Postprint of Spatiotemporal Evolution and Attribution Analysis of Anthropogenic Impacts on Vegetation Cover in the Loess Plateau, 2001–2018

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Abstract

Based on MODIS-NDVI and MODIS-LST data from 2001–2018, as well as various human and social data including land use, transportation, and population, the Temperature Vegetation Dryness Index (TVDI) was used to reflect soil moisture conditions on the Loess Plateau, and the residual method was employed to eliminate the influence of soil moisture and obtain the anthropogenic impact on vegetation cover change, supplemented by trend analysis, Hurst index, Geodetector, and other methods to explore the characteristics of anthropogenic impact on vegetation cover, future change trends, and attribution of anthropogenic influences on the Loess Plateau. The results indicate: (1) The trend of anthropogenic impact on vegetation cover on the Loess Plateau from 2001–2018 was 0.36$×$10-2 a-1, with anthropogenic influences on vegetation cover developing toward a positive effect. (2) The future change trend of anthropogenic impact on vegetation cover on the Loess Plateau is shifting from positive to negative effects; notably, the future positive anthropogenic impact on vegetation cover in key areas implementing the Grain for Green Program shows a weakening trend. (3) Based on the integrated results of correlation analysis and Geodetector, the dominant anthropogenic factors influencing vegetation cover change were identified as high-level tourist attractions, urban distribution, transportation, and land use. (4) Future implementation of the Grain for Green Program and maintenance of ecological construction projects should emphasize ecological development alongside urban economic growth, mitigate the environmental hazards posed by the transportation industry, promote green tourism development, and reduce the impacts of anthropogenic activities such as land use change.

Full Text

Spatio-temporal Evolution and Attribution Analysis of Human Effects on Vegetation Cover on the Loess Plateau from 2001 to 2018

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Abstract: Based on MODIS data, this study uses the Temperature Vegetation Dryness Index (TVDI) to reflect soil moisture conditions on the Loess Plateau. The residual method is employed to eliminate the influence of soil moisture and isolate the anthropogenic impact on vegetation cover. Supplementary methods including trend analysis, Hurst index, and Geodetector are used to explore the characteristics of human influence on vegetation cover, future change trends, and attribution of anthropogenic effects. The results show that: (1) The anthropogenic influence trend on vegetation cover on the Loess Plateau from 2001 to 2018 is 0.36$\times10^{-2}$ a^{-1}, indicating that human impacts on vegetation cover are developing in a positive direction. (2) The future trend of anthropogenic influence on vegetation cover will shift from positive to negative effects across the Loess Plateau. Notably, the positive human influence on vegetation cover in key implementation areas of the Grain-for-Green Program shows a weakening trend. (3) Based on comprehensive correlation analysis and Geodetector results, the dominant anthropogenic factors influencing vegetation cover change mainly include high-level tourist attractions, urban distribution, transportation, and land use. (4) For future implementation of the Grain-for-Green Program and maintenance of ecological construction projects, emphasis should be placed on ecological construction alongside urban economic development, mitigating the ecological harm caused by the transportation industry, strengthening the development of green tourism, and reducing the impacts of human activities such as land use change.

Keywords: human effects of vegetation cover; Temperature Vegetation Dryness Index; residual method; Geodetector; Loess Plateau

Since 1978, China' s socioeconomic landscape has undergone tremendous transformation, with human impacts profoundly imprinted on vegetation cover changes. While the economy has developed rapidly, the ecological environment faces enormous risks. In recent years, intense human activities such as large-scale urbanization, multi-directional extension of rail transit, the rise of tourist attractions across regions, and changes in land resources have all caused varying degrees of negative impacts on the ecological environment, placing the relationship between humans and the natural environment in a tight balance and exacerbating abnormal climate changes and geological disasters. Therefore, strengthening quantitative analysis of human impacts on regional ecological environments will not only promote precise ecological restoration but also provide quantitative foundations for regional sustainable development, holding important theoretical and practical significance.

Evaluation methods for human impacts on vegetation cover change mainly include qualitative-semi-quantitative assessment methods and quantitative evaluation methods. Quantitative evaluation primarily includes the residual trend method, regression models, and biophysical process-based models. Each evaluation method has its advantages and disadvantages, but the residual trend method has been widely used in recent years and is recognized as a good model for evaluating human factors in vegetation cover change. Therefore, this study selects the residual trend method to evaluate the human influence on vegetation cover change. Previous studies have often used the residual trend method to remove climate factors (temperature, precipitation, etc.) from vegetation cover change to obtain the magnitude of human influence. However, in reality, soil moisture is the direct influencing factor for vegetation growth. It is a comprehensive factor under the combined effects of precipitation, temperature, and evapotranspiration, and its impact on vegetation is much greater than that of single factors like temperature or precipitation. Additionally, previous analyses of human influences have mostly used qualitative or comparative methods, lacking quantitative exploration of the positive and negative directions of specific human factors affecting vegetation cover change, making it difficult to provide precise and effective support for regional ecological environmental protection.

Since the implementation of the Grain-for-Green Program, vegetation cover and the ecological environment on the Loess Plateau have undergone significant changes, with the ecological effects of measures such as returning farmland to forest and grassland being self-evident. However, the human influencing factors and their impact patterns on vegetation cover change on the Loess Plateau still lack substantial quantitative demonstration. Therefore, this study constructs the Temperature Vegetation Dryness Index (TVDI) to reflect soil moisture levels on the Loess Plateau. Through the residual method, soil moisture is removed to express the human influence on vegetation cover. The spatio-temporal evolution pattern of human influence is analyzed, and Geodetector and correlation analysis methods are used to explore the degree, positive/negative direction, and temporal variation patterns of various human factors on vegetation cover on the Loess Plateau. This aims to identify the dominant human factors affecting vegetation cover change and provide a solid basis for maintaining previous ecological construction projects and implementing future Grain-for-Green programs, contributing to the healthy, benign, and sustainable development of the Loess Plateau' s ecological environment.

1.1 Data Sources

The data used in this study mainly includes vegetation cover, land surface temperature, ecological zoning, and various human-social data such as agricultural GDP, urban distribution, urbanization rate, population, transportation, land use, and high-level tourist attractions on the Loess Plateau. Vegetation cover data comes from the MOD13A2 dataset, with temporal data obtained through reprojection. Land surface temperature (LST) data comes from the MOD11A2 temporal dataset. Ecological zoning data is sourced from the China Ecosystem Assessment and Ecological Security Pattern Database (www.ecosystem.csdb.cn/index.jsp).

Human-social data including agricultural GDP, urbanization rate, population, and other data are obtained from county-level statistical yearbooks across the Loess Plateau from 2001 to 2018, and spatially interpolated using Empirical Bayesian Kriging. Urban data consists of municipal administrative centers, which are analyzed using Euclidean distance analysis to obtain urban distribution. Transportation data comes from the National Geographic Information Resources Directory Service System' s 1:1,000,000 National Fundamental Geographic Database, from which railways, national highways, provincial highways, and county roads are extracted. Line density analysis is performed on each and weighted to obtain transportation distribution. Land use data comes from the Chinese Academy of Sciences Resource and Environmental Science Data Center (http://www.resdc.cn/), with 2001-2018 land use data reclassified into first-level land use categories. Neighborhood analysis is combined with land use grading indices to obtain land use degree for each of the 18 years, and finally, cubic spline function interpolation is used to obtain land use degree for each year. High-level tourist attractions are sourced from provincial tourism government websites covering the Loess Plateau, mainly including 5A and 4A-level attractions. The latitude and longitude coordinates of each attraction are queried through the Baidu coordinate picker, and kernel density analysis is performed on 4A and 5A attractions separately and weighted to obtain the distribution of high-level tourist attractions.

1.2 Soil Moisture Estimation

Due to invalid data in the study area causing temporal discontinuity in MODIS LST data, the Whittaker smoother is used to reconstruct the time series data, with data extracted at intervals to obtain 18 years of data. This study uses TVDI to characterize soil moisture, based on the triangular feature space of NDVI and LST to estimate annual TVDI data for each year, and then uses the average value synthesis method to synthesize annual data. The principle is as follows:

$$TVDI = \frac{T_s - T_{smin}}{T_{smax} - T_{smin}}$$

where T_s is the land surface temperature of each pixel, T_{smin} is the minimum land surface temperature on the wet edge corresponding to the pixel, and T_{smax} is the maximum land surface temperature on the dry edge corresponding to the pixel.

1.3 Human Influence on Vegetation Cover

This study extracts the TVDI time series of each pixel to establish a regression equation for estimation. The difference between the actual NDVI value and the predicted value estimated by the regression equation is the residual series, used to analyze the spatio-temporal evolution of human influence on vegetation cover. The principle is:

$$e_i = y_i - \hat{y}_i = y_i - (\beta_0 + \beta_{1x} i + \zeta)$$

where y_i is the actual NDVI value, $\hat{y}_i$ is the predicted value estimated by the regression equation, x_i is the TVDI value, e_i is the residual (difference between actual and predicted values), and i represents time (year in this study).

1.4 Future Evolution Analysis

The Theil-Sen trend analysis is performed on the human influence on vegetation cover, with the Mann-Kendall test used to indicate the significance of the trend. Significance is divided into four levels: extremely significant ($P < 0.01$), significant ($0.01 \leq P < 0.05$), weakly significant ($0.05 \leq P < 0.1$), and not significant ($P \geq 0.1$). The Hurst index is used to reflect the persistence characteristics of human influence change on vegetation cover, divided into three levels: anti-persistence (Hurst < 0.35), weak persistence ($0.35 \leq$ Hurst ≤ 0.65), and persistence (Hurst > 0.65). Overlay analysis of the trend and Hurst index reclassification results is used to reflect the future evolution trend of human influence on vegetation cover on the Loess Plateau.

1.5 Geodetector

This study uses the factor detection module in Geodetector to analyze the attribution and change characteristics of human influence on vegetation cover on the Loess Plateau. Factor detection is used to explore the explanatory power of each factor on the spatial differentiation of human influence on vegetation cover, measured by the q-value. A larger q-value indicates stronger explanatory power of factor X on the spatial differentiation of human influence on vegetation cover, and vice versa. The q-value indicates the proportion of spatial differentiation of human influence on vegetation cover explained by factor X. Specific methodological details can be found in relevant literature.

2.1 Trend of Human Influence on Vegetation Cover on the Loess Plateau

From 2001 to 2018, the trend of human influence on vegetation cover on the Loess Plateau is 0.36$\times$10^{-2} a^{-1}, with human impacts on vegetation cover developing in a positive direction. The spatial differentiation of human influence trends is obvious (Fig. 1), with positive-effect development areas widely distributed, accounting for 84.85% of the study area, mainly located in the Northern Shaanxi Plateau–Central Gansu Plateau and the region between them. Negative-effect development areas are concentrated in the Fenwei Basin, Huangshui Valley, Qiantao Plain, and the Qinling Mountains in the southern part of the study area. From the perspective of different ecological zones, the deciduous and evergreen broad-leaved forest ecological zone in the Qinling Mountains shows a negative-effect direction for human influence on vegetation cover, while all other ecological zones show positive-effect directions. Among them, the agricultural and grassland ecological zone of the Loess Plateau shows strong positive human influence, with a residual trend of 5.28$\times$10{-2}, followed by the typical grassland ecological zone in central – eastern Inner Mongolia and the desert grassland ecological zone
2}. The mountainous deciduous broad–leaved forest ecological zone of Yanshan–
Taihang Mountains and the alpine meadow grassland ecological zone of the river source area—Southern Gansuha
2}.

Using the mean value of human influence on vegetation cover as a baseline, the positive/negative of the mean, the positive/negative of the trend, and their significance are spatially overlaid (Fig. 1). From the spatial distribution, the "negative-negative" impact area indicates that the negative effect of human influence is strengthening over time, accounting for only 0.76% of the study area, mainly distributed in the Fenwei Basin and the area east of southwestern Henan–Xiaoshan. The "negative-positive" impact area indicates that the negative effect of human influence is weakening, accounting for 6.34% of the area, mainly distributed in the desert grassland areas of northwestern Longzhong–Central Ningxia and the Ordos Plateau. The "positive-negative" impact area indicates that the positive effect of human influence is weakening, accounting for 24.49% of the area, mainly concentrated in various agricultural areas of the study area, including the Fenwei Basin, the hilly area between Taihang and Taiyue Mountains, the Ningxia Plain, and the Huangshui Valley, followed by the Qinba Mountains in the southern part of the study area, the Yinshan Mountains in the north, and the Taihang Mountains in the east. The "positive-positive" impact area indicates that the positive effect of human influence is strengthening, with the widest distribution across the study area, accounting for 42.94% of the total area, with extremely significant areas mainly distributed in the eastern typical grassland area of the Ordos Plateau and the hilly and gully areas of northern and central Shaanxi.

[Figure 1: see original paper]

2.2 Future Evolution Trend of Human Influence on Vegetation Cover on the Loess Plateau

Based on the annual mean series of human influence on vegetation cover across the Loess Plateau, the Hurst index is 0.2916, showing anti-persistent characteristics. Combined with the trend analysis, human influence has developed in a positive direction during the study period, reflecting that the future trend on the Loess Plateau will shift from positive to negative effects. The weak persistence area of human influence on vegetation cover accounts for as much as 86.41%; followed by anti-persistent areas at 10.42%; persistent areas account for only 3.17%, indicating strong randomness in the temporal variation of human influence on vegetation cover (Fig. 2).

Overlaying the positive/negative of the mean human influence, the positive/negative of the trend, and the persistence of the series (Fig. 2), combined with statistical values, reflects the future changes in human influence. The "positive-positive-anti" type indicates that the future positive effect of human influence on vegetation cover will change from strengthening to weakening, with the widest distribution area accounting for 49.42% of the total, distributed throughout the study area. The "positive-negative-anti" and "negative-positive-anti" types account for 7.30% and 7.25% respectively, with obvious regional differences in spatial distribution. The "positive-negative-anti" type is mainly distributed in the southeastern agricultural areas, followed by the western Huangshui Valley and Qiantao Plain agricultural areas, while the "negative-positive-anti" type is mainly distributed in the northwestern desert grassland areas. Notably, the "positive-positive-anti" type, which accounts for the largest proportion among the five future change types and is the key implementation area of the Grain-for-Green Program, shows a weakening trend in the future positive human influence on vegetation cover. Therefore, it is necessary to conduct in-depth analysis of human influence on vegetation cover in this area to provide a solid basis for the healthy development of the Loess Plateau' s ecological environment.

[Figure 2: see original paper]

Based on literature review and data reliability, this study selected eight factors related to human influence on vegetation cover as the main aspects of anthropogenic factors (agricultural GDP, urban distribution, urbanization rate, population, transportation, land use, and high-level scenic spots). Using the annual spatial distribution of human influence on vegetation cover as the dependent variable (Y) and the spatial distribution of the eight influencing factors as independent variables (X), both equal interval and natural breakpoint methods were used to discretize the influencing factors. Geodetector was applied to obtain annual q-statistics between the spatial differentiation of human influence on vegetation cover and the eight factors. The natural breakpoint method yielded larger q-values than equal interval discretization, reflecting higher consistency between the natural breakpoint discretization results of influencing factors and the spatial differentiation of human influence. Therefore, the natural breakpoint discretization results were selected as input for Geodetector, and q-values were visualized in a color scale to reflect the temporal variation patterns of various human factors' influence on vegetation cover (Table 1).

From the q-statistics of human factors (2001-2018), urban distribution and high-level tourist attractions have relatively high influence on vegetation cover, followed by land use distribution. Other factors have relatively weak influence, in order: population, transportation, urbanization rate, and agricultural GDP. The main reasons are: urban distribution areas are centers where resources, information, and population converge. Large-scale and rapid urban expansion damages the original ecological environment, thus showing greater influence of urban distribution on vegetation cover. High-level tourist attractions have relatively active tourism activities, where infrastructure construction and intensive tourist activities easily disturb the ecological environment of scenic areas, causing vegetation degradation, thus showing greater influence of high-level tourist attractions on vegetation cover. Land use is the process of human management and transformation of land for certain economic and social purposes, which affects vegetation ecology, making land use another important human factor affecting vegetation cover change.

Correlation analysis was used to obtain correlation coefficients between the annual spatial differentiation of human influence on vegetation cover and the eight factors, visualized in a color scale to reflect the direction and temporal variation patterns of multiple human factors' influence on vegetation cover (Table 2). The correlation coefficients clearly show that human influence has relatively high correlations with high-level tourist attractions, urban distribution, land use, and transportation, which basically matches Geodetector results, with differences mainly in transportation. In recent years, the rapid development of rail transit and its impact on the ecological environment cannot be ignored. Therefore, combining correlation analysis with Geodetector, the dominant human factors affecting vegetation cover change mainly include high-level tourist attractions, urban distribution, transportation, and land use.

From the temporal variation of correlations, the correlation between human influence and various factors from 2001 to 2018 shows obvious temporal variation characteristics, with correlation coefficients showing a "negative-positive-negative" change pattern. The Grain-for-Green Program began in 1999. In the initial stage of the program (2001-2005), various dominant factors showed negative effects on vegetation cover on the Loess Plateau. From 2006-2015, dominant factors showed obvious positive effects, mainly due to ecological environment improvements from the Grain-for-Green Program, but this positive effect showed a clear downward trend. Starting from 2016, various factors showed negative effects on vegetation cover on the Loess Plateau, with this negative effect showing a clear increasing trend, especially strong negative effect changes in 2017-2018.

Therefore, based on the correlation between human influence and various factors in recent years, for the maintenance of early ecological construction projects, emphasis should be placed on developing green tourism to increase tourism output value while protecting the environment and ecological balance. With continuous urban expansion, the influence of urban distribution on vegetation cover change will continue to increase. Additionally, the rapidly developing tourism and transportation industries and rapidly changing land use are gradually increasing their influence on vegetation cover change. According to the increasing negative effect characteristics of dominant human factors in recent years, future implementation of the Grain-for-Green Program should focus on mitigating the ecological harm caused by the transportation industry, followed by strengthening the development of green tourism and reducing the impacts of human activities such as land use change.

3 Conclusions

The main conclusions of this study are:

(1) From 2001 to 2018, the trend of human influence on vegetation cover on the Loess Plateau is 0.36$×10^{-2}$ a^{-1}, with human activities affecting vegetation cover in a positive direction. The spatial differentiation of human influence trends is significant, with positive-effect development areas widely distributed, mainly in the Northern Shaanxi Plateau–Central Gansu Plateau and the region between them. Negative-effect development areas are concentrated in the Fenwei Basin, Huangshui Valley, Qiantao Plain, and the Qinling Mountains in the southern part of the study area.

(2) Geodetector screening identified urban distribution, high-level tourist attractions, and land use as human factors with relatively high influence on vegetation cover. Correlation analysis identified high-level tourist attractions, urban distribution, transportation distribution, and land use as human factors with relatively high influence on vegetation cover. Combining correlation analysis and Geodetector results, the dominant human factors affecting vegetation cover change mainly include high-level tourist attractions, urban distribution, transportation, and land use.

(3) As urban scale continues to expand, the influence of urban distribution on vegetation cover change will continue to increase. The rapidly developing tourism and transportation industries and rapidly changing land use are also gradually increasing their influence on vegetation cover change. Future implementation of the Grain-for-Green Program and maintenance of ecological construction projects should emphasize ecological construction alongside urban economic development, mitigate the ecological harm caused by the transportation industry, strengthen the development of green tourism, and reduce the impacts of human activities such as land use change.

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Note: Figure translations are in progress. See original paper for figures.