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Spatio-Temporal Variation Characteristics and Influencing Factors of Vegetation Cover in Loess Plateau Based on Model of Spatial Autocorrelation and Geodetector

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Abstract. The Loess Plateau is located in the transition zone between subhumid, arid and semi-arid in China, where water resources are rare and ecological environment are fragile. Since 1999, the large-scale “Grain For Green” project has improved environment significantly. On the basis of summarizing the spatial variation characteristics of vegetation cover in the region, this study used spatial autocorrelation to analyze the correlation between Net Primary Production(NPP), precipitation and vegetation cover change. Natural factors such as temperature, precipitation, Digital Elevation Model(DEM) and soil moisture and human factors such as population density, Gross Domestic Production (GDP), road density and grain yield NPP were statistically divided by geodetector. The influence degree of each driving factor on Normalized Difference Vegetation Index (NDVI) was systematically discussed, and the spatial-temporal variation characteristics of vegetation in the basin and the driving force of the driving factors were explored.

Keywords: Vegetation cover; Spatio-temporal variation; Spatial autocorrelation analysis; Geodetector; the Loess Plateau.

1. Introduction

The Loess Plateau is located in the transitional zone of sub-humid, arid and semi-arid in China. Due to the natural factors of large porosity, loose texture, strong water permeability, high collapsibility, poor anti-erosion ability, relatively concentrated rainfall, and large-scale human activities after the rise of agriculture and animal husbandry, the Loess Plateau has become one of the regions with the most serious soil and water loss in the world, and is a key area for soil and water conservation in China [1-2]. Therefore, in order to boost vegetation cover, prevent soil erosion and further improve the quality of ecological environment, the Loess Plateau has implemented a large-scale project to return farmland to forest and grassland since 1999, which has changed the regional ecosystem structure and exerted a certain impact on various ecosystem services [3]. On the whole, returning farmland to forest and grassland has significantly alleviated soil and water loss in the project area, effectively controlled land desertification and greatly increased forest and grass vegetation. Plus, the forest cover rate has increased by more than 4 percent on average, and the total value of annual ecological benefits has reached 1.42 trillion yuan [4]. The project has created a miracle in the history of world ecological construction [5], whose capital investment, implementation scope and public participation have all reached a record high. It has also contributed more than 4% to global net green growth area.

At present, pixel dichotomy is a remote sensing estimation model that uses Normalized Difference Vegetation Index (NDVI) to extract Fractional Vegetation Cover (FVC), and it has been widely used due to its advantages of easy construction and nice physical significance [6-8]. Many scholars use NDVI data based on pixel dichotomy to explore the temporal and spatial changes of FVC and its impact factors. Chang et al. [9] used three models of pixel dichotomy, linear spectral mixing and adaptive reflectivity spatio-temporal fusion to study the spatio-temporal variation of FVC in the middle mountain area of the north slope of Tianshan Mountains. Fensholt et al. [10] summarized the changes of FVC in semi-arid regions of the world from 1981 to 2007 and analyzed the driving factors. Li et al. [11] used trend analysis, slope regression analysis and other methods to study the spatio-temporal variation of FVC in the north slope of Tianshan Mountains during the past 30 years. Li et al. [12] analyzed the spatial pattern, intermonthly and interannual variation of FVC in the Yellow River Basin from 1982 to 2021 by Theil-Sen Median and Mann-Kendall et al. The above studies analyzed the spatio-temporal variation characteristics and driving mechanisms of FVC in different regions but mainly used linear correlation analysis, which only considered the climatic factors such as precipitation and temperature and ignored the effects of human factors and topographic factors on FVC. As a result, it was impossible to quantitatively study the effects of various influencing factors [13-14].

In view of the above background, based on the NDVI and various natural and socio-economic data from 2010 to 2020, this paper uses methods of spatial autocorrelation and geodetector to explore the spatial-temporal changes and influencing factors of vegetation cover in the Loess Plateau during the implementation of Grain For Green. It provides reference for the deepening implementation of vegetation restoration, and reveals the impacts of Grain For Green policy from a new perspective.

2. Study area and method

2.1. Overview of the study area

The Loess Plateau (100°83 '-114°52' E, 33°68 '-41°27' N) is located in the northwest of China, spanning the seven provinces of Qinghai, Gansu Ningxia, Inner Mongolia, Shaanxi, Shanxi and Henan, with an elevation of 81-5010m. The total area is about 650,000 km2 and the total population is about 86 million. In order to effectively tackle the serious problems of ecosystem degradation and soil erosion, the Chinese government has implemented the policy of Grain For Green. In 1999, pilot projects were launched in Shaanxi and Gansu provinces. In 2002, on the basis of the success of the pilot project, the Grain For Green was fully launched across the country, and the Loess Plateau was one of the key areas for the implementation of the policy [15-17].

2.2. Data source and processing

In this paper, NDVI data is used to characterize vegetation cover change. Natural factors such as air temperature, precipitation, soil moisture, Digital Elevation Model(DEM) elevation, and social and economic factors such as grain yield NPP, population, Gross Domestic Production(GDP), and road density are used to comprehensively explore the impact of various factors on vegetation cover change.

Table 1 Relevant Data

Data	Data type	Resolution	Source	Year
Soil moisture	Raster	0.25°	https://www.scidb.cn/en/detail?dataSetId=434a6fad0daa4c32a7396dc7db575fc8	2010. 2015. 2020
NDVI	Raster	1000m	https://search.earthdata.nasa.gov/search	2010. 2015. 2020
Precipitation	Raster	1000m	https://data.tpdc.ac.cn/zh-hans/data/faae7605-a0f2-4d18-b28f-5cee413766a2	2010. 2015. 2020
Road	Vector	/	https://www.openstreetmap.org/	2010. 2015. 2020
DEM	Raster	500m	https://www.gebco.net/data_and_products/gridded_bathymetry_data/	2010. 2015. 2020
GDP	Raster	500m	https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/YGIVCD	2010. 2015. 2020
Population	Raster	1000m	https://landscan.ornl.gov/	2010. 2015. 2020
Temperature	Raster	1000m	https://data.tpdc.ac.cn/zh-hans/data/71ab4677-b66c-4fd1-a004-b2a541c4d5bf	2010. 2015. 2020
NPP	Raster	500m	https://lpdaac.usgs.gov/product_search/?view=listhttps://lpdaac.usgs.gov/product_search/?view=list	2010. 2015. 2020

3. Research Methods

3.1. NDVI classification

According to the improved pixel bipartite model [18], NDVI value consists of the part covered by vegetation, and the phase bipartite model of vegetation coverage is shown in the formula.

$$FVC=\frac{NDVI-NDVI_S}{NDVI_V-NDVI_S} \quad (1)$$

Where FVC stands for Fractional Vegetation Cover; $NDVI_S$ is the NDVI value of bare soil, desert or non-vegetated area. $NDVI_V$ represents the NDVI value of the vegetated area. In practice, land use type will affect the vegetation cover to some extent. The value range of NDVI is [-1,1], and the maximum and minimum values of NDVI are selected as the values of $NDVI_V$ and $NDVI_S$

3.2. Spatial autocorrelation analysis

Spatial autocorrelation includes global autocorrelation and local autocorrelation, which are commonly used to test whether the correlation between a phenomenon and its adjacent spatial units is significant. The Local Moran Index measures the similarity and significance level of attributes between adjacent spatial units. Local Indicators of Spatial Autocorrelation (LISA) cluster maps are commonly used to divide the spatial connection patterns between regions into five types: high-high cluster, low-low cluster, high-low cluster , low-high cluster and not significant.

$$L = \frac{(x_i - \bar{x})}{S_i^2 \sum_{i=1, j\neq 1}^{n} w_{ij}(x_i - \bar{x})} \quad (2)$$

Where L refers to local autocorrelation and the specific position and condition of data, x_i and x_j represent the data of time series, n is the length of time series, $\bar{x}$ represents the average of the attribute value of a single spatial unit sample. S_i^2 is the variance of the spatial unit sample, and w_{ij} is the weight between several adjacent spatial units.

3.3. Analysis of geodetector

The study area has a large spatial span, which is not only different in weather, soil and elevation, but also influenced by social and economic activities such as population density and GDP. The ecological problems have also attracted wide attention [19].

Geodetector is a statistical method based on spatial statistics and spatial autocorrelation theory, which can conduct spatial differentiation exploration, reveal the influence and significance of each single factor between the driving factor and the research object, the risk area and interaction intensity between the detection factor, and carry out ecological exploration. In this study, factor detection tools and interaction detection tools of this method were used to analyze the spatio-temporal characteristics and influencing factors of vegetation coverage in the region.

1) Factor detection [20] is used to detect the spatial differentiation of dependent variable Y (FVC) and the influence of independent variable X (natural and socio-economic factors) on the spatial differentiation of Y, expressed by q. The formula is as follows:

$$q=1- \frac{1}{N\sigma^2} \sum_{h=1}^{L} N_h\sigma_h^2 = 1- \frac{SSW}{SST} \quad (3)$$

$$SSW=\sum_{h=1}^{L} N_h\sigma_h^2 \quad (4)$$

$$SSW=N\sigma^2 \quad (5)$$

Where h=1, 2, ···L, is the classification of X or Y; The range of q is [0, 1], and the larger the value of q, the stronger the influence of X on the spatial differentiation of Y. Nh and N represent the number of units in class h and the number of units in the total area of space, and the variance of Y in class h and region respectively; SSW and SST are the sum of variances and total regional variances of class L, respectively.

Plus, a simple transformation of q values is noncentral F distribution, where λ is a noncentral parameter.

$$F=\frac{N-L}{L-1}\frac{q}{1-q} \sim F(L-1, N-L; \lambda) \quad (6)$$

In this study, the basin area was divided into a 1km×1km grid, with a total of 6693 central points selected as sampling points, and the corresponding X and Y attribute values were extracted in space, and finally they were substituted into the geodetector for calculation and processing. By natural breakpoint method, driving factors such as precipitation, temperature,DEM, soil moisture, GDP, population density, and grain yield NPP were divided into 10 categories [21], and road density was divided into 5 categories.

2) Interaction detection: Identify the interaction between different independent variables X, reflect whether the influence of the two factors interacting on Y is related or independent, and use the q value [q(X1∩X2)] to get the conclusion.

3.4. Vegetation change analysis method

$$FC= (FVC_n - FVC_{n-1})/ FVC_{n-1} \tag{7}$$

Where, FVC_i is the vegetation coverage of year i; FVC_n and FVC_{n-1} represent the vegetation coverage values of two different months.

FC, as an indicator to measure vegetation change, is divided into five levels according to the percentage change of vegetation coverage: significant improvement (≥15%), no obvious change ([-15%,15%]), slight degradation ([-25%,-15%]), moderate degradation ([-35%, -25%]) and severe degradation (≤-35%) [22]

4. Results

4.1. Spatial change of vegetation cover

Table 2 Classification statistics of vegetation cover change in a period in the Loess Plateau

Vegetation degradation	2010~2015		2015~2020		2010~2020	
	Area (Km²)	percentage (%)	Area (Km²)	percentage (%)	Area (Km²)	percentage (%)
Severe degradation	933.41	0.144	8392.233	1.291	696.63	0.953
Moderate degradation	3885.57	0.598	14942.648	2.3	13376.605	2.058
Slight degradation	20496.52	3.153	36937.269	5.683	33412.897	5.14
No obvious change	552573.62	85.011	518763.8	79.81	489159.199	75.255
Improvement	72110.88	11.094	70964.052	10.918	107854.668	16.593

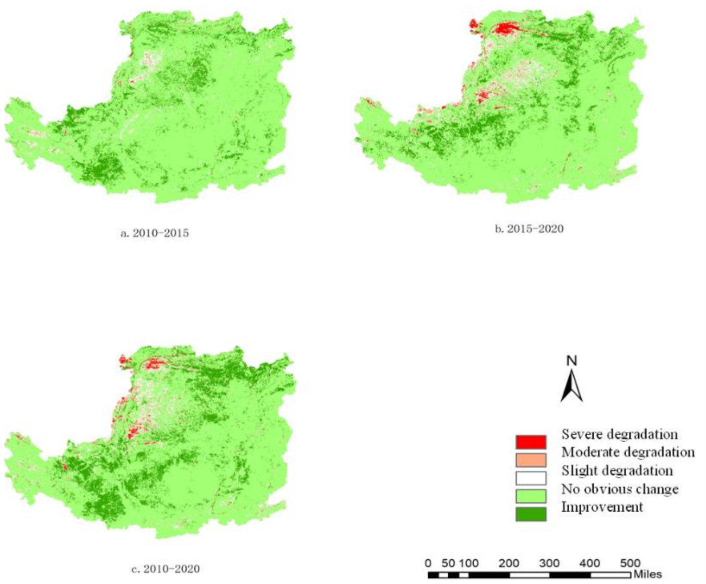

Fig. 1 Vegetation cover change map of the Loess Plateau

In general, from 2010 to 2020, the areas with severe degradation, moderate degradation and slight degradation are less, and they are mainly concentrated in the northwest of the Loess Plateau. The improvement area is mainly distributed in the middle, southwest and northeast of the Loess Plateau. The areas with no obvious changes occupy the majority.(Fig. 1, Table 2)

4.2. Spatial autocorrelation analysis

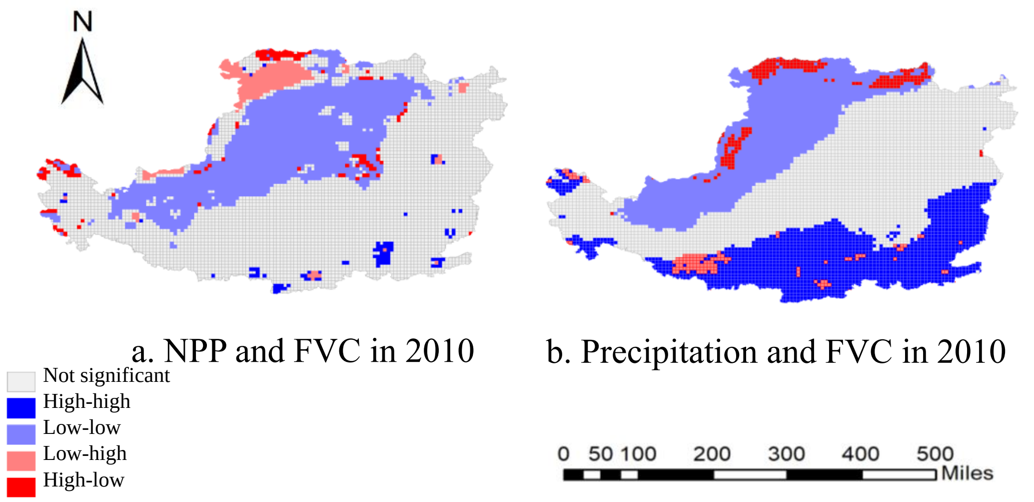

Fig. 2 Correlation in 2010

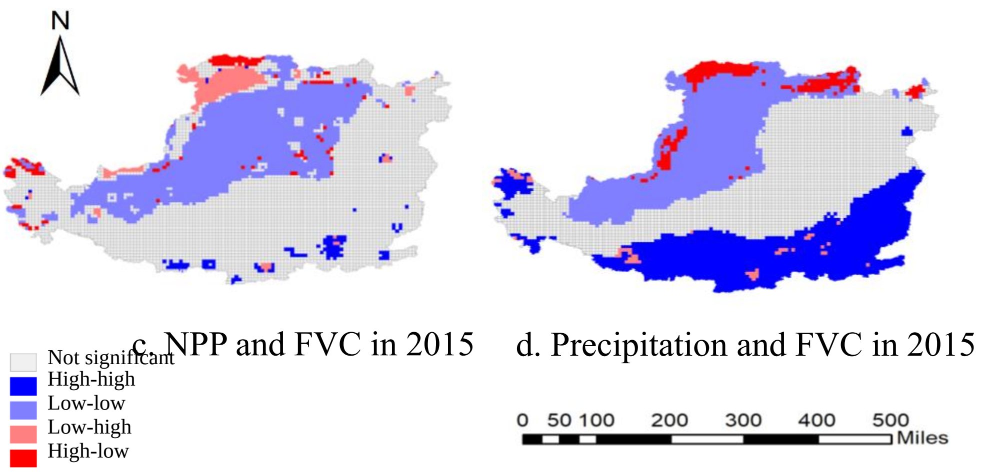

Fig. 3 Correlation in 2015

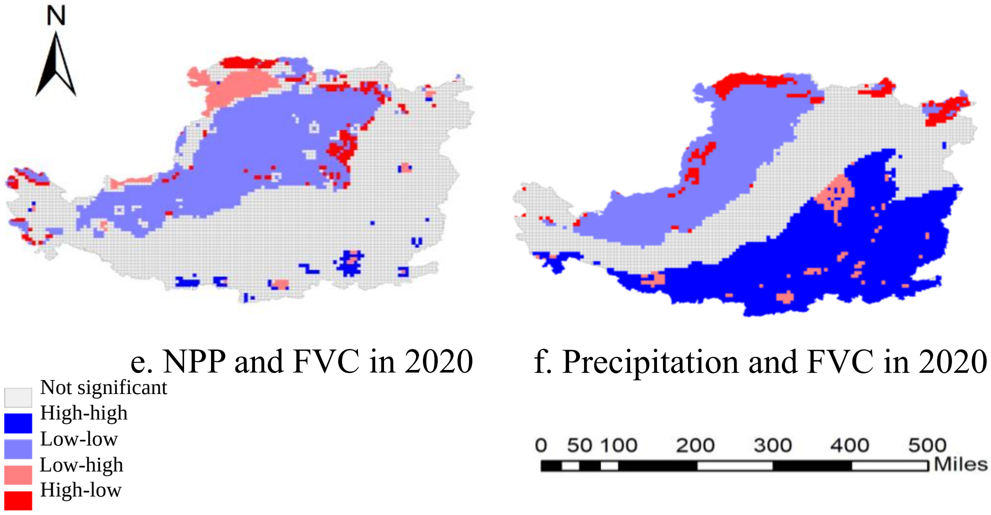

Fig. 4 Correlation in 2020

In 2020, there is a positive correlation between vegetation cover and precipitation in most areas of the Loess Plateau. With the increase of precipitation, vegetation cover will also increase. The correlation between the northeast and southwest of the Loess Plateau is not significant. The negative correlation is mainly concentrated in the northern and southern parts of the Loess Plateau. There was no significant correlation between vegetation coverage and grain yield in most areas of the Loess Plateau, and it mainly distributed in the central and southeast part, showing a trend of northeast and southwest. In the northwest central region, the vegetation cover was positively correlated with the grain yield, and the vegetation cover decreased with the decrease of grain yield. The vegetation cover in the northwest of the Loess Plateau showed a dense negative correlation with grain yield, and other scattered areas also had a negative correlation.(Fig. 4)

Through the correlation analysis of vegetation cover, precipitation and grain yield in 2010, 2015 and 2020, it can be drawn out that vegetation cover is positively correlated with grain yield in most regions of the Loess Plateau, mainly in the central and northwestern regions. The negative correlation is distributed in the northwest, and some places are scattered. The areas with positive correlation between vegetation cover and precipitation are mainly distributed in southeast, central and northwest, while the areas with negative correlation are distributed in northwest and scattered places. The correlation between precipitation and food yield and vegetation cover is not significant enough in most regions, mainly distributed in the northeast and southwest strip-shaped regions.(Fig. 2, Fig. 3, Fig. 4)

4.3. Analysis of single influencing factors of each driving factor on vegetation cover change

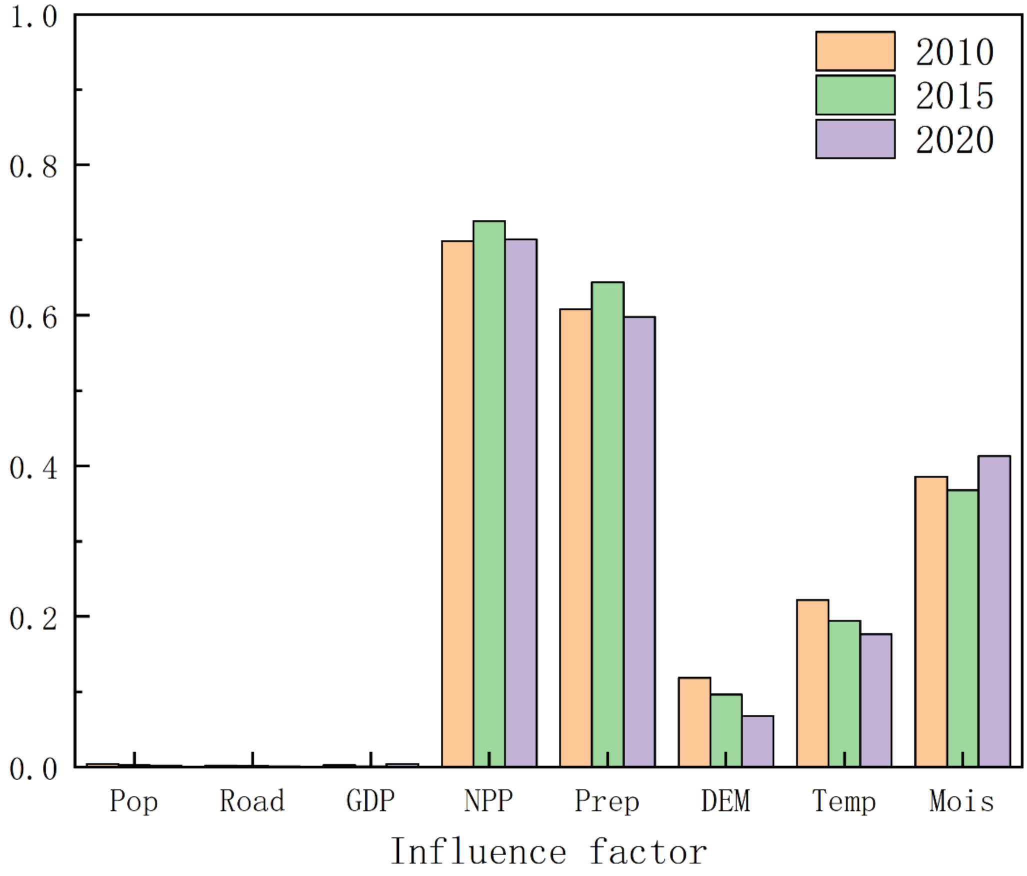

Fig. 5 Influencing factors of vegetation cover change

It can be seen from the above figure that NPP has the greatest impact on grain yield, followed by Precipitation, Population, Road and GDP. The influence degree of DEM and Temperature both showed a decreasing trend with the increase of years. The effects of both NPP and Precipitation were strongest in 2015, while the effects of soil moisture were the weakest in 2015.(Fig.5)

4.4. Analysis of interactive influencing factors of each driving factor on vegetation cover change Analysis of influencing factors in 2010

Table. 3 q values of drivers of FVC in the Loess Plateau in 2010

Road	GDP	NPP	Precipitation	DEM	Temperature	Population	Soil Moisture
0.002	0.003	0.699	0.608	0.118	0.222	0.004	0.386

Based on the geodetector, the driving factor q value in the region in 2010 was calculated and analyzed. The influence of each driving factor on FVC is as follows: NPP(0.699)>Precipitation(0.608)>moisture(0.386)>tempemture(0.222)>DEM(0.118)>population(0.004)>GDP(0.003)>Road(0.002). The spatial variation of FVC within the region is the result of the interaction of natural and human factors. Among them, the contribution of grain yield and precipitation to FVC is strong with q values greater than 0.6, while the contribution of road, GDP, DEM and population is relatively small. In the analysis of FVC spatial variation factors in the region, the grain yield factor dominated the human factors, and the precipitation factor dominated the natural factors. From all the factors explored, grain yield has the greatest impact. Therefore, human factors need to be paid more attention in future studies on FVC changes and ecological environment evolution on the Loess Plateau.(Table 3)

Table. 4 Statistic values of interactive driving forces (q) of FVC driving factors in the Loess Plateau in 2010

Driving factor	Road	GDP	NPP	Precipitation	DEM	Temperature	Population	Soil Moisture
Road	0.002							
GDP	0.005	0.003						
NPP	0.702	0.716	0.699					
Precipitation	0.611	0.615	0.814	0.608				
DEM	0.126	0.126	0.767	0.704	0.118			
Temperature	0.227	0.228	0.748	0.695	0.285	0.222		
Population	0.006	0.010	0.712	0.615	0.122	0.226	0.004	
Soil Moisture	0.391	0.400	0.765	0.663	0.541	0.529	0.397	0.386

In order to explore the influence of human and natural factors on FVC, the interaction between the same driving factor and different driving factors and their influence on the spatial variation of FVC were quantitatively analyzed by geodetector. The following main conclusions can be drawn from the table above: 1) For the independent influencing factors, the influence of human factors on grain yield NPP is the largest and reaches up to 0.699, while that of natural factors on Precipitation is the largest, reaching 0.608; However, the interaction of any two driving factors is greater than that of a single influencing factor; 2) For the interaction factors, the q values of grain yield NPP and precipitation were all greater than 0.6 when they were combined with other driving factors. 3) The interaction between grain yield NPP and precipitation, DEM, temperature, population, soil moisture, road, GDP, and precipitation and DEM is significant, with q values greater than 0.7, in which the interaction between precipitation and grain yield NPP is the most obvious, reaching 0.814. It can reflect the strong degree of influence of the factor of grain yield NPP.(Table 4)

4.5. Analysis of influencing factors in 2015

Table. 5 q values of drivers of FVC in the Loess Plateau in 2015

Road	GDP	NPP	Precipitation	DEM	temperature	Population	Moisture
0.001	0.001	0.725	0.644	0.096	0.194	0.003	0.368

The results of calculation and analysis of driver q value in 2015 in the region are shown in the table above. The influence of each driver on FVC is as follows:

NPP(0.725)>Precipitation(0.644)>moisture(0.368)>tempemture(0.194)>DEM(0.096)>population(0.003)>GDP(0.001)≥Road(0.001).(Table 5)

Table. 6 Statistic values of interactive driving forces (q) of FVC driving factors in the Loess Plateau in 2015

Driving factor	Road	GDP	NPP	Precipitation	DEM	temperature	Population	Moisture
Road	0.001							
GDP	0.003	0.001						
NPP	0.729	0.740	0.725					
Precipitation	0.648	0.652	0.847	0.644				
DEM	0.106	0.103	0.782	0.737	0.096			
temperature	0.201	0.200	0.762	0.696	0.254	0.194		
Population	0.005	0.005	0.737	0.651	0.100	0.198	0.003	
Moisture	0.375	0.380	0.791	0.671	0.536	0.493	0.378	0.368

The following main conclusions can be drawn from the table above: 1) As for the independent influence factors, among the human factors, the influence of grain yield NPP is the largest, reaching 0.725, and among the natural factors, Precipitation is the largest, reaching 0.644. However, the interaction of any two driving factors is greater than that of a single influencing factor; 2) For the interaction factors, the q values of grain yield and precipitation were all greater than 0.6 when they were combined with other driving factors. 3) The interaction between grain yield NPP and other influencing factors as well as precipitation and DEM is significant, with q values greater than 0.7, among which the interaction between precipitation and grain yield NPP is the most obvious, reaching 0.847.(Table 6)

4.6. Analysis of influencing factors in 2020

Table. 7 q values of drivers of FVC in the Loess Plateau in 2020

Road	GDP	NPP	Precipitation	DEM	temperature	Population	Moisture
0.001	0.004	0.701	0.598	0.068	0.176	0.002	0.413

Results of calculation and analysis of driver factor q value in 2020 in the region are shown in the table above. Influence of driving factors on FVC is shown as NPP(0.701)>Precipitation(0.598)>Moisture(0.413)>Temperature (0.176) > DEM GDP (0.004) (0.068) > Population (0.002) > Road (0.001).(Table 7)

Table. 8 Statistic values of interactive driving forces (q) of FVC driving factors in the Loess Plateau in 2020

Driving factor	Road	GDP	NPP	Precipitation	DEM	temperature	Population	Moisture
Road	0.001							
GDP	0.006	0.004						
NPP	0.706	0.726	0.701					
Precipitation	0.603	0.618	0.824	0.598				
DEM	0.077	0.082	0.753	0.718	0.068			
temperature	0.183	0.191	0.729	0.684	0.234	0.176		
Population	0.004	0.006	0.718	0.607	0.074	0.183	0.002	
Moisture	0.419	0.438	0.783	0.678	0.533	0.507	0.427	0.413

The following main conclusions can be drawn from the table above: 1) As for the independent influencing factors, the human factor has the largest influence on grain yield NPP (0.701), while the natural factor has the largest influence on Precipitation (0.598). However, the interaction of any two driving factors is greater than that of a single influencing factor; 2) For the interaction factors, the q values of grain yield and precipitation were all greater than 0.6 when they were combined with other driving factors. 3) The interaction between grain yield NPP and other influencing factors as well as precipitation and DEM is significant, with q values greater than 0.7, among which the interaction between precipitation and grain yield NPP is the most obvious, reaching 0.824.(Table 8)

4.7. Discussion

This study analyzed the effects of natural, social and economic factors on vegetation cover in the same time series for more than 10 years, and it can provide a more directional plan for vegetation restoration in the Loess Plateau in the future.

On the whole, the vegetation cover of the Loess Plateau improved significantly from 2010 to 2020, and the improvement areas were mainly distributed in the central and western parts of the study area, while the vegetation change in the southeast region was relatively not obvious. Through the analysis of influencing factors by geodetector, it is obvious that the social and economic factor of food yield NPP has the strongest influence. With the implementation of the national policy of "Grian For Green", the local government and all walks of life have responded positively to the conversion of cultivated land to forest land, which has significantly increased the vegetation cover on the Loess Plateau, thus reflecting a strong impact on grain yield. Specifically, from 2015 to 2020, compared with 2010 to 2015, the vegetation cover in a wider area has improved to a greater extent, indicating that the long-term implementation of "Grian For Green" in the Loess Plateau has achieved remarkable results, which is also a reflection of the long-term effect of NPP on grain yield. In addition, with the growth of vegetation cover from 2010 to 2015, the restoration and growth of vegetation also improved the local microclimate of the Loess Plateau to a certain extent [23], which indirectly led to a large increase in the area of improved vegetation cover from 2015 to 2020 [24]. In the long run, the implementation of the policy is indeed conducive to the increase of vegetation cover on the Loess Plateau, doing good to the recovery of the ecological environment on the Loess Plateau. However, it may also affect grain yield to some extent, and even lead to a tense relationship between human and grain [25], which makes the policy reach a certain bottleneck. Therefore, it is suggested that the Loess Plateau should be balanced between the restoration of vegetation cover and grain yield in the future to realize the sustainable development of regional economy and society.

In addition, while affecting the change of vegetation cover in the Loess Plateau, each geographical factor also interacts with each other, such as the interaction between temperature and precipitation, the fluctuation of terrain will affect the change of temperature and precipitation, and the change of precipitation will affect the change of soil moisture, etc. In the future, the study of the interaction between each influence factor should be strengthened in order to obtain more scientific and accurate results. The influencing factors of vegetation cover may also change further. For example, it is predicted that the demand of soil water for vegetation restoration will continue to increase in the future [26], so that the influence degree of soil moisture will continue to increase, and natural factors such as precipitation and soil moisture will also increase.

5. Conclusion

This study explored the spatio-temporal variation characteristics of vegetation cover in the Loess Plateau from 2010 to 2020, and comprehensively analyzed the natural factors and human factors by geodetector to analyze the impact of each driving factor on NDVI in the region. Overall, NPP, a social and economic factor, has the strongest influence on grain yield, followed by natural factors such as precipitation. In the future, we should pay attention to the influence of human factors while taking into account the natural factors such as meteorological factors, and balance the restoration of vegetation cover and grain yield to realize the sustainable development of regional economy and society. The main results of this study are as follows:

1. Through the correlation analysis of vegetation cover, precipitation and grain yield in 2010, 2015 and 2020, it can be seen that vegetation cover in the central and northwestern part of the Loess Plateau is positively correlated with grain yield. There was a negative correlation in the northwest and in a few scattered places. In the southeast, central and northwest, vegetation cover was positively correlated with precipitation. The negative correlation is distributed in the northwest, and some places are scattered. It was found that the correlation between vegetation cover, grain yield and precipitation was not significant enough in most regions, and it is mainly distributed in the northeast and southwest strip-shaped regions.

2. The improvement area of vegetation coverage on the Loess Plateau from 2010 to 2020 reach 107,854.668 km^2, accounting for 16.593%. The area with no obvious change occupies the largest proportion of 75.255%. The proportion of moderate degradation is only 0.953%, and the area is 696.63 km^2. In general, from 2010 to 2020, the areas with severe degradation, moderate degradation and slight degradation are less, and they are mainly concentrated in the northwest of the Loess Plateau. The improvement area is mainly distributed in the middle, southwest and northeast of the Loess Plateau. The areas with no obvious changes occupy the majority.

3. Through the analysis of various factors from 2010 to 2020, it can be found that population, road and GDP have little impact on vegetation cover, while DEM and temperature have a decreasing trend with the increase of years, and the grain output in 2015 is the highest. In terms of the interaction of influencing factors, the single influence of grain yield was almost all greater than or equal to 0.699. The influence factors of precipitation are greater than or equal to 0.598. The interaction of any two factors is greater than that of a single factor, and the highest interaction factor between grain yield and precipitation in 2015 reached 0.847

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