Postprint: Spatial Mismatch Patterns and Influencing Factors of Grain for Green and Vegetation Restoration on the Loess Plateau

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Abstract

Vegetation restoration is a prerequisite for ecological restoration, and systematically analyzing the spatial mismatch relationship between Grain for Green intensity and vegetation restoration constitutes the foundation for scientifically formulating ecological protection and restoration policies. By utilizing the relative differences between vegetation restoration potential realization degree and Grain for Green intensity, this study analyzes the spatiotemporal variation characteristics of the spatial mismatch pattern of vegetation restoration on the Loess Plateau, and employs Geographically Weighted Regression to investigate the influencing factors of the spatial mismatch pattern of vegetation restoration. The results indicate: (1) From 2000 to 2022, the vegetation restoration effect on the Loess Plateau has continuously improved, with the vegetation restoration potential realization degree exceeding 0.75 overall in 2022. The theoretical maximum potential value of vegetation restoration in southern Qinghai and western Shanxi is higher than 0.60, but the potential realization degree is lower than 0.65, representing key areas for future vegetation restoration. (2) Within the farmland conversion areas, the spatial mismatch index value between Grain for Green intensity and vegetation restoration is generally higher than 0.70, manifesting as severe spatial mismatch, and the spatial mismatch phenomenon is gradually diffusing throughout the entire region. (3) Rural population pressure and agricultural industrial structure are the main factors exacerbating the spatial mismatch between Grain for Green intensity and vegetation restoration on the Loess Plateau, posing challenges to the successful achievement of the ecological objectives of the Grain for Green policy on the Loess Plateau. In the future, the Loess Plateau should focus on policy measures such as optimizing the agricultural industrial structure and enhancing the intensification degree of urban construction land to alleviate the spatial mismatch relationship between Grain for Green intensity and vegetation restoration.

Full Text

Spatial Mismatch Pattern and Its Influencing Factors between the Grain for Green Project and Vegetation Restoration in the Loess Plateau

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Abstract

Vegetation restoration is a prerequisite for ecological recovery. Systematically analyzing the spatial mismatch between Grain for Green Project intensity and vegetation restoration provides the foundation for scientifically formulating ecological protection and restoration policies. Using the relative difference between vegetation restoration potential realization degree and Grain for Green Project intensity, this study analyzed the spatio-temporal variation characteristics of the spatial mismatch pattern of vegetation restoration on the Loess Plateau, and explored its influencing factors using geographically weighted regression. The results showed that: (1) From 2000 to 2022, the vegetation restoration effect on the Loess Plateau continuously improved, with the overall vegetation restoration potential realization degree exceeding 0.75 in 2022. The theoretical maximum potential value for vegetation restoration in southern Qinghai and western Shanxi exceeded 0.60, but the potential realization degree was lower than 0.65, making these areas the focus for future vegetation restoration. (2) Within the converted farmland area, the spatial mismatch index between Grain for Green Project intensity and vegetation restoration was generally higher than 0.70, indicating a serious spatial mismatch, and this mismatch phenomenon was gradually spreading throughout the entire region. (3) Rural population pressure and agricultural industrial structure were the main factors exacerbating the spatial mismatch between Grain for Green Project intensity and vegetation restoration on the Loess Plateau, posing challenges to achieving the ecological objectives of the Grain for Green Project. In the future, the Loess Plateau should focus on policy measures such as optimizing the agricultural industrial structure and increasing the intensification of urban construction land to alleviate the spatial mismatch between Grain for Green Project intensity and vegetation restoration.

Keywords

Grain for Green Project; vegetation restoration; spatial mismatch; potential realization degree; geographically weighted regression

Introduction

Since the reform and opening up, China' s rapid economic development and urbanization have led to ecological protection being neglected at times, resulting in a series of environmental problems including soil degradation, water and soil loss, resource shortages, and ecological damage. To protect and improve the ecological environment, the Chinese government has implemented a number of ecological restoration and management policies, including the Grain for Green Project, natural forest protection, and the Three-North Shelterbelt Program. However, there is widespread spatial heterogeneity between the intensity of ecological policy implementation and ecological restoration effects—that is, areas with strong policy implementation do not necessarily achieve good ecological restoration results, leading to spatial mismatch phenomena that weaken regional ecological restoration efficiency. This suggests that there may be room for further optimization of the relationship between ecological restoration policies and vegetation restoration effects on the Loess Plateau.

The Loess Plateau, the cradle of ancient Chinese culture, experienced large-scale deforestation and land reclamation due to pressures from population growth and economic development, leading to serious ecological and environmental problems. To promote vegetation restoration and ecological improvement on the Loess Plateau, the Chinese government included the region in the first batch of pilot areas for the Grain for Green Project. As an important factor in ecological restoration, the intensity of ecological policy implementation inevitably has a significant impact on vegetation restoration effects. Since the pilot implementation of the Grain for Green Project on the Loess Plateau in 1999, regional vegetation coverage has increased substantially, and ecological environmental management has achieved positive results.

For a long time, research on spatial mismatch relationships has mainly focused on sociology, regional planning, and economic management, while studies on spatial mismatch relationships in the ecological environment field have only gradually emerged in recent years, aiming to maximize the input-output ratio of policies and improve the implementation efficiency of ecological projects. For example, some scholars have noted that during the implementation of the Grain for Green Project in Yan' an City, there was a spatial mismatch between policy implementation intensity and potential soil and water conservation effects, arguing that this phenomenon caused waste of resources and funds and led to low efficiency in soil and water conservation of the Grain for Green Project. Additionally, many scholars have paid attention to the spatial mismatch relationship between the Grain for Green Project and vegetation restoration. Some studies have pointed out that Wuqi County in Shaanxi Province was the first to launch a large-scale Grain for Green Project, earning the reputation of "the first county for returning farmland to forest in China," yet its vegetation index growth rate ranked at the bottom of the province, further confirming the existence of spatial mismatch between Grain for Green Project intensity and vegetation restoration. Therefore, to further optimize policy investment in the

Grain for Green Project on the Loess Plateau and improve vegetation restoration efficiency, investigating the spatial mismatch pattern between the Grain for Green Project and vegetation restoration is of great significance.

Furthermore, when evaluating the implementation effects of ecological policies, vegetation coverage has become an indicator widely adopted by many scholars. However, factors influencing vegetation restoration are multifaceted, including natural conditions and human policy factors. Traditional vegetation indices calculated at county, provincial, or watershed scales can only reflect vegetation coverage levels and are not entirely equivalent to the implementation effects of the Grain for Green Project, as this method does not account for the influence of different resource endowment characteristics under spatial differentiation patterns, resulting in reduced accuracy of policy effect evaluation. Only by eliminating the influence of natural condition differences in space can the actual contribution of ecological policies to vegetation restoration be accurately assessed, which requires policy effect evaluation to consider geographical features such as terrain and soil at local scales.

Based on the comprehensive similarity characteristics of geographical environments, Zhu et al. [23] proposed the Third Law of Geography, which states that the more similar the geographical environment, the more similar the characteristics of geographical targets. The First Law of Geography emphasizes the spatial correlation of geographical phenomena, suggesting that the closer the geographical location, the higher the spatial correlation. Building on this, Zhang et al. [24] combined the First Law of Geography to develop a vegetation restoration potential model based on local sliding window technology. This model can effectively strip out the influence of resource endowments and more accurately identify the actual contribution of ecological policies to vegetation restoration compared to traditional vegetation indices. This model considers both spatial dependence and spatial heterogeneity, falling within the scope of the Third Law of Geography. Therefore, the Third Law of Geography can serve as the theoretical basis for this model, while the model can be regarded as an extended application of the Third Law of Geography in ecological policy effect evaluation.

Based on this, this study uses the vegetation restoration potential realization degree model to accurately measure the vegetation restoration effects brought by ecological policy implementation on the Loess Plateau from 2000 to 2022. At the same time, it constructs a spatial mismatch index to explore the spatial mismatch pattern between Grain for Green Project intensity and vegetation restoration on the Loess Plateau, and introduces a geographically weighted regression model to identify the causes of spatial mismatch in each county. The main contribution of this study lies in using local sliding window technology to overcome the influence of resource endowment conditions on vegetation restoration, and employing the spatial mismatch index to more objectively and accurately evaluate the spatial mismatch relationship between Grain for Green Project intensity and vegetation restoration on the Loess Plateau, providing a policy reference for future adjustment and optimization of national ecological policies.

1.1 Study Area Overview

The Loess Plateau is located at the junction of northern and northwestern China and is the largest loess accumulation area in the world, primarily including seven provincial-level administrative regions: Shanxi, Shaanxi, Gansu, Qinghai, Ningxia, Henan, and Inner Mongolia (Fig. 1 [Figure 1: see original paper]), with a total area of approximately 6.82×10^{5} km^{2} and a total population exceeding 6×10^{7} people. The Loess Plateau has a typical temperate continental monsoon climate, with hot and rainy summers, cold and dry winters, an average annual temperature of 3.6–14.3°C, and average annual precipitation of 150–750 mm decreasing from southeast to northwest, with an average elevation between 1000–2000 m. Since the 1960s, vegetation on the Loess Plateau has experienced large-scale deforestation due to pressures from population growth and economic development, leading to serious ecological and environmental problems. To promote ecological civilization construction in the Loess Plateau region, the Chinese government implemented the Grain for Green Project in 1999, and after more than 20 years of development, vegetation coverage in the Loess Plateau region has increased substantially, and ecological civilization construction has achieved great results. To accurately reflect vegetation restoration effects after the implementation of the Grain for Green Project, this study masked out areas with low topographic slopes.

1.2 Data Sources

The data used in this study are mainly divided into three parts. The first part includes soil type, elevation, slope, and aspect data, primarily used to construct similar habitat layers to control the influence of resource endowment conditions on vegetation restoration and accurately measure the effect of the Grain for Green Project on vegetation restoration in the Loess Plateau. The second part includes land use data and Enhanced Vegetation Index (EVI) datasets, mainly used to calculate the spatial mismatch index between Grain for Green Project intensity and vegetation restoration effects on the Loess Plateau. Grain for Green Project intensity reflects the scale of farmland conversion at a certain time point or period; this study calculates the ratio of converted farmland area to forest land area to represent the intensity at the county level. Vegetation restoration effects are characterized by vegetation restoration potential realization degree. The third part includes annual average temperature, annual cumulative precipitation, rural population pressure, agricultural industrial structure, and rural economic level, mainly used for analyzing influencing factors under spatial effects of the spatial mismatch index. Additionally, this study uses Fractional Vegetation Cover (FVC) data to replace vegetation restoration potential realization degree to recalculate the spatial mismatch index for robustness analysis. Detailed descriptions of the relevant data are shown in Table 1 .

This study uses local sliding window technology to obtain the maximum vegetation restoration potential of similar habitat units. Bisson et al. [27] argue that local windows are theoretically smaller spatial units, and some macroenvironmental variables including climate variables vary little within local windows and can be considered as having the same or similar values for vegetation restoration impact. Although the water and heat resources differ significantly between the southeast and northwest of the Loess Plateau, which has an important impact on regional vegetation restoration [28], temperature and precipitation within similar habitat units under local window radius will not have obvious differences. Therefore, this study only considers elevation, slope, aspect, and soil variables that vary at the local window scale when constructing similar habitat units, and classifies and encodes each control variable. To ensure statistical robustness, the classification of each control variable should not be too detailed, and the specific encoding pattern follows relevant research [17].

1.3.1 Similar Habitat Potential Model

The First Law of Geography states that all geographic elements have spatial correlation [26]. Combined with the Third Law of Geography' s principle that more similar geographic environments have more similar geographic features [23], this study assumes that the vegetation restoration effect at each location should be equivalent to the EVI values under similar growth conditions in its surroundings. Based on this, this study uses classified layers to construct similar habitats, and the maximum EVI within the habitat can be defined as the vegetation restoration potential (VRP) of the Loess Plateau. The sliding window-based similar habitat potential model refers to research by Zhang et al. [24] and Zhang Daojun et al. [17], with the following calculation formula:

$$VRP_{ij}(V_N) = \max(EVI_{kl}) \quad \text{for } (k,l) \in \text{similar habitat within radius } R$$

Where VRP_{ij} is the theoretical maximum vegetation restoration potential value for grid cell (i,j), representing the maximum EVI value under similar habitat conditions within a window radius R from 2000 to 2022.

1.3.2 Potential Realization Degree Model

At the regional scale, scholars typically use vegetation index growth rates as an indicator of vegetation restoration effects [29]. To accurately measure ecological policy implementation effects, this study adopts vegetation restoration potential realization degree (VRPRD) to characterize vegetation restoration under the Grain for Green Project. VRPRD is defined as the ratio of actual EVI to theoretical maximum VRP, showing the degree to which vegetation restoration has been achieved. To avoid data errors, this study uses the maximum quantile value when calculating VRP, so VRPRD is forcibly defined as 1 in cases where actual EVI may exceed VRP. The calculation formula is as follows:

$$VRPRD_{ij}(t) = \begin{cases} 0 & \text{if } EVI_{ij}(t) \le 0 \\ \frac{EVI_{ij}(t)}{VRP_{ij}} & \text{if } 0 < EVI_{ij}(t) \le VRP_{ij} \\ 1 & \text{if } EVI_{ij}(t) > VRP_{ij} \end{cases}$$

Where $VRPRD_{ij}(t)$ is the vegetation restoration potential realization degree for grid cell (i,j) in year t, $EVI_{ij}(t)$ is the actual EVI value, and VRP_{ij} is the theoretical maximum EVI under similar habitat conditions.

1.3.3 Spatial Mismatch Index

If there are areas with high Grain for Green Project intensity but poor vegetation restoration effects, or areas with low Grain for Green Project intensity but good vegetation restoration effects, this is called spatial mismatch between Grain for Green Project intensity and vegetation restoration effects. This study draws on the spatial mismatch calculation method used by An et al. [10] to construct a spatial mismatch index (SMI) between Grain for Green Project intensity and vegetation restoration effects, which can not only quantitatively reflect the spatial mismatch relationship between the two but also comprehensively analyze the bidirectional results of spatial mismatch. The calculation formula is as follows:

$$SMI_i = \left| \frac{GFGP_i(t) - \min(GFGP(t))}{\max(GFGP(t)) - \min(GFGP(t))} - \frac{VRPRD_i(t) - \min(VRPRD(t))}{\max(VRPRD(t)) - \min(VRPRD(t))} \right|$$

Where SMI_i is the spatial mismatch index for county i in period t, with values in [0,1]. Values closer to 0 indicate smaller spatial mismatch, while values closer to 1 indicate more severe spatial mismatch. $GFGP_i(t)$ is the Grain for Green Project intensity for county i, and $VRPRD_i(t)$ is the vegetation restoration effect. The max and min values represent the maximum and minimum intensities and effects across the Loess Plateau.

1.3.4 Geographically Weighted Regression

Geographically weighted regression (GWR) is a local regression method based on ordinary least squares regression (OLS) at different spatial scales, which incorporates geographical factors. This model can be used to explore differences in how various driving factors affect dependent variables in different regions [30]. This study uses GWR to analyze the main factors influencing the spatial mismatch between Grain for Green Project intensity and vegetation restoration effects in counties of the Loess Plateau and to identify optimization measures. The calculation formula is as follows:

$$y_i = \beta_0(v_i) + \sum_{k=1}^{n} \beta_k(v_i) x_{ik} + \varepsilon_i$$

Where y_i is the spatial mismatch index for county i, $\beta_k(v_i)$ is the coefficient to be estimated for the kth influencing factor at the geographical coordinates v_i of county i, x_{ik} is the kth influencing factor, and ε_i is the random error term. Some studies have pointed out that vegetation restoration is mainly affected by climate conditions and socioeconomic factors [31]. Therefore, this study selected annual average temperature, annual cumulative precipitation, rural population pressure, agricultural industrial structure, and rural economic level as influencing factor indicators.

2.1.1 Changes in Vegetation Coverage

This study selected multiple time nodes to produce EVI distribution maps for the Loess Plateau. As shown in Figure 2 [Figure 2: see original paper], vegetation coverage on the Loess Plateau has significantly improved, indicating that the region has gradually emphasized ecological environmental protection, with effective vegetation restoration and the green map expanding toward the northwest. Specifically, the period from 2000 to 2010 was the fastest stage of vegetation restoration on the Loess Plateau, with substantial changes in the distribution of EVI values. From 2010 to 2022, the improvement rate of vegetation restoration effects gradually slowed, though the vegetation growth advantage in the southeastern Loess Plateau was maintained while vegetation coverage in central areas increased significantly.

By 2022, vegetation restoration effects had considerably improved across more than half of the Loess Plateau' s area, with the most significant improvements in central regions. However, some areas in western Gansu, Qinghai, and Ningxia still had relatively low values. Although vegetation coverage on the Loess Plateau has been substantially enhanced, the current results cannot confirm that these improvements are entirely attributable to anthropogenic policy factors. Therefore, it is necessary to separate the influence of resource endowment conditions to accurately assess the actual effects of the Grain for Green ecological policy on vegetation restoration.

2.1.2 Assessment of Vegetation Restoration Potential Realization Degree

This study constructed similar habitat layers and used local sliding windows to calculate the vegetation restoration potential of the Loess Plateau. As shown in Figure 3 [Figure 3: see original paper], the VRP of the Loess Plateau shows a decreasing trend from southeast to northwest, with values of 0.6–1.0 in the southeast and minimum values of 0.0–0.2 in the northwest, consistent with the water-heat distribution trend of the Loess Plateau. Since similar habitat units are constructed based on four natural conditions—elevation, slope, aspect, and soil—this means that the resource endowment conditions in the southeast are more suitable for vegetation growth. According to the proportion of different potential values, the number of grids with VRP $>$ 0.6 accounts for 67.14%

of the entire study area, indicating that vegetation on the Loess Plateau has substantial growth potential.

Next, this study used formula (2) to measure the vegetation restoration effects on the Loess Plateau from 2000 to 2022. As shown in Figure 4 [Figure 4: see original paper], VRPRD shows a spatially decreasing trend from southeast to northwest across all years. Specifically, in 2000, the overall VRPRD of the Loess Plateau was relatively low, with most areas having realization levels below 0.40. By 2010, VRPRD had further improved, and vegetation restoration effects reached the highest level during the study period, with the most significant improvements in the intersection area of Shaanxi and Shanxi in central Loess Plateau. After 2015, VRPRD on the Loess Plateau remained at a high level, though it decreased slightly. The theoretical maximum potential values in southern Qinghai and western Shanxi were higher than 0.60, but the actual VRPRD was lower than 0.65, indicating that vegetation coverage still has room for further improvement, and these areas will be the focus of future vegetation restoration.

2.2.1 Temporal Variation Characteristics of SMI

Considering the time lag in vegetation restoration caused by afforestation—meaning that newly planted forests typically need time to grow before vegetation coverage changes can be clearly detected by remote sensing satellites—Zhang et al. [33] found that new afforestation land generally needs 3-5 years to be stably monitored as forest land. Therefore, this study selected four time nodes to produce SMI distribution maps for different stages (Figure 5 [Figure 5: see original paper]).

From 2000 to 2010, the average SMI on the Loess Plateau showed an upward trend, indicating that the spatial mismatch between Grain for Green Project intensity and vegetation restoration gradually intensified. The regional average SMI increased by 5.33%, with the largest increase in central Loess Plateau areas. From 2010 to 2015, the average SMI decreased by 4.23%, with western Shanxi being the region with the largest decline. From 2015 to 2022, SMI increased again, and the spatial mismatch relationship intensified. Overall, the temporal variation of SMI experienced three stages: intensification, alleviation, and re-intensification.

2.2.2 Spatial Variation Characteristics of SMI

There are significant spatial differences in the spatial mismatch between Grain for Green Project intensity and vegetation restoration on the Loess Plateau (Figure 5 [Figure 5: see original paper]). From the perspective of gravity center migration trajectory, the SMI gravity center was mainly concentrated in Yan'an City, Shaanxi Province, and its migration trajectory can be divided into three stages (Figure 6 [Figure 6: see original paper]). During 2000-2010, the gravity center moved northwest; during 2010-2015, it turned southeast; and during 2015-2022, it moved northeast.

From the shape of the standard deviation ellipse, the ellipses in different years also experienced three stages: first moving northwest, then southeast, and finally northeast (Figure 6 [Figure 6: see original paper]), consistent with the gravity center migration trend. Additionally, the ellipse area decreased in different years, while the ratio of long to short axes increased. Specifically, the 2022 standard deviation ellipse area was 36.89$×10^{4}$ km^2, a reduction of 65.98% compared to 2000, and the long-to-short axis ratio was 1.52, an increase of 58.94% compared to 2000. This means that the spatial distribution directionality of SMI weakened while dispersion increased, indicating that spatial mismatch phenomena are spreading throughout the Loess Plateau and gradually intensifying.

Overall, SMI values were generally above 0.70, at a relatively high level, indicating serious spatial mismatch between Grain for Green Project intensity and vegetation restoration.

2.3.1 Collinearity Test

The improvement of vegetation coverage is the result of multiple factors working together. Therefore, this study uses geographically weighted regression to explore how different factors influence the spatial mismatch between Grain for Green Project intensity and vegetation restoration on the Loess Plateau (Figure 7 [Figure 7: see original paper]). To avoid multicollinearity problems among different variables that could bias regression results, this study calculates variance inflation factors (VIF) for selected influencing factor indicators. Table 2 shows that all variables have VIF values below 7, indicating no redundant variables and that the selected model does not have multicollinearity problems.

2.3.2 Spatial Heterogeneity Analysis of Influencing Factors

As shown in Figure 7 [Figure 7: see original paper], climate conditions (annual average temperature, annual cumulative precipitation) and socioeconomic factors (rural population pressure, agricultural industrial structure, rural economic level) have significant spatial differences in their effects on SMI.

From climate conditions, the correlation coefficient between annual average temperature and SMI changed from positive promotion to negative inhibition, while annual cumulative precipitation mainly had a positive promoting effect on SMI. Specifically, the number of counties with negative correlation coefficients between annual average temperature and SMI accounted for 43.70% of all counties on the Loess Plateau in 2000, increasing to 65.10% in 2010 and 72.73% in 2022, showing an overall upward trend. This indicates that as global climate warms, rising temperatures help alleviate the spatial mismatch between Grain for Green Project intensity and vegetation restoration. The correlation coefficient between annual cumulative precipitation and SMI was positive in

56.30% of counties in 2000, 61.00% in 2010, and 69.50% in 2022, indicating that increased precipitation exacerbates the spatial mismatch.

From socioeconomic factors, rural population pressure showed an overall increasing trend in its correlation coefficient with SMI, indicating that rural population size is an important factor affecting vegetation restoration effects. The spatial pattern of correlation coefficients between rural population pressure and SMI shifted from increasing from east to west in 2000 to increasing from south to north in 2022, with high-value areas concentrated in northern Loess Plateau, especially in Inner Mongolia where correlation coefficients exceeded 0.6, showing high sensitivity in ecologically fragile areas.

The impact of agricultural industrial structure on SMI showed little temporal and spatial variation. Temporally, the correlation coefficient between SMI and agricultural industrial structure was consistently positive across the Loess Plateau, meaning that increased agricultural output value continuously exacerbated the spatial mismatch, though the growth rate was small, with most regional correlation coefficients in the 0.2–0.4 range. Spatially, high-value areas of the correlation coefficient between SMI and agricultural industrial structure were consistently concentrated in western and southern Loess Plateau, with maximum coefficients exceeding 0.6, showing strong positive promotion effects.

The impact of rural economic level on SMI consistently showed negative inhibition over time, but this negative effect had significant spatial heterogeneity, most evident in central and western Loess Plateau. The negative impact of rural economic level on SMI in the Loess Plateau overall showed a weakening trend. In 2000, the absolute value of correlation coefficients in central Loess Plateau ranged from 0.4–0.6, decreasing to 0.0–0.2 by 2022, indicating that rural economic level is no longer a main factor in alleviating vegetation restoration spatial mismatch. However, in western Loess Plateau, the absolute value of correlation coefficients increased from 0.2–0.4 in 2000 to 0.4–0.6 in 2022, indicating that in this stage, rural economic level had a more significant effect on improving the spatial mismatch relationship.

2.3.3 Robustness Analysis

To further verify whether the geographically weighted regression results are biased, this study used FVC (Fractional Vegetation Cover) data to characterize vegetation restoration effects. By obtaining a new SMI based on FVC data and GFGP intensity data, and recalculating SMI using EVI data, the two SMI values were significantly correlated. Their correlation coefficient was greater than 0.85, with P-values all below 0.001, indicating that the model passed the robustness test. This demonstrates that using VRPRD data to calculate SMI in this study is robust and reliable.

3 Discussion

The VRPRD indicator constructed in this study can effectively separate the influence of resource endowments on vegetation restoration and accurately measure the ecological effects of the Grain for Green Project. The study found that with the deepening implementation of the Grain for Green Project, vegetation restoration effects on the Loess Plateau have been effectively enhanced, with the vegetation green line moving northwest, consistent with the research results of Sun et al. [36] and Xie et al. [37]. However, vegetation restoration is influenced not only by the Grain for Green Project but also by other human activities.

On the one hand, the spatial pattern of VRPRD showing a decrease from southeast to northwest is mainly because the eastern and southern parts of the Loess Plateau are home to the Taihang Mountains and Qinling Mountains, where complex terrain limits human activities, resulting in better vegetation growth conditions [38]. On the other hand, the SMI between Grain for Green Project intensity and vegetation restoration on the Loess Plateau shows a growth trend, with the index gravity center mainly concentrated in Yan' an City in the central region and showing a trend of moving eastward. This is primarily because the central and eastern Loess Plateau has relatively concentrated populations, and with the continuous advancement of urbanization and infrastructure construction, the management and protection of returned farmland has declined, leading to large amounts of construction land encroaching on forest land and obvious vegetation degradation [39].

Additionally, this study explored the mechanisms by which different factors affect vegetation restoration spatial mismatch on the Loess Plateau. Rural population pressure and agricultural industrial structure show positive correlations with SMI and are the main factors exacerbating the spatial mismatch between Grain for Green Project intensity and vegetation restoration. Contrary to expectations, despite gradual rural population hollowing, rural population pressure has a positive impact, mainly caused by the rapid urbanization rate on the Loess Plateau. In recent years, as large numbers of rural populations have transferred to cities, construction land has expanded dramatically, occupying some forest land and weakening vegetation restoration effects [38]. Moreover, as agricultural output value continues to increase, large amounts of human production activities also damage some vegetation resources, leading to reduced vegetation coverage [39].

To ensure the sustainability of ecological construction on the Loess Plateau and alleviate the spatial mismatch between Grain for Green Project and vegetation restoration, two main approaches should be taken. First, agricultural industrial structure should be optimized, prioritizing the development of ecological economy industries such as eco-tourism and under-forest economies. These green industries can increase farmers' income while reducing their dependence on land resources, providing sufficient growth space for vegetation restoration and enhancing the synergistic relationship between Grain for Green Project intensity and vegetation restoration. Second, urban spatial expansion should be controlled, the intensification of urban construction land should be increased to reduce pressure on forest land protection, and the management and protection system for returned farmland should be improved to help restored vegetation receive effective protection.

However, this study still has some limitations that require further exploration. First, water resource carrying capacity is an important factor affecting VRPRD, but water consumption differs among different afforestation tree species. Due to difficulty obtaining specific information on afforestation tree species, it is currently not possible to accurately calculate water resource vegetation carrying capacity for different regions. Therefore, future evaluations of Grain for Green Project implementation effects should collect as much tree species information as possible and comprehensively consider the impact of water resource vegetation carrying capacity under different afforestation tree species on VRPRD to improve the accuracy of ecological policy effect evaluation. Second, the current study discussed the spatial mismatch relationship between Grain for Green Project intensity and vegetation restoration from the perspective of project scale; the next step will consider incorporating relevant data such as policy funding investment to further verify the scientific validity and representativeness of the research results.

4 Conclusions

(1) The vegetation restoration effect in the Grain for Green Project areas of the Loess Plateau continuously improved from 2000 to 2022, with the green map gradually expanding toward the northwest. The vegetation restoration potential realization degree (VRPRD) shows a pattern of "high in the southeast, low in the northwest." By 2022, the overall VRPRD in converted farmland areas exceeded 0.75. The theoretical maximum potential value for vegetation restoration in southern Qinghai and western Shanxi was higher than 0.60, but the actual VRPRD was lower than 0.65, making these areas the focus for future vegetation restoration on the Loess Plateau.

(2) The Grain for Green Project intensity and vegetation restoration on the Loess Plateau show serious spatial mismatch. Temporally, the spatial mismatch index (SMI) between Grain for Green Project intensity and vegetation restoration on the Loess Plateau was generally above 0.70, at a relatively high level, indicating serious spatial mismatch. Spatially, the gravity center migration of SMI experienced three stages: northwest, southeast, and northeast, with spatial mismatch phenomena gradually spreading throughout the Loess Plateau.

(3) Rural population pressure and agricultural industrial structure are the main factors affecting the spatial mismatch relationship between Grain for Green Project intensity and vegetation restoration on the Loess Plateau.

Throughout the study period, rural population pressure and agricultural industrial structure showed positive correlations with SMI, posing challenges to achieving the ecological objectives of the Grain for Green Project on the Loess Plateau.

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