupling coordination degree of the economy – resource – environment system: Case of Wuhan City in China. *Journal of Environmental Management*, 230, 474 – 487.
- Xiu, L., Yan, C., Li, X., Qian, D., Feng, K., 2018. Monitoring the response of vegetation dynamics to ecological engineering in the Mu Us Sandy Land of China from 1982 to 2014. *Environmental Monitoring and Assessment*, 190(9), 543.
- Xu, X., Zhang, D., 2021. Comparing the long - term effects of artificial and natural vegetation restoration strategies: A case study of Wuqi and its adjacent counties in northern China. *Land Degradation & Development*, 32(14), 3930 – 3945.
- Xu, X., Zhang, D., Zhang, Y., Yao, S., Zhang, J., 2020. Evaluating the vegetation restoration potential achievement of ecological projects: A case study of Yan' an, China. *Land Use Policy*, 90, 104293.
- Yang, J., Huang, X., 2021. The 30 m annual land cover dataset and its dynamics in China from 1990 to 2019. *Earth System Science Data*, 13(8), 3907 – 3925.
- Yin, H., Pflugmacher, D., Li, A., Li, Z., Hostert, P., 2018. Land use and land cover change in Inner Mongolia—Understanding the effects of China's re-vegetation programs. *Remote Sensing of Environment*, 204, 918 – 930.
- Yu, Y., Zhao, W., Martinez-Murillo, J. F., Pereira, P., 2020. Loess Plateau: From degradation to restoration. *Science of The Total Environment*, 738, 140206.
- Zhang, D., Ren, N., Hou, X., 2018. An improved logistic regression model based on a spatially weighted technique (ILRB

- SWT v1.0) and its application to mineral prospectivity mapping. *Geoscientific Model Development*, 11(6), 2525 – 2539.
- Zhang, Y., Zhang, D., 2021. Efficiency measurement and influencing factors of ecological compensation: A case study from Wuqi and Zhidan on the Loess Plateau. *Natural Resources Research*, 30(6), 4905 – 4921.
- Zhang, Z., Lu, W. X., Zhao, Y., Song, W. B., 2014. Development tendency analysis and evaluation of the water ecological carrying capacity in the Siping area of Jilin Province in China based on system dynamics and analytic hierarchy process. *Ecological Modelling*, 275, 9 – 21.
- Zhou, D., Zhao, S., Zhu, C., 2012. The Grain for Green Project induced land cover change in the Loess Plateau: A case study with Ansai County, Shanxi Province, China. *Ecological Indicators*, 23, 88 – 94.
- Zhu, A., Lu, G., Liu, J., Qin, C., Zhou, C., 2018. Spatial prediction based on third law of geography. *Annals of GIS*, 24 (4), 225 – 240.
- Zhu, Y., Jia, X., Qiao, J., Shao, M., 2019. What is the mass of loess in the Loess Plateau of China? *Science Bulletin*, 64 (8), 534 – 539.