Spatiotemporal Evolution of Ecological Quality in Typical Karst Ecologically Fragile Areas Based on Remote Sensing Ecological Indexes

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Abstract Fast and effective remote sensing monitoring is an important means for analyzing the spatio-temporal changes in ecological quality in fragile karst regions. This study focuses on Guanling Autonomous County, a national-level demonstration county for comprehensive desertification control. Based on Landsat TM/OLI remote sensing image data from 2005, 2010, 2015, and 2020, remote sensing ecological indices were used to analyze the spatio-temporal changes in ecological quality in Guanling Autonomous County from 2005 to 2020. The results show that: ① the variance contribution rates of the first principal component for the four periods were 66.31%, 71.59%, 63.18%, and 75.24%, indicating that PC1 integrated most of the characteristics of the four indices, making the RSEI suitable for evaluating ecological quality in karst mountain areas; ② the remote sensing ecological index grades have been increasing year by year, with an overall trend of improving ecological quality. The area of higher-grade ecological quality has increased spatially, while fragmented patches have gradually decreased, becoming more concentrated in the low-altitude areas in the northwest and east, and there is a trend of expansion towards higher-altitude areas; ③ the ecological environment quality in most areas has improved, with the improvement in RSEI spatio-temporal variation becoming more noticeable with increasing slope. Areas of higher-grade quality appeared in 2010, and the range of higher-grade quality expanded with increasing slope.

Key words Ecological quality; Remote sensing ecological index; Karst mountainous area; Ecological fragility; Guanling Autonomous County

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A good ecological environment is a guarantee for the sustainable development of society and even the survival of all mankind. It is the pursuit of the harmonious unity between humans and nature, the realization of the sustainable development of the Chinese nation, and the soul rooted in the blood of the Chinese people. Desertification has always been the most prominent ecological issue in karst mountainous areas, and it has been the focus of scholars. In karst rocky mountain areas, the soil layer is thin, and the bedrock is shallow, making it prone to strong erosion by heavy rain. After significant soil erosion, the rock gradually becomes exposed. In addition, extensive cultivation on steep slopes and long-term destruction of natural vegetation have led to surface exposure and the phenomenon of "rock desertification". Over time, the degree and extent of "rock desertification" have continued to intensify. These human factors are the main causes of desertification, with the most direct consequence being the loss of land resources[1-2]. Furthermore, due to the lack of vegetation and difficulty in maintaining water resources in desertified areas, rapid economic development has also led to further environmental degradation. Environmental quality assessment and monitoring in karst mountain areas can provide guidance for formulating environmental protection and ecosystem sustainable development policies.

To date, numerous studies on environmental quality assessment have been conducted, with the majority of data sources for early urban environmental assessments coming from statistical, research, and monitoring data. The main evaluation methods include mathematical modeling as well as statistical approaches, which encompass specific methods such as factor analysis[3], fuzzy evaluation[4], urban ecological environment suitability models[5], and ecological environment status indices[6]. However, with the rapid advancement of technology, research on ecological quality assessment has achieved new breakthroughs in the field of remote sensing ecological indicators over the past two decades. Nowadays, remote sensing ecological indices have become an integral component of ecological environment research, leading the way with their objectivity and simplicity. Remote sensing indices such as the vegetation index[7-8] and land surface temperature[9-10] have significantly improved the efficiency of ecological environment assessments and are being increasingly utilized in the field of ecological environment evaluation[11].

Currently, there are three main categories of methods for ecological environment quality assessment based on remote sensing[13]: ① analyzing ecological environment changes through the distribution and trends of vegetation cover obtained from remote

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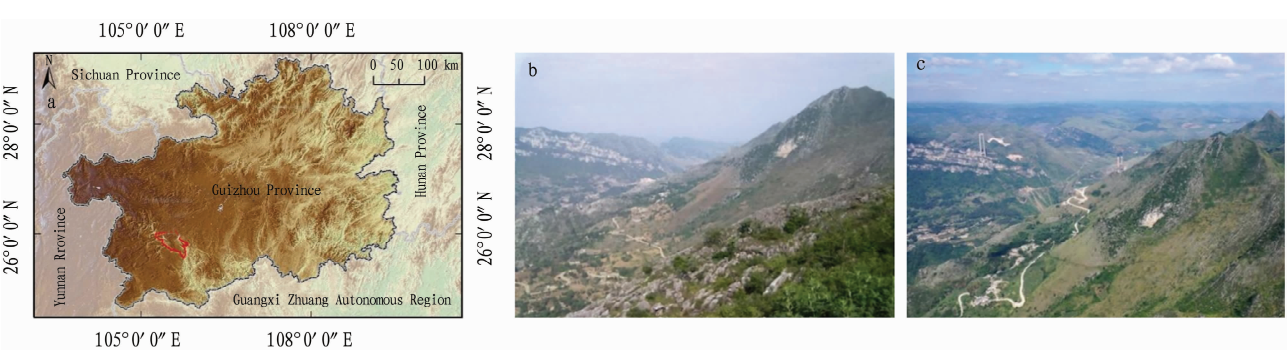
sensing interpretation[14], as well as reflecting the ecological environment through the regional temperature distribution characteristics derived from inversion; governments mainly use ecological environment status indices to evaluate the ecological environment quality of a certain area[15]. ② A framework of indicators established using various indices comprehensively reflects the changes in the regional environment. Indices such as biodiversity, vegetation, water network density, land pressure, and pollution load, obtained through remote sensing inversion, collectively reflect the environmental conditions of the area[16]. ③ The spatialization of remote sensing information allows for the direct acquisition of indices that illustrate the ecological environment from remote sensing imagery, achieving the visualization of ecological environment changes. For example, vegetation coverage, soil moisture content, and topography are selected as three ecological environment elements for evaluation indicators[17-19]. Previously, there were drawbacks such as the inability of a single ecological environment index to reflect comprehensive and actual environmental changes, and the disadvantages of artificially assigning weights to each indicator within the system.

Xu Hanqiu[12] proposed a remote sensing-based ecological index (RSEI) that addresses issues such as the complexity and diversity of factors affecting ecosystems and the difficulty for a single ecological factor to fully reveal changes in the ecological environment. This index can quickly monitor and assess the ecological condition of a city[15]. The index integrates four indicators using the principal component analysis method: the normalized difference vegetation index (NDVI), the wetness index (WET), the normalized difference bare soil index (NDBSI), and land surface temperature (LST). It is objective, reliable, and highly comparable, and has been widely applied in the field of ecological environment assessment.

Located in one of the most typical karst landform regions in the world, the exposed karst area in Guizhou Province accounts for 61.92% of the total provincial area, making it with the largest area, most diverse types, deepest degree, and most severe damage of rocky desertification in China. Guanling Buyei and Miao Autonomous County is a typical karst landform area, where the fragile ecological environment highlights the heavy task of resource conservation. Guanling Autonomous County is currently the only southern typical grassland ecological protection demonstration area and one of the four comprehensive rocky desertification control demonstration areas in Guizhou Province. Guanling Autonomous County uses artificial grass planting to control rocky desertification, combining economic development with desertification control, and pursuing the path of industrial ecology and ecological industrialization. By establishing a grass system for Guanling cattle feeding through artificial grass planting, it achieves a win-win situation of industrial poverty alleviation and desertification control in synchrony. This paper evaluated the changes in the ecological environment in Guanling Autonomous County from 2005 to 2020 using the RSEI model, providing theoretical references for ecological monitoring and environmental protection in karst rocky desertification areas.

1 Data and methods

1.1 Overview of the study area Guanling Bouyei and Miao Autonomous County is a county administered by Anshun City in Guizhou Province, located between 105°15′ - 105°49′ E, and 25°29′ - 26°9′ N. The total area of the county is 1 468 km^2. The entire county is located on the southern slope of the eastern ridge of the Yunnan - Guizhou Plateau, facing the Guangxi hilly area. The landscape features significant undulations and complex diversity. Carbonate rock is widely distributed, with the highest altitude at 1 850 m and the lowest point at 370 m, with an average elevation of 1 025 m. The mountains in Guanling Autonomous County belong to the Wumeng Mountain Range, with widespread carbonate rock distribution. In the 12.5% of the low heat valley area within the county, the accumulated annual average temperature is 16.2 ℃, with an average maximum temperature of 16.9 ℃ and a minimum temperature of 15.4 ℃. The annual precipitation ranges from 1 205.1 to 1 656.8 mm, making it one of the concentrated precipitation centers in the province. The area of rocky desertification in Guanling Autonomous County is extensive. After implementing ecological restoration projects, the area of rocky desertification in the county has decreased from 666.9 km^2 in 2015 to 254.9 km^2 in 2020, a reduction of 412 km^2. The rate of rocky desertification has decreased from 45.42% in 2015 to 17.36% in 2020 (Fig. 1).



Note: a. Spatial location of Guanling County; b. Natural environment of the southern dry and hot valley of Guanling County as photographed on May 23, 2011; c. Natural environment of the southern dry and hot valley of Guanling County as photographed on July 11, 2023.

Fig. 1 Map of the study area

1.2 Data sources and processing In order to ensure the reliability of the analytical results, this study selected image materials from the same season, utilizing optical remote sensing images with few clouds and good quality. The data had relatively long intervals between years to ensure that the selected images had cloud cover of less than 5% over the study area. The remote sensing image data used in the study included Landsat TM images from April 7, 2005, and April 30, 2010, as well as Landsat OLI images from April 19, 2015, and April 25, 2020. Radiometric calibration, atmospheric correction, and geometric correction were sequentially performed in ENVI 5.3, and preprocessing tasks such as image restoration, mosaic creation, and study area clipping were completed to obtain well-corrected data for the four study periods of Landsat TM/OLI data in the study area. Additionally, due to the minimal water bodies in the study area and their small size, no masking treatment was applied to them.

1.3 Research methods

1.3.1 Remote sensing ecological index (RSEI). The ecological environment quality of Guanling Autonomous County mainly depends on factors such as vegetation, humidity, aridity, and temperature. These environmental factors are interrelated, complementary, and mutually constrained, and any change in any environmental factor can lead to changes in other environmental factors affecting the entire environment. Therefore, this study chooses the remote sensing ecological index (RSEI)[12] as the research method, integrating four indicators including vegetation index (greenness index), humidity index, soil index (dryness index), and temperature index to comprehensively reflect the ecological environment quality of the study area.

(1) Normalized differential vegetation index (NDVI). In remote sensing ecological indices, the normalized differential vegetation index (NDVI) is usually used to represent greenness[11]. The normalized vegetation index can more accurately reflect the background image of the plant canopy and intuitively reflect the coverage of surface vegetation. It is often used in vegetation monitoring[20] and is an effective means to quickly obtain vegetation growth conditions[21]. It can more accurately display the surface spatial changes in the area. This article uses the NDVI index to represent the greenness index. The calculation formula is:

$$INDVI = \frac{\rho NIR - \rho Red}{\rho NIR + \rho Red} \quad (1)$$

In the formula, *INDVI* represents greenness; ρNIR represents the spectral reflectance of the near-infrared band, and ρRed represents the spectral reflectance of the red band.

(2) Humidity index (WET). Soil moisture determines the water supply status of vegetation. If it is too low, it can lead to wilting and death of vegetation. If it is too high, it can affect soil aeration and the life activities of plant roots. It is an important indicator for monitoring surface environments. In remote sensing technology, the Tasseled Cap Transformation can effectively extract soil moisture, remove redundant data, and study the use of the moisture component in the Tasseled Cap Transformation to represent the humidity index[22]. The formula is[23]:

$$IWET,\ TM = 0.0315\rho Blue + 0.2021\rho Green + 0.3102\rho Red + 0.1594\rho NIR - 0.6806\rho SWIR1 - 0.6109\rho SWIR2 \quad (2)$$

$$IWET,\ OLI = 0.1511\rho Blue + 0.1972\rho Green + 0.3283\rho Red + 0.3407\rho NIR - 0.7117\rho SWIR1 - 0.4559\rho SWIR2 \quad (3)$$

In the formula, *IWET* represents the humidity index, and ρBlue, ρGreen, ρSWIR1, and ρSWIR2 represent the spectral reflectance of blue light, green light, short-wave infrared 1, and short-wave infrared 2, respectively.

(3) Normalized building-soil index (NDBSI). The normalized building-soil index, also known as the dryness index, plays an important role in the monitoring and assessment of ecological environments. Calculated by combining the bare soil index (ISI) and the building index (IIBI), it is used here to characterize dryness. The formula is:

$$ISI = \frac{(\rho SWIR1 + \rho RED) - (\rho NIR + \rho BLUE)}{(\rho SWIR1 + \rho RED) + (\rho NIR + \rho BLUE)} \quad (4)$$

$$IIBI = \frac{2\rho SWIR1/(\rho SWIR1 + \rho NIER) - [\rho NIR/(\rho NIR + \rho RED) + \rho GREEN/(\rho GREEN + \rho SWIR1)]}{2\rho SWIR1/(\rho SWIR1 + \rho NIER) + [\rho NIR/(\rho NIR + \rho RED) + \rho GREEN/(\rho GREEN + \rho SWIR1)]} \quad (5)$$

$$ISI = \frac{(ISI + IIBI)}{2} \quad (6)$$

where ρBLUE, ρGREEN, ρRED, ρNIR, and ρSWIR1 represent the reflectance of the blue, green, red, near-infrared, and medium-infrared band 1 of the image, respectively.

(4) Land surface temperature (LST). Currently, there are three main algorithms for land surface temperature inversion: atmospheric correction method, single-channel algorithm, and split-window algorithm. In this study, the atmospheric correction method is used for temperature inversion, and the surface temperature inversion correction method (LST) is used to represent heat[24].

$$L_{6/10} = G\text{gain} \times DDN + B\text{bias} \quad (7)$$

$$FV = \frac{(INDVI - INDVI,\ s)}{(INDVI,\ v - INDVI,\ s)} \quad (8)$$

$$\varepsilon surf = 0.9625 + 0.0614FV - 0.0461FV2 \quad (9)$$

$$\varepsilon build = 0.9589 + 0.0860FV - 0.0671FV2 \quad (10)$$

$$T = [L_{6/10} - L\uparrow - \tau(1-\varepsilon)L\downarrow]/\tau\varepsilon \quad (11)$$

$$TLST = \frac{K2}{ln(K1/T + 1)} \quad (12)$$

where $L_{6/10}$ is the radiation value of the thermal infrared band (corresponding to bands 6 and 10 of the TM image); *DDN* represents pixel grayscale values; *G*gain and *B*bias can be obtained from the image header file, representing band gain values and bias values respectively; *FV* represents vegetation coverage; *INDVI*, *s* and *INDVI*, *v* represent *NDVI* values for non-vegetated and pure vegetated pixels, respectively, with empirical values of 0.05 and 0.70; εsurf and εbuild represent the surface albedo of natural surfaces and urban areas respectively; *T* represents the blackbody radiance value; $L\uparrow$ and $L\downarrow$ are atmospheric upward and downward radiation radiance values; τ is the transmittance of the thermal infrared band[11].

After connecting the four standardized indicator layers, ENVI software is used to analyze the major components. The index with the largest contribution rate is selected to establish the initial remote sensing ecological index, which is then standardized using extreme value normalization to obtain the remote sensing ecological index, with a value range of [0, 1]. The larger the value, the better the ecological environment quality[25]. Following Xu Hanqiu's classification standards for RSEI levels, RSEI is divided into five levels: worse (0 – 0.2), poor (0.2 – 0.4), moderate (0.4 – 0.6), good (0.6 – 0.8), and excellent (0.8 – 1.0).

1.3.2 Terrain factor analysis. Different slopes directly affect the amount of solar radiation received by the slope surface and the content of inorganic and organic matter in the soil, thereby influencing the exchange of substances and the form and degree of energy conversion, and indirectly affecting vegetation types, distribution, and coverage. Generally, the steeper the slope, the more prone it is to soil erosion, but the relationship between slope angle and soil erosion is not a simple linear one[26]. As a typical karst mountainous area, Guanling Autonomous County aims to reveal the spatial and temporal distribution patterns of ecological quality. According to the *Technical Regulations for Current Land Use Surveys*, slopes are divided into five levels: <2°, 2 – 6°, 6 – 15°, 15 – 25°, and >25°, with each slope level accounting for 1.83%, 10%, 34.27%, 30.7%, and 23.2% of the total land area of the county, respectively (Fig. 2).

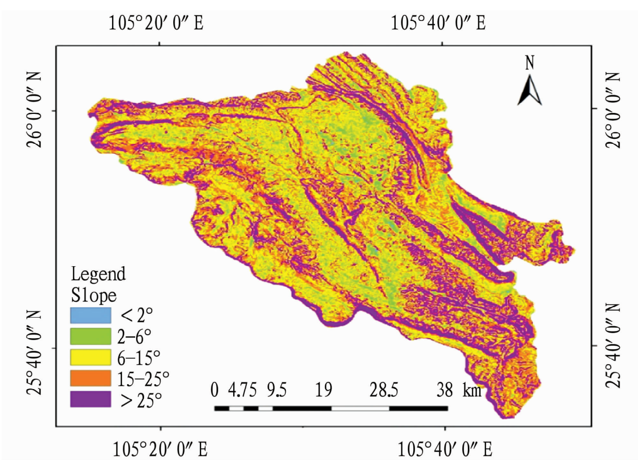


Fig. 2 Spatial distribution of different slope grades in Guanling Autonomous County

2 Results and analysis

2.1 Principal component analysis The variance contribution rates of the first principal component (PC1) for the four years were calculated to be 66.31%, 71.59%, 63.18%, and 75.24%, respectively. This indicates that PC1 has integrated most of the characteristics of the four indicators. The combined contribution rate of PC1 and PC2 exceeds 90%, and the contribution rates of each indicator to PC1 are relatively stable. However, the other principal components (PC3 – PC4) do not show any apparent regularity and are unable to reveal the intrinsic mechanisms of the environmental advantages and disadvantages. Therefore, PC1 was selected to create the remote sensing ecological index (RSEI). Changes in the average values of ecological monitoring indicators from 2005 to 2020 were shown in Fig. 3.

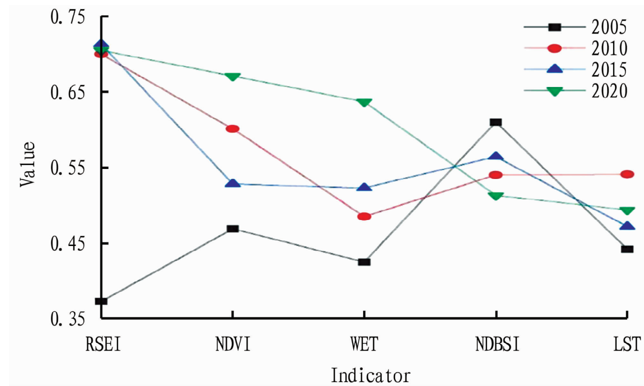


Fig. 3 Changes in the average values of ecological monitoring indicators from 2005 to 2020

2.2 Temporal and spatial changes in ecological quality From a temporal perspective, the ecological environment quality of Guanling County is predominantly in the 'good' category, with a trend towards improvement. Overall, from 2005 (excellent: 0%, good: 20.87%, poor: 1.07%) to 2015 (excellent: 15.26%, good: 74.77%, poor: 0.06%), the area of 'excellent' and 'good' grades in Guanling Autonomous County's ecological environment quality increased significantly and continuously, while the area of 'poor' grade persistently decreased. In 2020, there was a slight setback in ecological quality, but the distribution of 'excellent' and 'good' areas was uniform, indicating that the overall ecological environment quality of the study area has improved significantly over the 15-year period.

In terms of spatial distribution, in 2005, the 'poor' and 'fair' grades of ecological environment quality were distributed in a patchy pattern within the county; from 2010 to 2015, the distribution of 'poor' and 'fair' grades noticeably decreased. In 2015, except for the western region where a relatively distinct 'moderate' band was still present, other areas showed a scattered distribution. By 2020, the ecological environment in the western region had further improved, with the original 'moderate' band becoming scattered. From 2005 to 2020, the area of 'excellent' grade increased, gradually concentrating in the low-altitude areas of the northwest and east, and showing a trend of expansion into higher altitude regions.

2.3 RSEI variation in different slope areas

2.3.1 Areas with slope <2°. During the period from 2005 to 2020, the area proportions of the "excellent" and "good" grades changed, while the area of the "poor" grade remained at 0, indicating that there was no extreme deterioration in the area. The area with a slope of less than 2° is considered a flat slope, which is less affected by solar radiation received on the slope surface, and the inorganic and organic matter in the soil are not easily lost, providing a stable environment for the greenness and humidity that influence the RSEI grades. The ecological environment in the area with a slope of less than 2° improved year by year from 2005 to 2015, with a significant overall quality increase in 2010. However, there was a slight regression in the RSEI grade in 2020. From 2005 to 2020, the overall ecological environment quality in the study area with a slope of less than 2° was mainly in the "moderate" and "good" categories. Over time, the RSEI grade in most areas of the study region remained in the "good" category. From 2005 to 2010, the proportion of the "good" grade area increased significantly, from 31.61% to 87.95%, indicating a marked improvement in the ecological environment during this period. However, from 2015 to 2020, the proportion of the "good" grade decreased, from 75.59% to 57.5%, which may reflect the degradation of the ecological environment or a slowdown in the rate of improvement. In 2010, areas with an "excellent" grade appeared, and the range of "excellent" grade expanded. In 2020, there was a slight regression in the RSEI grade, with a decrease in the area of "good" and "excellent" grades and an increase of about 12% in the "moderate" grade, indicating that although there was no extreme deterioration, certain aspects of the ecological environment may have experienced slight degradation (Fig. 4).

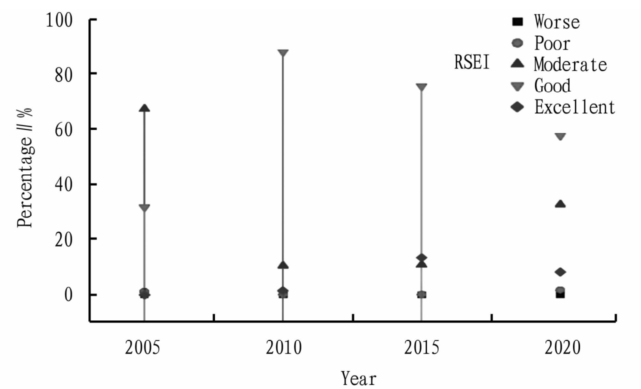


Fig. 4 Changes in different ecological quality levels in areas with slopes <2°

2.3.2 Areas with slopes of 2 – 6°. The area with a slope of 2 to 6° is considered a gentle slope and is an important region for the socio-economic development layout and human activities in Guanling County. Urban development and agricultural activities have a significant impact on the regional ecological environment. At the same time, the inorganic and organic matter within the soil are not easily lost, providing a relatively stable environment for the greenness and humidity that affect the RSEI levels. From 2005 to 2020, the overall ecological environment quality of the 2 to 6° slope area in the study area has been improving, with the most significant changes occurring between 2005 and 2010, where most areas saw an improvement in RSEI levels from moderate to good. From 2005 to 2010, the proportion of areas rated as 'excellent' increased from 0 to 1.81%, indicating an improvement in the ecological environment during this period. However, by 2020, the proportion of 'excellent' areas had decreased to 9.45%, which may suggest that the improvement in the ecological environment is not stable. The proportion of areas rated as 'moderate' reached its lowest point at 8.65% in 2010 and then gradually increased to 27.62% by 2020. This increase may indicate that the pace of ecological improvement has slowed down or that there are factors that are not conducive to the ecological environment. The proportion of areas rated as 'poor' was 1.25% in 2005, then decreased, but increased to 1.51% by 2020. This may indicate that although there has been no extreme deterioration, certain aspects of the ecological environment may have experienced slight degradation (Fig. 5).

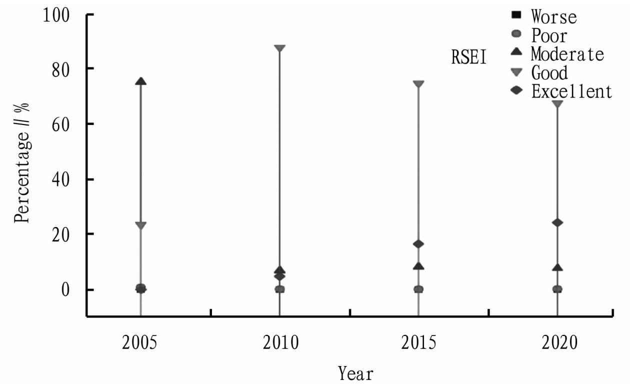


Fig. 5 Changes in different ecological quality levels in areas with slopes of 2 – 6°

2.3.3 Areas with slopes of 6 – 15°. The remote sensing ecological index for the area with a slope of 6 to 15° in Guanling County from 2005 to 2020 showed an improving trend in the ecological environment, with a significant increase around 2010. The area with a slope of 6 to 15° is considered a gentle incline, slightly affected by the amount of solar radiation received on the slope, which can influence the movement of water and nutrients within the soil, and to some extent, the levels of greenness and humidity. The overall quality of the RSEI grade was significantly improved in 2010. From 2015 to 2020, the RSEI grade remained at a relatively stable level. From 2005 to 2020, the overall ecological environment quality of the study area with a slope of 6 to 15° was still mainly in the 'moderate' and 'good' categories, with a notable increase in the 'excellent' grade compared to the areas with slopes of less than 2° and between 2 to 6°. From 2015 to 2020, the grades were in a relatively stable state, with most areas in the study region maintaining a 'good' RSEI grade. In 2010, areas with an 'excellent' grade appeared, and the range of 'excellent' grade showed a clear expansion trend. In 2020, there was a slight regression in the RSEI grade, with a decrease in the area of 'good' and 'excellent' grades, an increase of about 8% in the 'moderate' grade, and a slight increase of about 0.74% in the 'poor' grade (Fig. 6).

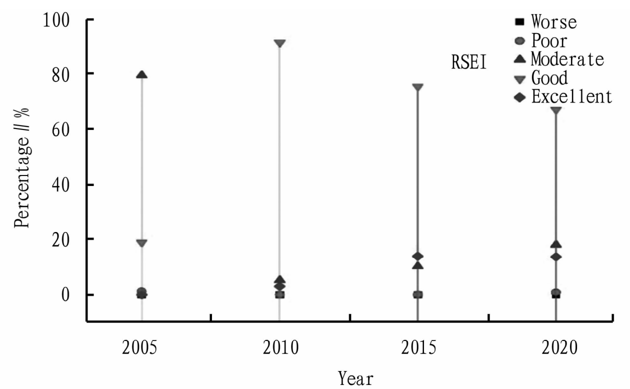


Fig. 6 Changes in different ecological quality levels in areas with slopes of 6 – 15°

2.3.4 Areas with slopes of 15 – 25°. The remote sensing ecological index for the 15 to 25° slope areas in Guanling County from

2005 to 2020 has shown an improving trend in the ecological environment, with a significant enhancement observed around 2010. The 15 to 25° slope areas, characterized as steep slopes, are more heavily influenced by the amount of solar radiation received on the slope, leading to a relatively unstable environment for the greenness and humidity indicators of the RSEI grades, as the inorganic and organic matter in the soil are more prone to loss. In most areas, the RSEI grade shifted from 'moderate' to 'good'. Between 2010 and 2015, some areas that were previously rated 'good' regressed to 'moderate', while areas rated 'excellent' showed a steady improvement over each time period. In terms of changes in the 'excellent' grade: from 2005 to 2020, the proportion of 'excellent' grade increased from 0 to 20.07%, indicating a significant improvement in the ecological environment of the area. In 2005, the 'good' grade proportion was 18.71%, which increased to 90.8% by 2010, and then slightly decreased to 67.7% by 2020. This suggests a substantial improvement in the ecological environment around 2010, though the pace of improvement has since slowed down. The proportion of 'moderate' grade dropped to its lowest point of 4.41% in 2010 and then gradually increased to 11.87% by 2020, which may reflect a deceleration in the rate of ecological improvement. The proportion of 'poor' grade slightly increased from 1.06% in 2005 to 0.34% in 2020, indicating that the trend of ecological degradation has been controlled to some extent (Fig. 7).

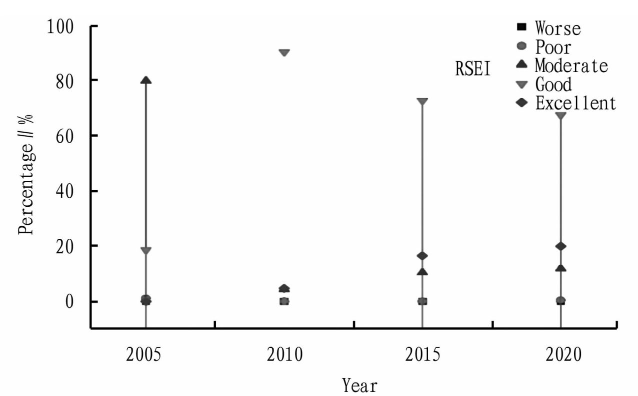


Fig. 7 Changes in different ecological quality levels in areas with slopes of 15 – 25°

2.3.5 Areas with slope >25°. The remote sensing ecological index in Guanling County for areas with slopes greater than 25° from 2005 to 2020 has shown a trend of ecological environment improvement, with a significant enhancement observed around 2010, characterized by a step-like increase, with the most notable changes in the 'good' grade between 2005 and 2010. From 2005 to 2020, the proportion of the 'excellent' grade increased from 0 to 24.35%, indicating a significant improvement in the ecological environment of the area during this period; the proportion of the 'good' grade reached its highest point of 88.13% in 2010 and then slightly decreased to 67.86% by 2020; the proportion of the 'moderate' grade dropped to its lowest point of 6.89% in 2010 and then gradually increased to 7.63% by 2020, which may indicate a slowdown in the rate of ecological improvement; the proportion of the 'poor' grade decreased from 0.78% in 2005 to 0.14% in 2020, showing that the trend of ecological degradation has been effectively controlled (Fig. 8).

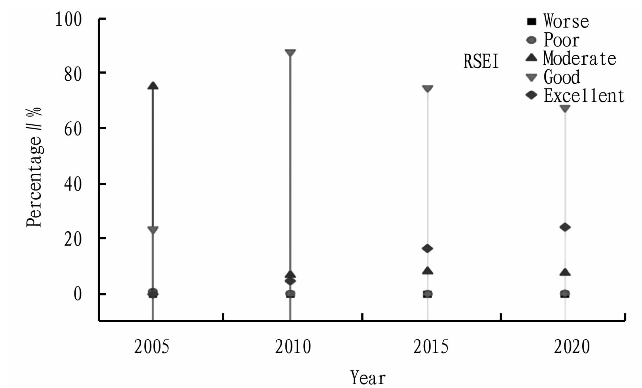


Fig. 8 Changes in different ecological quality levels in areas with slope >25°

3 Conclusion

The research findings have unveiled the quality and changes in the ecological environment of Guanling Autonomous County, providing empirical evidence of the effectiveness of ecological restoration efforts in Guanling County, and offering a reference for the next phase of environmental protection and sustainable development. The main research conclusions are as follows:

(1) The results of the principal component analysis indicate that aridity and heat have a negative impact on environmental quality, while greenness and humidity have a positive impact. Among the indicators, the greenness index contributes the most to the RSEI index, suggesting that vegetation coverage, which the greenness index reflects, is crucial for improving the ecological quality of Guanling County.

(2) From 2005 to 2020, the ecological environment quality of Guanling County has seen a steady improvement, with a slight regression in 2020. However, considering the spatial distribution, the areas rated as 'good' or below were more scattered in 2020 compared to the previous period, and there was an increase in the area rated as 'excellent'. Overall, there has been a transition in ecological environment quality from 'moderate' to 'good' and 'excellent' grades between 2005 and 2020.

(3) In most areas of the study region, the RSEI grade has been maintained at the 'good' level. The overall ecological environment quality has improved from 'moderate' to 'good', with the degree of improvement in the RSEI spatiotemporal variation becoming more pronounced with increasing slope. 'Excellent' grade areas emerged in 2010, and the range of 'excellent' grade has expanded with the increase in slope. In 2020, there was a slight regression in the RSEI grade, with a decrease in the area of 'good' and 'excellent' grades, an increase in the 'moderate' grade, and a slight regression in the 'poor' grade.

4 Discussion

(1) The spatiotemporal changes in the remote sensing ecological index of Guanling County from 2005 to 2020 show that al-

though improvements have been made in some years, the stability of the ecological environment still faces challenges. The spatial distribution of ecological environment quality within the county is of significant importance for the adjustment of spatial functional zoning and land use types. In areas with poorer ecological environment quality, the land use types are mainly concentrated on construction land and arable land, primarily distributed in urban and agricultural spatial functional areas with frequent human activities. In contrast, areas with higher ecological quality are dominated by forest land, mainly located in ecological spatial functional areas with a higher degree of environmental protection. Factors such as rocky desertification control and climate change have a significant impact on the ecological environment. To achieve sustainable ecological environment management, it is necessary to consider both natural and anthropogenic factors comprehensively and take a multifaceted approach. This includes continuing the implementation of rocky desertification control projects, adapting to and mitigating the impacts of climate change, rational planning of land use, strengthening the enforcement of environmental protection policies and regulations, and increasing public awareness and participation in environmental protection. Concurrently, advanced remote sensing technology and ecological assessment methods should be utilized to continuously monitor and evaluate changes in the ecological environment, providing a scientific basis for decision-making.

(2) This study involves multiple images, which exhibit certain seasonal differences. Additionally, due to the large time span and the relative scarcity of years with high-quality remote sensing image data with few clouds, future research could employ multi-source remote sensing data fusion techniques to enhance the accuracy of ecological environment assessments. This would allow for a better analysis of the evolution patterns of ecological environment quality. Moreover, the influencing factors of the ecological environment in karst mountainous areas are complex and diverse. Future research should focus more on studying the drivers of ecological environment changes to uncover the intrinsic mechanisms of ecological evolution.

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