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Original Research

Dynamic Change Analysis of Ecological Quality in Loess Plateau Based on Remote Sensing Ecological Index – a Case Study of Ganquan County in Yan' an City, China

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Abstract

The Loess Plateau is located in the middle reaches of the Yellow River, with serious soil erosion and important ecological status. Scientific assessment of the ecological environment quality of the Loess Plateau is the premise to realize the sustainable development of regional ecology, which is of great significance to the improvement of the ecological quality of the Loess Plateau. Based on the Landsat series data, this study constructed the remote sensing ecological index (RSEI) and evaluated the ecological environment quality of the Loess Plateau. The results show that: (1) From 2006 to 2020, the average RSEI experienced three stages of degradation-slow improvement-rapid improvement; from 2005 to 2010, the RSEI decreased from 0.6465 to 0.5516, and the area of variation accounted for 46.7% of the total area. From 2010, the ecological environment quality began to improve. In 2015, the improved area accounted for 31.84%. By 2020, the improved area accounted for 45.6%. (2) On the whole, from 2006 to 2020, the ecological environment quality level of Ganquan County has improved, of which the improved area accounts for 33.4%, while the deteriorated area accounts for 14.74%, and the improved area is 2.3 times the deteriorated area. (3) From the perspective of spatial aggregation, there is aggregation in the distribution of ecological environment quality in Ganquan County, mainly H-H and L-L aggregation. The H-H region is located in the mountain forest area with relatively high altitude around Ganquan County, and the L-L region is mainly distributed from northwest to southeast near the Yanluo River and its tributaries, that is, the sandy hilly and gully area of the Loess Plateau. However, with the passage of time, the area corresponding to L-L gradually decreased, and its significance gradually decreased. In this study, RSEI ecological index was used to

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provide a scientific basis for timely and accurate determination of the spatial and temporal changes of ecological environment quality and economic development in the Loess Plateau.

Keywords: ecological environmental quality, remote sensing ecological index, spatial autocorrelation, spatiotemporal Change, Ganquan County

Introduction

With the rapid development of China's economy, ecological and environmental problems are becoming more and more serious, such as forest degradation, natural environmental pollution and other environmental problems, which have brought great harm to the ecological environment [1]. The ecological environment problem has become an important factor affecting regional security and social and economic sustainable development, and it is also a hot issue of common concern to scholars and relevant departments at home and abroad [2, 3]. However, in the process of rapid urbanization and industrialization in China, there is still a big contradiction between its ecological environment and social and economic development. Therefore, it is of great significance to study the temporal and spatial variation law and mechanism of ecosystem quality for ensuring ecological security, promoting sustainable development and improving people's living standards. The ecological environment of the Loess Plateau is fragile, and the ecological environment problem has always been the focus of attention, and its ecological quality research is also a hot topic for scholars.

Compared with traditional field measurement and observation data, satellite remote sensing data has a wide range of monitoring, fast dynamic monitoring, easy access to information, real-time imaging, fast processing speed, real-time transmission, and less impact on the surface, which can realize real-time monitoring of environmental conditions. Early scholars used single factor evaluation [4]. Later, most scholars used a more comprehensive index system [5, 6]. On this basis, with the advantages of satellite remote sensing and the construction of remote sensing indicators, the whole ecosystem [7, 8], city [9] and region [10] of natural resources are studied. Therefore, remote sensing indicators have been widely used in the study of ecological environment quality and change, which provides an effective method for quantitative, visualization and evaluation of ecological environment quality, and improves the evaluation level of ecological environment quality [11-13]. A variety of ecological methods based on remote sensing have been widely used in soil and water conservation [14], ecological quality monitoring and restoration [15-17], ecosystem evolution [18, 19] and so on. Li et al. combined surface coverage with NDVI to quantitatively analyze the ecological environment quality and spatial and temporal changes of Mu Us Sandy Land [20]. Wu et al. proposed a remote sensing ecological vulnerability index to evaluate regional ecological factors and their changing characteristics [21]. Although these ecological indicators can reflect some characteristics of the environment, there are still some challenges in the acquisition of indicators and the construction of indicator systems. For example, in the construction of indicators such as weight ratio, abiotic factors of the environment, and biological factors, Xu Hanqiu proposed a remote sensing ecological index in 2013, namely the RSEI index. The index is completely based on remote sensing technology, and the index is easy to obtain. There is no need to set weights artificially, and the results are intuitive. This index can not only effectively integrate the original separated indicators, but also quantitatively describe the degree of ecological quality change and solve the problem of single index analysis [22]. Since then, many studies have improved the index system according to the characteristics of the study area to make it conform to the natural environment characteristics of the study area [23, 24]. For example, Guo et al.studied the spatial and temporal evolution pattern of rocky desertification in Bijie City over the past 35 years through remote sensing images [25]. Hu et al. (2018) and Yang et al. (2019) studied the spatial changes of urban ecological quality in Fuzhou and Suining based on remote sensing ecological index, respectively [26, 27]. The RSEI index is based on the remote sensing method to extract ecological indicators, and comprehensively evaluates the regional ecological quality from the perspective of four ecological factors : greenness, humidity, heat and dryness. The evaluation indicators are easy to obtain [28-30]. The above proves that RSEI has practical significance and high credibility for realizing rapid monitoring and evaluation of regional ecological quality.

The Loess Plateau is an important birthplace of Chinese civilization. It is located in the middle reaches of the Yellow River Basin. It is an important economic region in China. As the most widely distributed area of loess in the world and the main source area of sediment in the Yellow River, it has the characteristics of ecological vulnerability. The Loess Plateau has an important ecological status in China and is an indispensable barrier to maintain China's ecological balance. Ganquan County, as a typical city in the hilly and gully region of the Loess Plateau, has various terrain changes and abundant vegetation resources. It has certain typicality and representativeness in the entire Loess Plateau and its ecological sensitivity and resource constraints are the biggest problems restricting urban development. It is urgent to analyze the ecological problems of Ganquan County from the perspective of sustainable development and implement systematic ecological planning. This study uses remote sensing ecological index to carry out dynamic monitoring and analysis of ecological environment evolution in Ganquan County, aiming to grasp the dynamic changes of ecological quality development in Ganquan County from a macro perspective, and provide reference for its ecological quality evaluation, accurate management and sustainable development of economy and society.

Materials and Methods

Study Area

Ganquan County is located in Yan 'an City, Shaanxi Province, 108°45'34″~109°33' 46″ E, latitude 36°6'57″~36°37'33″ N, with a total area of 2300 km^2 and an altitude of 950-1625 m. It belongs to the plateau continental monsoon semi-humid climate and is located in the hilly and gully area of the central Loess Plateau. The Loess Plateau has an important ecological status in China and is an indispensable barrier to maintain the ecological balance of our country. The northeastern part of Ganquan County belongs to the Loess Hilly and Gully Soil Erosion Control Ecological Function Zone in the Loess Hilly and Gully Soil Erosion Control Area, the soil erosion grade is extremely sensitive-highly sensitive, and the soil conservation function is extremely important; the northeastern part of the county belongs to the soil and water conservation area on the south side of the Baiyu Mountain in the ecological function area of soil and water loss control in the loess hilly gully. It is located in the upper reaches of the Yanhe River and the Luohe River. The soil erosion level is extremely sensitive-highly sensitive, and the water conservation function and soil conservation function are important. Therefore, Ganquan County has a very important ecological location. At present, the ecological degradation and environmental damage in the Loess Plateau have brought many problems to the development of Ganquan City and have had a great impact on people's lives. In the new period, Ganquan County, a city in the hilly and gully region of the Loess Plateau, should implement sustainable development based on ecological construction.

Data Sources and Pre-Processing

Since 23 July, 1972, NASA's land satellite program has launched eight satellites. These satellite data can be downloaded from the US Geological Survey website (https://earthexplorer.usgs.gov/). Land satellite data are long-term large-scale ecological environment monitoring data. The spatial resolution of Landsat data is 30 m, with system radiation and geometric correction. The data set used in this study is provided by the geospatial data cloud site (http://www.gscloud.cn) of the Computer Network Information Center of the Chinese Academy of Sciences. This study maximizes the accuracy of surface information in the study area and ensures that four satellite images of September 10, 2006, June 16, 2010, June 23, 2015 and September 10, 2020 are selected respectively. In order to accurately explore the changes of regional ecological environment quality, this paper selects the years with good data quality and appropriate time interval in the study area in the past 15 years, and uses Landsat remote sensing images in 2006, 2010, 2015 and 2020 as data sources. The data in this paper are derived from the United Stated Geological Survey (USGS) website ; the remote sensing image used in this study in 2006 and 2010 was Landsat 5 TM [31], and the remote sensing image used in 2015 and 2020 was Landsat 8 OLI/TIRS [32]. The spatial resolution of

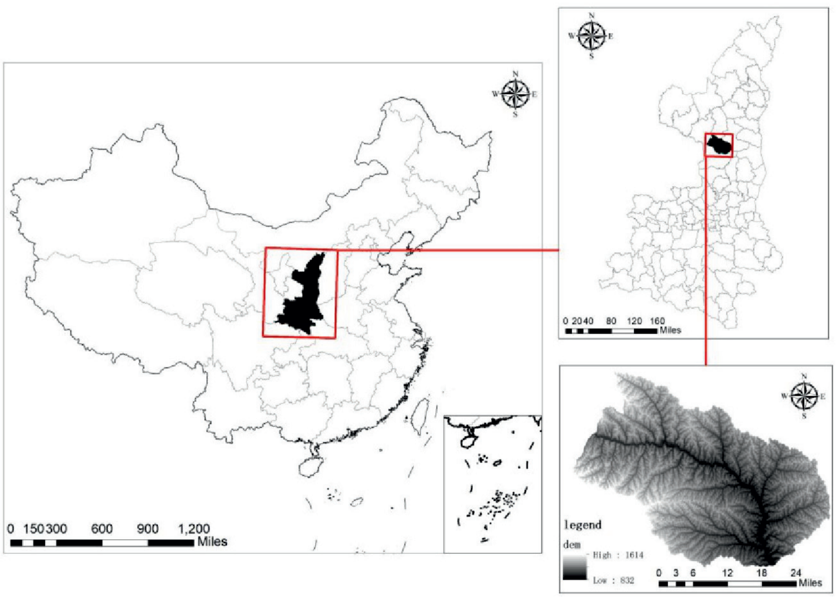

Fig. 1. Map of the study area.

Landsat data is 30 m. In order to maximize the accuracy of surface information in the study area, the cloud cover of the image is guaranteed.

Build RSEI

In recent years, the remote sensing ecological index method has been widely used in ecological quality evaluation [33-35]. The index couples the four ecological elements of greenness, humidity, heat and dryness together through vegetation index, humidity information, surface temperature and bare soil construction information, and comprehensively expresses the regional ecological environment quality through principal component analysis. Compared with the traditional ecological environment index (EI) method, the remote sensing ecological index method can not only quantitatively evaluate the ecological quality, but also visually display the evaluation results, which is more helpful for decision makers to understand the regional ecological structure layout. In addition, the data of remote sensing ecological index method is easy to obtain, and the evaluation results are comparable to the EI index, which is suitable for the ecological quality monitoring of Ganquan County under the rapid development. Among the indicators of RSEI, NDVI and NDBSI can show the response of ecological quality to land cover change, and WET and LST reflect the response of ecological quality to surface environmental change.

Four indicators of RSEI were calculated based on Landsat series data [36]. The four indicators are inconsistent and need to be normalized before principal component analysis. In addition, by normalizing the first principal component (PC1) of principal component analysis, the regional ecological environment quality index RSEI that can reflect the regional ecological environment quality is obtained. The value range of RSEI is between 0-1. The closer the value is to 1, the better the ecological quality is. The final RSEI grade reflects the ecosystem of the study area. The calculation formula of RSEI is as follows:

$$RESI = f(NDVI, WET, NDSI, LST) \tag{1}$$

In formula (1): RSEI represents remote sensing ecological index, LST represents surface temperature, NDVI represents vegetation index, WET represents humidity information, and NDSI represents building-bare soil information.

Humidity Index

Humidity adopts the method of humidity component extraction in tasseled cap transformation. The humidity component reflects the humidity content in vegetation, water and soil, which can effectively express the water content in the study area.The expression of humidity index is as follows:

$$WET = C1B1 + C2B2 + C3B3 + C4B4 - C5B5 - C6B6 \tag{2}$$

In Equation (2), B1–B6 represent blue, green, red, nearred, mid-infrared 1, and mid-infrared 2 bands, respectively, and c1–c6 are the sensor parameters. The humidity component calculation parameters for the TM and OLI sensors differ due to the different satellite sensor types.In the case of the TM sensor, the values of c1–c6 are 0.0315, 0.2021, 0.3012, 0.1594, −0.6806, and −0.6109, respectively [37], whereas they are 0.1511, 0.1973, 0.3283, 0.3407, −0.7117, and −0.4559, respectively, for the TM sensor [38].

Dryness Index

The dryness index is used to reflect the drying degree of the surface. Both bare land and built land increase the drying degree of the surface. The brightness values of built-up land and bare land are higher than other land types. The NDSI index comprehensively reflects the drought caused by bare soil and construction land. Therefore, the normalized accumulation and exposed soil index (NDSI), which characterizes the drying degree of RSEI, was constructed by using the soil index SI (the dryness degree caused by the exposed soil part) and the building index IBI (the dryness degree of the construction land part). The calculation formula is as follows [39]:

$$SI = ((B1+B2)-(B3+B4)) / ((B1+B2)+(B3+B4)) \tag{3}$$

$$IBI = \left[\frac{2B1}{B1+B3} - \left(\frac{B3}{B2+B3} + \frac{B5}{B4+B5}\right)\right] \Big/ \left[\frac{2B1}{B1+B3} + \left(\frac{B3}{B2+B3} + \frac{B5}{B4+B5}\right)\right] \tag{4}$$

$$NDSI = (SI+IBI)/2 \tag{5}$$

In Equation (3), (4), (5), B1-B5 represent short-wave infrared band 1, nearred, red, green, blue, respectively.

Heat Index

The heat index is reflected by land surface temperature (LST). Since the Landsat TM data contains only one thermal infrared band, this study selects a single-channel algorithm to invert the surface temperature [40]. This method is suitable for sensors with multiple bands and infrared bands. The simplified expression is as follows:

$$LST = T \Big/ \left(1 + \frac{\lambda T}{\rho} \ln \varepsilon\right) \tag{6}$$

$$T = K_2 \Big/ \left(\ln\left(\frac{K_1}{B_{TIR}} + 1\right)\right) \tag{7}$$

In Equations (6) and (7), BTIR is the thermal infrared band radiation, obtained from the sixth and tenth bands of the TM and OLI sensors, respectively, T is the brightness temperature at the sensor, and K1 and K2 are the sensor calibration parameters. For the sixth band of the Landsat-5 TM, K1 = 607.76 W/(m^2 sr μm) and K2 = 1260.56 K. For the tenth band of Landsat-8 OLI/TIR, K1 = 774.89 W/(m^2 sr μm) and K2 = 1321.08 K. λ is the central wavelength of the thermal infrared band, ρ = 1.438 × 10-2 (m K), and ε is the specific emissivity of the feature.

Greenness Index

Greenness index was normalized vegetation index (NDVI), which represented the regional vegetation coverage and growth state. The specific expression is as follows [41]:

$$NDVI = (B1 - B2)/(B1 + B2) \tag{8}$$

In Equation (8), B1 and B2 represent the near red and red bands, respectively.

Spatial Autocorrelation Analysis

The first law of geography was proposed by American geographer W.R.Tobler in 1970: Everything is related to everything else, but near things are more related than distant things [42]. Later, it was also called Tobler's first law (TFL) [43]. Therefore, this study intends to study the correlation between the ecological environment in the adjacent areas from the perspective of spatial autocorrelation. The purpose of spatial autocorrelation analysis [44] is to determine whether a variable has spatial correlation. In the field of remote sensing, it can represent the correlation between the ecological environment quality of the central pixel and the adjacent space [45].

This study used global/local spatial autocorrelation (global Moran's I/local Moran's I) to test the geographical correlation of RSEI [46, 47]. The global Mollan index reflects the correlation between different attributes in adjacent geographical units. The absolute value of Moran's I is closer to 1, indicating a stronger geographical autocorrelation [48]. The specific expressions are as follows:

$$\text{Global Moran's I} = n \times \sum_{i=1}^{n}\sum_{j=1}^{n}\omega_{i,j}z_i z_j \Big/ \sum_{i=1}^{n}\sum_{j=1}^{n}\omega_{i,j}{z_i}^2 \tag{9}$$

In the formula (9), n is the total number of spatial units. zi and zj represent the attribute values of the i th and j th spatial units, respectively. z is the mean value of all spatial unit attribute values, and Wij is the spatial weight value. The value range of I is [− 1,1]. I>0 indicates that the ecological environment quality of each region is positively correlated. The larger the attribute value, the easier the clustering. I = 0 indicates that the region is randomly distributed and has no spatial correlation. I<0 indicates that the attribute values of each region are negatively correlated ; in other words, the greater the value of the attributes, the less likely they are to come together. [49].

Local spatial autocorrelation can detect whether there is variable aggregation in the local area. This can further clarify the ecological environment quality distribution of adjacent pixels and make up for the lack of global spatial autocorrelation to determine the specific aggregation area. Hotspot analysis can further analyze the local spatial autocorrelation of ecological environment [50]. The expression of Local Moran's I (LISA) Index is as follows:

$$\text{Local Moran's} = \frac{(z_i - \bar{z})\sum_{j=1}^{n} w_{ij}(z_i - \bar{z})}{\sum_{i=1}^{n}(z_i - \bar{z})^2} \tag{10}$$

The parameter interpretation of formula (10) is the same as that of formula (9). There are five types of local spatial aggregation in LISA clustering graph: High-High (H-H); (L-L); low (L-H); high and low (H-L); and no significant. H-H indicates that the position value and spatial neighborhood value of ecological environment quality sampling points are high. L-L indicates that the location and spatial neighborhood values of ecological environment quality sampling points are low. L-H indicates that the ecological environment quality sampling point is low, but the spatial adjacent area value is high. H-L indicates that the sampling point position of ecological environment quality is high, but the spatial adjacent area value is low [51].

Results

Principal Component Analysis of the Ecological Environment Index

The results of principal component analysis are shown in Table 1. In the percentage eigenvalue results, the average value of the first principal component (PC1) is 93.05%, PC2 is 5.35%, PC3 is 1.25%, PC4 is 0.37%. It can be seen that the PC1 principal component has more than 90 % of the functions of the four principal components. In addition, the highest contribution rate of the four indicators to the first principal component (PC1) was 95.29% (2010), and the lowest was 90.56% (2006), indicating that it is feasible to construct RSEI based on PC1 in the study area, and it is a reliable indicator that comprehensively reflects the ecological environment. The characteristic values of greenness (NDVI) and humidity (WET) in PC1 are positive, indicating that greenness and humidity have a positive impact on RSEI. The characteristic values of dryness (NDSI) and heat (LST) are negative, indicating that dryness and heat have a negative impact on RSEI, which is consistent with the actual situation [52]. Therefore, it is reasonable to construct a remote sensing ecological index in the study area. The average NDVI is 0.94, and the average WET is 0.13586. It can be seen that the characteristic value of greenness is greater than that of humidity, indicating that the contribution of greenness to RSEI is greater than that of humidity, and the load of greenness ranks first in each period, highlighting the importance of vegetation in the ecological environment. The mean value of NDBSI is −0.2416525, and the mean value of LST is −0.1926575. The absolute value of the eigenvalues of NDSI is greater than that of LST, indicating that the contribution of LST to RSEI is less than that of NDSI.

It can be seen from Table 2 that from 2006 to 2020, RSEI shows that the overall ecological quality of Ganquan County decreased from 2006 to 2010, and the average RESI decreased from 0.6465 to 0.5516. From 2010 to 2020, the ecological quality is steadily improving. From 2010 to 2015, the average RSEI increased from 0.5516 to 0.6048, and the ecological quality has improved. From 2015 to 2020, the average RSEI increased from 0.6048 to 0.6983, and the ecological quality has improved dramatically. On the whole, from 2006 to 2020, RESI increased by 0.052, and the ecological environment was developing in a good trend. In the four time periods, the load of NDVI is always the largest, indicating that the green degree has a more obvious effect on the improvement of the ecological environment in the study area. The absolute value of the load value of the heat index and the dryness index is greater than the absolute value of the sum of the load values of the humidity index, indicating that the heat and dryness have a greater inhibitory effect on the ecological environment of the study area than the humidity.

Spatial and Temporal Characteristics of Ecosystem Quality in Ganquan County from 2006 to 2020

In order to facilitate the detailed study, according to the classification method of resi by Xu [22], the normalized RSEI is further divided into five grades according to the equal time interval : poor (0-0.2), poor (0.2-0.4), medium (0.4-0.6), good (0.6-0.8), excellent (0.8-1.0) (Table 3).

According to the calculated ecosystem quality index, the spatial and temporal distribution pattern

Table 1. Principal component analysis results of the RSEI for 2006, 2010, 2015, and 2020.

Year	Indicator	PC1	PC2	PC3	PC4
2006	NDVI	0.9323	0.31082	-0.14083	0.11986
	WET	0.17308	-0.32489	0.81287	0.45136
	NDSI	-0.2185	0.13808	-0.38922	0.88414
	LST	-0.23046	0.88248	0.40977	-0.01438
	Eigenvalue	0.03962	0.00328	0.0007	0.00015
	Percent eigenvalue	90.56%	7.50%	1.60%	0.34%
2010	NDVI	0.94867	0.2363	-0.16953	0.12432
	WET	0.15524	-0.21538	0.87125	0.41284
	NDSI	-0.21903	0.15752	-0.34755	0.89801
	LST	-0.16722	0.93432	0.30231	-0.08767
	Eigenvalue	0.04827	0.00166	0.00051	0.00021
	Percent eigenvalue	95.29%	3.28%	1.01%	0.41%
2015	NDVI	0.93986	0.22703	0.25398	0.02484
	WET	0.08689	-0.10279	-0.32132	0.93736
	NDSI	-0.28076	0.13357	0.88587	0.34434
	LST	-0.17405	0.95919	-0.21791	0.04662
	Eigenvalue	0.04185	0.00211	0.00024	0.0001
	Percent eigenvalue	94.46%	4.77%	0.55%	0.22%
2020	NDVI	0.93933	0.27798	-0.16973	0.10762
	WET	0.12823	-0.2998	0.65241	0.68413
	NDSI	-0.24832	0.18011	-0.62299	0.71957
	LST	-0.1989	0.89466	0.39678	0.05095
	Eigenvalue	0.01866	0.00119	0.00038	0.0001
	Percent eigenvalue	91.79%	5.86%	1.85%	0.50%

of ecosystem quality in Ganquan County from 2006 to 2020 was obtained (Fig. 2). From the perspective of spatial distribution, the ecological quality grade of 2006-2020 is mainly distributed near the Yanluo River Basin and its tributaries, which is related to the fact that the Luohe River, a tributary of the Yellow River, runs through the whole Ganquan County from southwest to northeast, while the Luohe River has serious soil erosion, low vegetation coverage and human factors. The excellent and good ecological grades are mostly distributed in mountainous multi-vegetation areas. Although there are dynamic changes, the change range is relatively small. From 2006 to 2010, the ecological environment in Ganquan County deteriorated sharply, mainly along the river, and the ecological environment on both sides changed from medium to poor, indicating that the soil erosion in this area intensified, resulting in deterioration of the ecological environment. From 2010 to 2015, the ecological environment has improved, the area with poor ecological environment on both sides of the river has gradually recovered to medium, and the overall ecological quality has improved ; from 2015 to 2020, the quality of ecological environment has become very good, the area of poor ecological quality has become less, most of the poor ecological area has become medium, and the medium quality area has also changed into good and excellent, indicating that through a series of policies and remediation measures, the ecological environment of Ganquan County has been well restored.

From Table 4, we can see that the ecological quality of Ganquan County in 2006 was mainly good and excellent, with a total area of 1469 km^2, reaching 64.66%, followed by medium, with an area of 444 km^2 (19.56%), and poor and poor only 358.33 km^2 (18.78). In 2010, the area with excellent ecological environment decreased significantly, accounting for 16.62%, which decreased by nearly 50%. The area with poor ecological environment increased from 110 km^2 to 277 km^2, accounting for 7.32%. The area with poor ecological environment increased by 5.38%, and the area with medium ecological environment was 461.16, almost unchanged, indicating that the ecological environment degradation was serious from 2006 to 2010. In 2015, the area of poor and poor decreased by 168.43 km^2 (7.41%) and 266.71 km^2 (11.74%) respectively, and the area of good was 1053 km^2 (46.34%), accounting for 12.56%. The change of medium and excellent area was relatively small, indicating that the ecological environment of Ganquan County was improved and the ecological quality was gradually improved. In 2020, the proportion of poor and poor ecological quality decreased to 1.56% and 3.94%, while the area of excellent ecological quality increased to 695.63 km^2, accounting for 30.62%, an increase of 14.49%, indicating that the ecological environment of Ganquan County improved greatly during this period, and the ecological quality was accelerating. Overall, the ecological environment quality of Ganquan County has improved.

Autocorrelation Analysis

In order to ensure the integrity of information and the accuracy of quantitative analysis, the image is resampled into a 100 m × 100 m grid according to the ecosystem and landscape pattern characteristics of the study area while considering the internal characteristics of the study area. In this study, based on more than 225,000 samples, the spatial correlation is explained from the spatial correlation and degree of the indicators. In order to find out the relationship between indicators and RSEI, LST and NDSI (negative indicators), WET and NDVI (positive indicators), RSEI are projected into three-dimensional space (Fig. 3). With the increase

Table 2. Statistics of four indicators and RSEI for 2006, 2010, 2015, and 2020.

Year	Item	NDVI	WET	NDSI	LST	RSEI
2006	Mean	0.631	0.6674	0.5666	0.3095	0.6465
	Standard deviation	0.2511	0.0606	0.0628	0.0931	0.218
	Load to PC1	0.9323	0.17308	-0.2185	-0.23046	
2010	Mean	0.6044	0.5909	0.4514	0.616	0.5516
	Standard deviation	0.291	0.0563	0.0701	0.0736	0.2456
	Load to PC1	0.94867	0.15524	-0.21903	-0.16722	
2015	Mean	0.6816	0.6602	0.4487	0.6531	0.6048
	Standard deviation	0.2656	0.0292	0.082	0.0783	0.2171
	Load to PC1	0.93986	0.08689	-0.28076	-0.17405	
2020	Mean	0.726	0.6562	0.4414	0.479	0.6983
	Standard deviation	0.1774	0.0343	0.0513	0.0577	0.1547
	Load to PC1	0.93933	0.12823	-0.24832	-0.1989	

Table 3. Area classification of ecological environment.

Grade Index	Description
Poor (0 < RSEI < 0.2)	The conditions are relatively poor and human life is limited.
inferior (0.2 < RSEI < 0.4)	The area has poor vegetation coverage, less precipitation and fewer species, which is easy to restrict human life.
Medium (0.4 < RSEI < 0.6)	The vegetation coverage is moderate, which is more suitable for human life and restricts human life to a certain extent.
Good (0.6 < RSEI < 0.8)	High vegetation coverage, rich biodiversity , suitable for human habitation.
Excellent (0.8 < RSEI < 1.0)	High vegetation coverage, rich biodiversity and stable ecological environment.

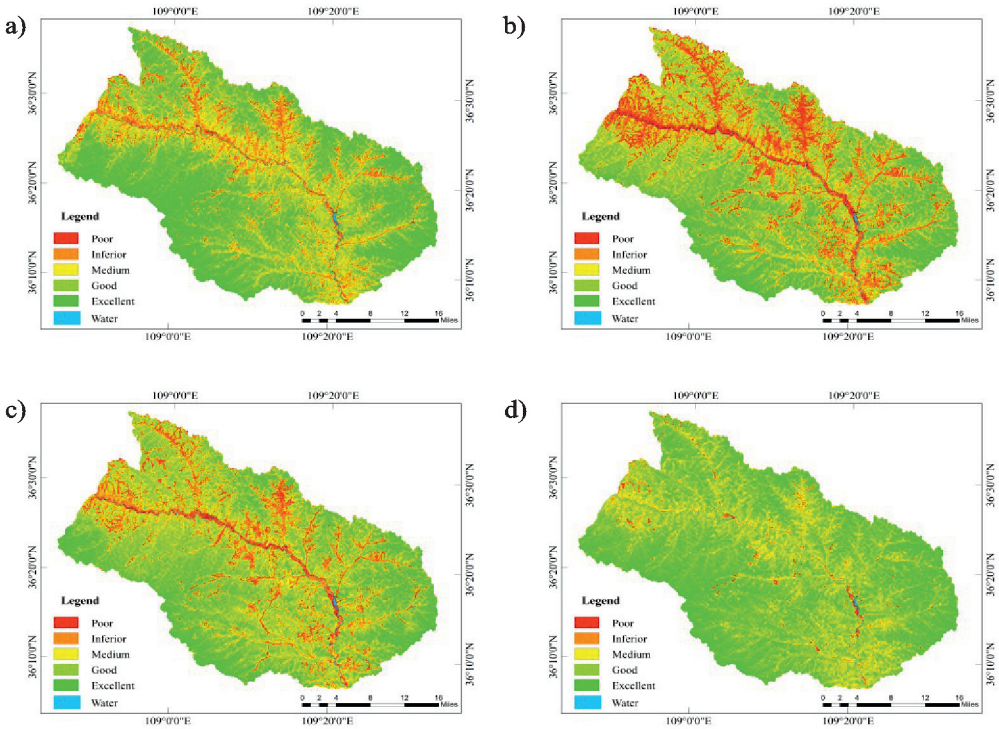

Fig. 2. Distribution of the ecological environmental quality levels in the Ganquan County, 2006-2020. a) 2006, b) 2010, c) 2015 and d) 2020.

of NDVI and WET values, RSEI values also increased, indicating that moisture and greenness were positively correlated with ecosystem quality (Fig. 3a). The RSEI value decreased with the increase of NDBSI and LST values, indicating that drought and high temperature were negatively correlated with ecosystem quality (Fig. 3b). This is consistent with the results of Yue et al. [7], indicating that RSEI is suitable for ecological quality evaluation in the study area.

Based on the above 220,000 resampling points, the spatial autocorrelation analysis of RSEI in Ganquan County was carried out by using the optimized Moran's I index. Moran's I scatter plot of RSEI was generated by Geoda software (Fig. 4). Most of the scatter points in each year are concentrated in the first and third quadrants, indicating that the ecological quality of Ganquan County is significantly positively correlated in space, and the ecological quality is mostly high-high or low-low aggregation. In 2006, 2010, 2015 and 2020, Moran's I index was 0.584, 0.592, 0.563 and 0.487 respectively. These data show that the spatial distribution of RSEI in Ganquan County during the 15 years is clustered, rather than randomly distributed. Among them, 2010 is the year with the strongest positive spatial correlation of ecological quality in Ganquan County.

Lisa clustering maps enhance the sample significant locations based on the location of the value. Its spatial lag in the Moran scatter plot indicated the type of spatial association [53]. According to the LISA clustering diagram (Fig. 5), all four categories are represented. Dark red indicates high-high (H-H) clustering, dark blue indicates low-low (L-L) clustering, light blue indicates

Table 4. Area and percentage of ecological quality level.

Level	2006		2010		2015		2020	
	Area km^2	%	Area km^2	%	Area km^2	%	Area km^2	%
Poor [0-0.2]	110.36	4.86%	276.57	12.18%	168.43	7.41%	35.48	1.56%
Inferior [0.2-0.4]	247.97	10.92%	366.30	16.13%	266.71	11.74%	89.52	3.94%
Medium [0.4-0.6]	444.43	19.56%	461.16	20.30%	419.88	18.48%	358.47	15.78%
Good [0.6-0.8]	778.70	34.28%	790.09	34.78%	1052.58	46.34%	1092.54	48.09%
Excellent [0.8-1]	690.18	30.38%	377.46	16.62%	364.04	16.03%	695.63	30.62%

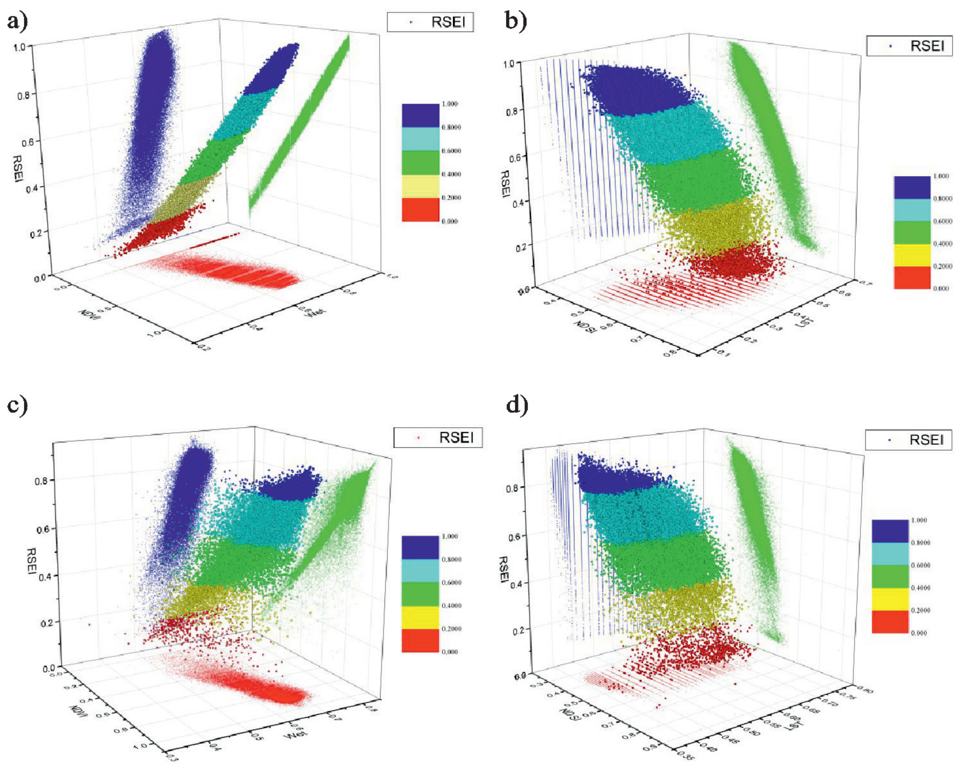

Fig. 3. 3-D Scatterplot illustrate the relationships between WET, NDVI, LST, NDBSI, and RSEI. a) The relationship among RSEI, NDVI and WET; b) The relationship among RSEI, NDBSI, and LST.

low-high (L-H) clustering, light red indicates high-low (H-L) clustering, and yellow indicates insignificant. Ganquan County is dominated by H-H and L-L types, and H-L and L-H types are less. In 2006, 2010, 2015 and 2020, the H-H area is mainly distributed in the hilly area with high altitude around Ganquan County, while the L-L area is distributed near the river from northwest to southeast. From 2006 to 2010, the area of H-H area decreased, while from 2010 to 2020, the area of H-H gathering area increased and the area of L-L gathering area decreased. It also shows that the ecological quality of Ganquan County has experienced a process of first degradation and then improvement from 2006 to 2020. The main area of H-H accumulation area reduction is around the study area, mainly due to deforestation and vegetation degradation, resulting in a rapid decline in the quality of fragile ecological environment. From 2010 to 2020, the area of L-L agglomeration area continued to decrease, reflecting that environmental protection measures inhibited the deterioration of environmental quality.

Dynamic Change Analysis of Ecological Quality

In order to analyze the spatial and temporal variation of ecological quality in the study area in the past 15 years, based on the RSEI index, the difference change of RSEI index in Ganquan County from 2006 to 2020 was detected, and the variation range was divided into 9 categories according to the range. W1 : slightly worse, W2 : moderately worse, W3 : obviously worse, W4 :

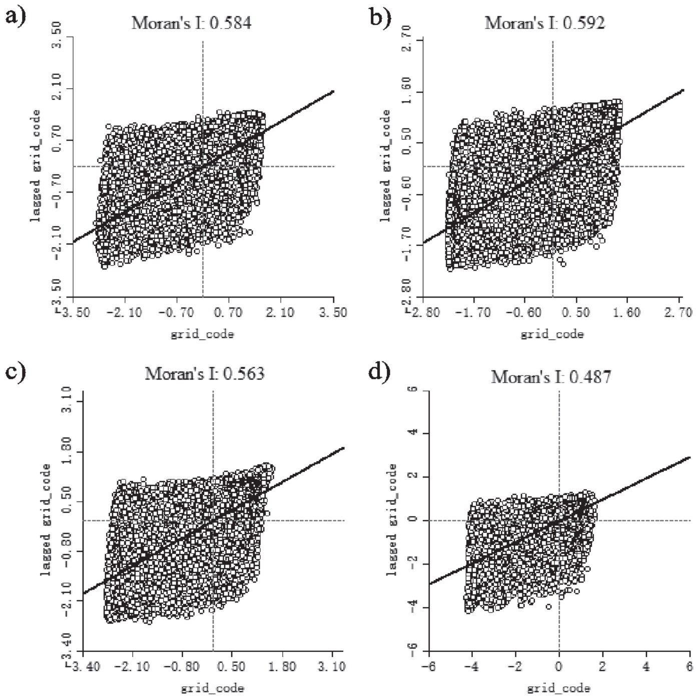

Fig. 4. Scatterplot of RSEI Moran's I in the Ganquan County, 2006-2020. a) 2006, b) 2010, c) 2015 and d) 2020.

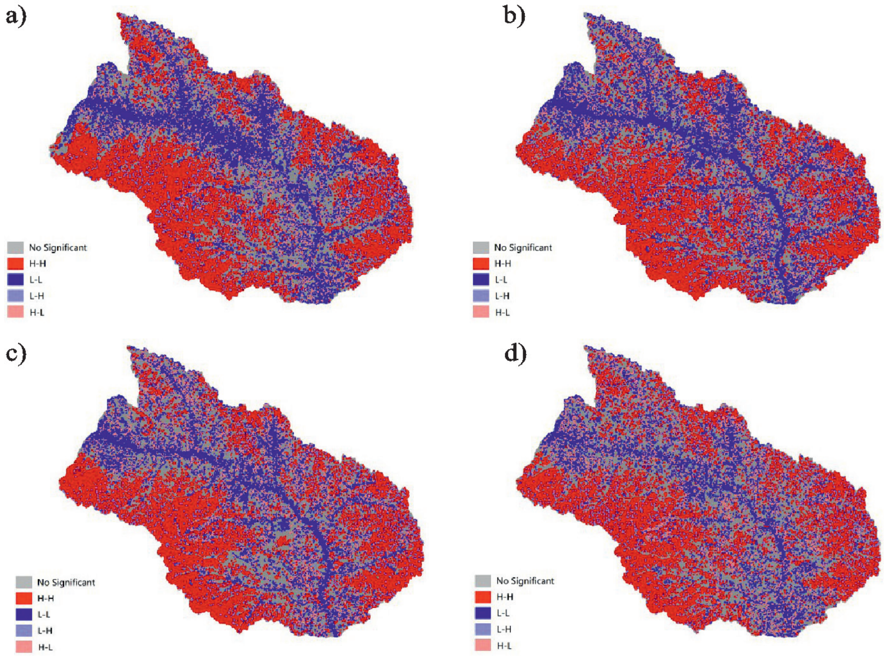

Fig. 5. LISA cluster map of the RSEI in Ganquan County, 2006-2020. a) 2006, b) 2010, c) 2015 and d) 2020.

significantly worse, B1 : slightly better, B2 : moderately better, B3 : obviously better, B4 : significantly better and 0 : basically unchanged. Fig. 6 and Table 5 are obtained.

Combined with Fig. 6 and Table 5, it can be seen that from 2006 to 2010, the whole area of Ganquan County was seriously degraded, and the degraded area reached 1054.6 km^2, accounting for 46.7% of the whole area. The area of ecological grade unchanged was 1075.33 km^2, accounting for 47.61% of the whole area. From 2010 to 2015, the ecological environment has improved, and the distribution characteristics of the improved areas are similar to those of the deteriorated areas. The areas with higher improvement are mainly distributed on both sides of Luohe River and its tributaries, and are also scattered in mountainous forest areas with higher altitude. The improved area is 719.1 km^2, accounting for 31.83% of the whole region, while the degraded area is only

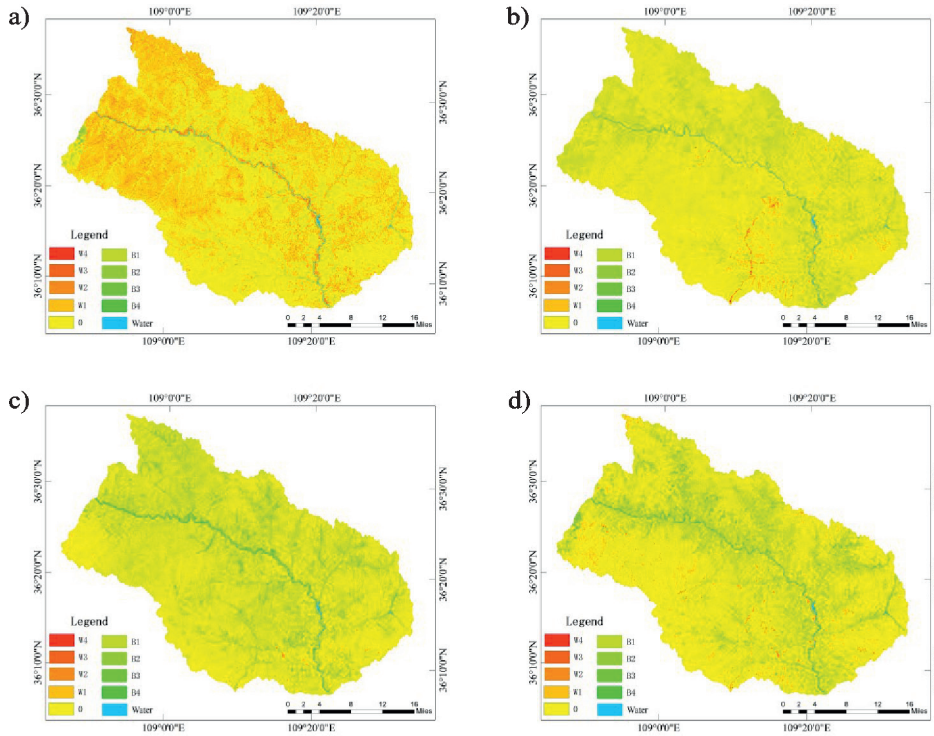

Fig. 6. The distribution of RSEI spatial difference in Ganquan County. Note: The legend is divided according to Table 5. a) 2006-2010, b) 2010-2015, c) 2015-2020 and d) 2005-2020.

Table 5. Changes in the ecological environment quality level.

Category	Level	2006-2010		2010-2015		2015-2020		2006-2020	
		Area km^2	%	Area km^2	%	Area km^2	%	Area km^2	%
Worse	Significantly	0.62	0.03%	0.93	0.04%	0.14	0.01%	0.75	0.03%
	Obviously	10.34	0.46%	2.72	0.12%	1.31	0.06%	4.62	0.20%
	Moderately	124.64	5.52%	10.79	0.48%	8.14	0.36%	21.10	0.93%
	Slightly	919.01	40.69%	191.93	8.50%	130.47	5.78%	306.50	13.57%
Unchanged	Nominally	1075.33	47.61%	1333.04	59.02%	1087.89	48.16%	1172.4	51.91%
Better	Slightly	122.13	5.41%	667.06	29.54%	810.94	35.90%	558.36	24.72%
	Moderately	5.87	0.26%	48.68	2.16%	183.88	8.14%	158.56	7.02%
	Obviously	0.77	0.03%	3.18	0.14%	35.29	1.56%	33.59	1.49%
	Significantly	0.01	0.00%	0.18	0.01%	0.97	0.04%	2.58	0.11%

206.36 km^2, accounting for 9.13% of the whole region. Therefore, the ecological environment of Ganquan County has been improved in this period. From 2015 to 2020, the ecological quality of the study area continued to improve, and the areas with higher improvement were still distributed on both sides of the Luohe River and its tributaries. The improvement area reached 1031.08 km^2, accounting for 45.64% of the entire region, which benefited from the management of soil erosion and the improvement of vegetation coverage in the Yellow River Basin in recent years.

On the whole, from 2006 to 2020, the ecological quality of the study area has generally improved, but some areas have also been slightly degraded. The improvement areas are mainly distributed on both sides of the Luohe River and its tributaries, and the improvement area has reached 753.1 km^2, accounting for 33.35% of the entire region ; mild degradation is mainly distributed in the surrounding mountains, with an area of only 332.77 km^2, accounting for 14.74% of the whole area, of which slight degradation accounts for 13.57%. The improved area is 2.26 times of the degraded area, so the ecological quality of Ganquan County has improved in the past 15 years.

Discussion

RSEI Calculation and Its Spatial Distribution Pattern

The factors affecting the quality of the ecological environment are complex, and the single index evaluation has high application value, but it is difficult to explain the comprehensive effect of multiple factors in the ecological environment. RSEI is composed of four indexes : greenness, moisture, calorific value and dryness, which can effectively solve the one-sidedness of single index in evaluating ecological environment quality. It can be seen from Table 1 that the average contribution rate of the four indicators to the first principal component (PC1) reached d 93.025%, indicating that PC1 concentrated most of the characteristics of the four indicators. Therefore, the RSEI based on PC1 will be more representative than a single indicator. From the results of Table 2, it can be seen that the average correlation coefficient of RSEI is 0.6253 in 15 years, which also shows that RSEI is more suitable for evaluating ecological environment quality than single index. Although RSEI can not fully reflect the ecological environment quality of the basin, it is the most comprehensive choice in the existing ecological indicators. Therefore, it is currently the most widely used.

In this study, NDVI and WET had positive effects on RSEI, while NDSI and LST had negative effects on RSEI, which were similar to the results reported in previous studies [54-56]. The impact of NDVI and LST is more significant than other indicators. Because the study area is located in the Yellow River Basin, the Luo River, a major tributary of the Yellow River, passes through the entire study area. The ecology of the Yellow River Basin has always been a hot topic of concern to scholars from all walks of life. Therefore, the quality of water ecological environment is also a problem faced by Ganquan County, but this work does not study the quality of water ecological environment and air ecological environment. In the future, the ecological environment evaluation of Ganquan County should further incorporate the ecological effects of water and air quality.

Spatio-Temporal Variation Analysis of Ecological Quality

The mean values of RSEI in Ganquan County from 2006 to 2020 were 0.6465, 0.5516, 0.6048 and 0.6983, respectively, and the proportion of good areas (0.6-0.8) increased from 34.28% to 48.09%. Since the past 15 years, the ecology of Ganquan County has experienced a process of first degradation and then recovery, so the improvement from 2006 to 2020 relative to the average is not significant. However, after experiencing ecological degradation in 2010 and being protected by a series of policies such as soil and water loss control in the Yellow River Basin, RSEI gradually improved, and significant effects were achieved by 2020. The poor and Inferior regions decreased from 12.18% and 16.13% to 1.56% and 3.94%, respectively, while the Good and Excellent regions increased from 34.78% and 16.62% to 48.09% and 30.62%, respectively.

In addition, the RSEI of Ganquan County has strong spatial autocorrelation, which is characterized by low-low aggregation and high-high aggregation erosion of non-significant areas. The low-low agglomeration area is mainly located around the river and the central area with dense human activities. The high-high agglomeration area is mainly distributed in the mountain forest area with high altitude at the county boundary, which has been protected by the ecological red line in recent years. The focus of future protection is still the management of soil erosion in the Yellow River Basin.

Cause Analysis of Temporal and Spatial Variation of Ecological Quality

According to the analysis of this paper, the areas with poor ecological environment quality in Ganquan County are concentrated in the surrounding areas of rivers extending from northwest to southeast, which represents the aggregation of areas with poor ecological environment quality. The main reason for this phenomenon is that the region belongs to the gully region of the Loess Plateau, its natural environment is poor, and geological disasters and soil erosion problems are serious. However, in the past 15 years (2006-2020), the area around the river in Ganquan County is also the area with the fastest improvement in ecological environment quality. This is due to the country's long-term active implementation of ecological and soil erosion control projects, such as the Grain for Green Project started in 1999; the loess plateau check dam pilot project started in 2003; the comprehensive agricultural development and soil and water conservation project implemented in 2005 has significantly restored the ecological environment in the middle and upper reaches of the Yellow River [57, 58]. Restoring the ecological environment is not a short-term task. While improving ecological policies, we must continue to maintain or increase investment in ecological environment protection. The ecological environment quality of high altitude hilly area in Ganquan County is relatively stable, mainly moderate and good. The main reason is that the rain is abundant and the temperature is moderate, which provides suitable conditions for vegetation growth and restoration. In the new era, the sustainable development of cities in the hilly and gully regions of the Loess Plateau, such as Ganquan, should be based on the implementation of ecological construction. The main direction is to control the disorderly expansion of cities and towns, improve the quality of the population, protect basic farmland, return farmland to forest and grass, carry out comprehensive management of mesoscale watersheds, and control soil erosion.

Based on the analysis of this paper, the ecological environment quality of Ganquan County in 2006-2020 has improved significantly ; but the whole period is divided into three stages, degradation (2006-2010) – slow improvement (2010-2015) – rapid improvement (2015-2020). The main reason is due to excessive deforestation, deforestation and theft since 2005, the county's natural vegetation has been severely damaged, coupled with natural disasters, soil erosion and other natural factors, resulting in rapid degradation of the regional ecological environment. After 2010, through some land ecological security policies such as vigorously promoting soil erosion control, preventing land desertification, returning farmland to forest and grass, strengthening the protection and construction of water sources, and preventing water pollution, the ecological environment of Ganquan County began to gradually improve. By 2020, the improved area reached 753.09 km^2, accounting for 33.34% of the entire region. In the future, the ecological environment quality of Ganquan County will continue to improve. Ecological protection and governance have been strengthened, and the living environment of the people has been improved. While developing the economy, we must also protect the ecological environment. Therefore, we should pay attention to the coordination of economic development and ecological environment protection, which is also the requirement of ecological protection and high-quality development.

Conclusions

In this paper, RSEI was used to analyze the changes of ecological environment quality in Ganquan County from 2006 to 2020. The ecological and exponential changes in the study area were analyzed using spatio-temporal change data, trend analysis and aggregation state analysis. Modeling and analysis based on remote sensing ecological index (RSEI) can timely and accurately obtain the temporal and spatial variation characteristics of ecological environment quality in Ganquan County, which is helpful to improve the overall development of the study area, which has broad application prospects for high-quality development strategy. The results show that in the past 15 years, the average RSEI is between 0.55 and 0.7 (0.6465, 0.5516, 0.6048, 0.6983). From a macro point of view, Ganquan County is at a good level of ecological environment, and the ecological situation has experienced a process from degradation to slight improvement to substantial improvement. The distribution of RSEI is characterized by the most significant changes in the areas with high surrounding, low center and poor ecological quality, mainly distributed in the gully areas near the rivers in the study area. These changes are mainly caused by soil erosion and geological disasters. From the results of dynamic changes, the degraded area of the study area decreased by 32.25%, the improved area increased by 27.26%, and the ecological environment quality showed an overall improvement trend. In 2006, 2010, 2015 and 2020, Moran's I indexes were 0.584, 0.592, 0.563 and 0.487, respectively, indicating that the spatial distribution of ecological environment quality in the study area was positively correlated, with clustering characteristics and low randomness. The spatial agglomeration degree increases first and then decreases. H-H is mainly distributed in the mountain forest area with high altitude around the study area, with low urbanization ratio, high vegetation coverage and good ecological environment. L-L is mainly distributed in the gully area near the river, where soil erosion is serious, geological disasters are frequent, and social activities are intensive. Our research provides a useful example for the sustainable development of the Loess Plateau. In addition, future research directions include the application of other high-precision multi-spectral satellite images in ecological environment evaluation, and should also pay attention to the internal relationship between ecological environment quality changes and their driving factors. It provides more favorable theoretical support for balancing regional sustainable development and achieving healthy development.

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Conflict of Interest

The authors declare no conflict of interest.

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