Spatiotemporal Variation Characteristics of the Ecological Environment in Arid Region Oasis Cities: A Case Study of Karamay City (Postprint)

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Abstract

The ecological environment of arid oasis cities is extremely fragile, and accurately understanding its spatiotemporal variation is of great significance. This study selected the typical arid oasis city of Karamay as the research object, utilizing remote sensing images from four periods (2001, 2006, 2011, and 2016). The Remote Sensing Ecological Index (RSEI) was calculated to characterize ecological environment quality, with analyses conducted regarding change trends, spatial distribution, classification, variation characteristics, and centroid migration. The results show that: (1) The RSEI in the study area exhibited fluctuating variation, maintaining a relatively low overall level of approximately 0.35, predominantly composed of low and relatively low ecological index grades. (2) Ecological index grade changes primarily manifested as single-level transitions, with few multi-level jumps, and both the area change magnitude and dynamic degree of different RSEI grades varied significantly across time periods. (3) The niche values from low to high RSEI displayed a clear upward trend, with all values being relatively small (maximum only 0.3677), indicating considerable potential for improvement across different ecological index grades. (4) The centroids of all RSEI grades experienced varying degrees of displacement, with high ecological index zones showing greater spatial mobility (average distance of 42.60 km), while low ecological index zones remained relatively spatially stable. This study explores the spatiotemporal variation patterns of ecological environments under human activity and holds practical significance for the sustainable development of arid oasis cities.

Full Text

Temporal and Spatial Variation Characteristics of Oasis Urban Ecological Environment in Arid Regions: A Case Study of Karamay City

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Abstract: The ecological environment of oasis cities in arid regions is extremely fragile. Accurately understanding the spatiotemporal changes in the ecological environment of such cities due to urbanization is of great significance. Karamay, Xinjiang, China, which is an oasis city in an arid region, was selected as the research object in this study. It is located in the most vast and flat gobi desert; this area has become a gathering point of the petroleum and petrochemical industry, which has greatly stressed the fragile ecological environment. Landsat TM/ETM+/OLI remote sensing images from four time periods (2001, 2006, 2011, and 2016) were collected, and a remote sensing ecological index was used to reflect the ecological environment. The variation degree, ecological niche, and gravity center methods were adopted to model the variation, spatial distribution, classification, variation characteristics, and gravity center transfer of the ecological environment. The following conclusions were obtained. (1) The remote sensing ecological index was not high in the study area and fluctuated approximately 0.35. The ecological index values were generally low. (2) Changes in the ecological index grade mainly manifested as rises and falls with few sudden increases. The areas of different types of remote sensing ecological index domains varied significantly among different time periods. (3) The changes in the ecological niche from low to high showed an obvious upward trend. This indicates that a higher ecological index level represents a higher ecological niche; in other words, better ecological environment quality improves the ability to obtain resources. However, the niche values of different types of remote sensing ecological indices were all small with a maximum value of 0.3677. Thus, there remains much space for improving the niche of different types of ecological indices. (4) The center of gravity of different types of remote sensing ecological indices shifted to different degrees. The regions with a high ecological index had strong spatial mobility with an average distance of 42.60 km, whereas regions with a low ecological index were relatively stable spatially. This study explored the temporal and spatial variations in the ecological environment due to human activities and found that urban farmland, park vegetation, residential greening, water, and other elements play a significant role in maintaining a good

ecological environment. These results demonstrate humans' ability to protect the environment. However, there was serious ecological deterioration around the G217 National Highway, which reflects the ecological damage caused by human activities. The above conclusions show that the acceleration of urbanization and implementation of environmental protection need not be in conflict. Understanding the relationship between urban development and environmental protection is significant for the sustainable development of oasis cities in arid regions.

Keywords: oasis; ecological environment; remote sensing ecological index; spatio-temporal variation; Karamay City

Introduction

With the continuous acceleration of urbanization, ecological environments have suffered persistent damage despite promoting economic and social development. In recent years, significant negative environmental effects caused by urbanization have prompted numerous geographers to investigate the coupling relationship between urbanization and the ecological environment, making coordinated development a hot topic among scholars. Regarding the selection of indicators for ecological environment evaluation, existing research can be broadly categorized into three types. The first type relies on comprehensive indicators constructed from statistical data. For example, Sun et al. built an ecological environment quality evaluation system using the analytic hierarchy process to study the ecological environment change trends in 30 provinces and municipalities. The second type involves the fusion of multi-source data, including statistical data, image data, and monitoring data. For instance, Liu et al. constructed an ecological environment evaluation model using multi-source data to analyze the ecological environment change characteristics in the water source area of the middle route of the South-to-North Water Diversion Project. The third type is based on remote sensing data models, such as the remote sensing ecological index model proposed by Xu, which has been widely applied. The accessibility of data sources and the operability of models are key considerations in selecting ecological environment evaluation models. With the rapid development of remote sensing technology, research based on remote sensing data provides significant support for ecological environment studies, enabling real-time, rapid, and efficient monitoring. Consequently, an increasing number of scholars are focusing on analyzing the spatiotemporal changes in ecological environments using remote sensing data. In terms of research methods, ecological environment evaluation primarily relies on quantitative assessment, with index weights determined through methods such as the analytic hierarchy process, expert scoring, and principal component analysis, among which the objectivity of quantitative analysis is increasingly recognized by scholars.

Xinjiang is a typical arid region with a fragile ecological environment. During urbanization, changes in the surrounding environment affect the ecological environment, which in turn affects the level of urbanization, creating obvious interactive stress between urbanization and the ecological environment. Therefore, timely and accurate understanding of spatiotemporal changes in the ecological environment under the background of urbanization is significant. Although numerous studies have explored the relationship between urbanization and the ecological environment in arid regions through empirical analysis, research based on remote sensing index analysis remains limited. Accordingly, this study selects Karamay, a representative oasis city in an arid region, as the research object. By constructing a remote sensing ecological index model, this study quantitatively analyzes the spatiotemporal change characteristics of the ecological environment, reveals the spatiotemporal variation patterns of oasis ecological environments, and provides a reference for ecological environment evaluation of oasis cities in northwest arid regions.

1.1 Study Area Overview

Karamay City is located in the western part of the Junggar Basin with relatively simple topography, mostly vast and flat gobi desert. The city comprises four districts, with the city center located in Karamay District, which serves as the political and economic center. Karamay is a typical resource-based city dominated by the petroleum and petrochemical industry, playing the role of a growth pole in western China. While oil extraction has brought wealth to Karamay, it has also posed great threats to the extremely fragile ecological environment. Therefore, this study selects Karamay District, the central area of Karamay City, as the research object to further understand the spatiotemporal change characteristics of the ecological environment under human activities and provide references for improving the ecological environment and building a livable city.

1.2 Data Sources

This study utilized Landsat TM/ETM+/OLI remote sensing image data with a resolution of 30 m from the Geospatial Data Cloud Platform (http://www.gscloud.cn) of the Chinese Academy of Sciences' Computer Network Information Center. The data primarily included four periods: 2001, 2006, 2011, and 2016. The imaging times were relatively close, with minimal cloud cover and good data quality.

2 Research Methods

This study primarily relied on image data, calculated the ecological index of the study area through the remote sensing ecological index model, classified the ecological index into grades, and conducted in-depth research from the perspectives of spatial distribution and transformation. The dynamic degree and ecological niche model were used to further refine the change degree and development trend of different grades of ecological indices. By calculating the gravity center positions and their offset distances and directions for different ecological indices, the spatial variation patterns of ecological indices were revealed.

2.1 Remote Sensing Ecological Index Model

The remote sensing ecological index (RSEI) proposed by Xu Hanqiu was adopted to evaluate the ecological environment. This method obtains the vegetation index, humidity component, surface temperature, and building-soil index through remote sensing means to represent the greenness, humidity, heat, and dryness of the ecosystem, respectively. Principal component analysis is then used to select effective principal components to reflect the ecological environment. The specific calculation formulas are as follows:

The normalized difference vegetation index (NDVI), wetness component (WET), land surface temperature (LST), and normalized difference building-soil index (NDBSI) are calculated through band operations. The coefficients for calculating humidity are as follows: for TM images, C_1=0.0315, C_2=0.2021, C_3=0.3102, C_4=0.1594, C_5=-0.6806, C_6=-0.6109; for ETM+ images, C_1=0.2626, C_2=0.2141, C_3=0.0926, C_4=0.0656, C_5=-0.7629, C_6=-0.5388; for OLI images, C_1=0.1511, C_2=0.1973, C_3=0.3279, C_4=0.3407, C_5=-0.7117, C_6=-0.4559.

The land surface temperature (LST) is calculated as:

$$LST = \frac{T}{1 + (\lambda \times T/\rho) \ln \varepsilon}$$

where T is the sensor temperature value; λ is the central wavelength of the thermal infrared band;   is the Boltzmann constant; and   is the surface emissivity.

The remote sensing ecological index is calculated as:

$$RSEI0 = 1 - PC1(NDVI, WET, LST, NDBSI)$$

where PC1 represents the first principal component obtained after principal component transformation of the vegetation index, humidity component, surface temperature, and building-soil index. Since the four indicators have different dimensions, normalization is required before principal component analysis.

The normalized RSEI is calculated as:

$$RSEI = \frac{RSEI0 - RSEI0_{min}}{RSEI0_{max} - RSEI0_{min}}$$

where RSEI0_{max} and RSEI0_{min} represent the maximum and minimum values of RSEI0, respectively.

To further analyze ecological environment changes from a graded perspective, the remote sensing ecological index was divided into five grades at equal intervals: low ecological index area (0.0-0.2), lower ecological index area (0.2-0.4), medium ecological index area (0.4-0.6), higher ecological index area (0.6-0.8), and high ecological index area (0.8-1.0), denoted as A, B, C, D, and E respectively.

Principal component analysis shows that the contribution rate of the first principal component exceeds 75%, which can reflect the comprehensive information of the four indices and can be used to characterize the ecological environment status. The calculation results are shown in [Figure 1: see original paper].

2.2 Dynamic Degree of Ecological Index Change

The dynamic degree of ecological index change refers to the quantitative change of a certain ecological index grade within a certain time range in the study area. This dynamic degree is transformed from the land use dynamic degree to quantitatively analyze the change magnitude or speed of various remote sensing ecological indices during the study period. It is a relative value representing the relative change speed of a certain type of remote sensing ecological index within a specific time period, calculated as follows:

$$K = \frac{U_b - U_a}{U_a} \times \frac{1}{T} = \frac{\Delta U}{U_a} \times \frac{1}{T}$$

where K is the dynamic degree; U_a and U_b represent the areas before and after the period, respectively; ΔU is the increase amount; and T is the time interval between the two periods, with a value of 5 years.

2.3 Niche Analysis

Niche is used to describe the relationship between a biological species and other species in its community and its interaction with the environment. Based on the niche model, different grades of remote sensing ecological indices in the study area are regarded as all species in the community to explore the depth and breadth of resources obtained by different grades of remote sensing ecological indices in the ecosystem. The niche value ranges between 0 and 1, with higher values indicating stronger ability to obtain resources. The calculation formula is as follows:

$$N_i = \frac{S_i + A_i P_i}{\sum_{j=1}^{n} (S_j + A_j P_j)}$$

where N_i is the niche of the i-th ecological index; S_i, A_i, and P_i represent the state, conversion coefficient, and potential of the i-th ecological index, respectively; and S_j, A_j, and P_j represent the state, conversion coefficient, and potential of the j-th ecological index, respectively. The "state" represents the value of different grades of remote sensing ecological indices, the "potential" represents the change amount of different grades of remote sensing ecological indices, and the conversion coefficient is 1.

2.4 Gravity Center Analysis

The gravity center of a certain element in a region refers to the balance point where the moment of that element can be achieved. In studying the gravity center of remote sensing ecological indices, based on the classification of remote sensing ecological index grades and using ArcGIS software to realize the gravity center analysis of various remote sensing ecological index regions, the calculation formula is as follows:

$$X = \frac{\sum_{i=1}^{n} W_i X_i}{\sum_{i=1}^{n} W_i}, \quad Y = \frac{\sum_{i=1}^{n} W_i Y_i}{\sum_{i=1}^{n} W_i}$$

where X and Y are the gravity center coordinates; W_i is the weight of region i; X_i is the longitude of region i; and Y_i is the latitude of region i.

3 Results and Analysis

3.1 Basic Statistics of Remote Sensing Ecological Index

Based on the research methods described above, the remote sensing ecological index values for the study area were obtained (). The study found that the remote sensing ecological index in the study area showed fluctuating changes, with an overall low level maintained at approximately 0.35. The values for 2001, 2006, 2011, and 2016 were 0.35, 0.34, 0.36, and 0.35, respectively. The overall level was not high, mainly because most of the Karamay District is covered by gobi desert. Areas with high remote sensing ecological indices were mainly concentrated in Xiaoguai Township in the southeast, Wuwu New Town in the southwest, the Manas River along the eastern border, and the later-developed large agricultural base. The standard deviations of the remote sensing ecological index for the four periods all fluctuated around 0.19, indicating relatively small spatial differences in the remote sensing ecological index in the study area. Among the four indicators constituting the remote sensing ecological index, the NDVI and WET values were within normal ranges with relatively small means and standard deviations, indicating small overall spatial differences. The LST and NDBSI values were relatively high with large standard deviations, and due to inconsistent units, they differed significantly from the other three indicators in numerical value, further demonstrating the necessity of unifying dimensions in model calculations.

3.2 Spatial Grade Distribution of Remote Sensing Ecological Index

The study found that low remote sensing ecological index areas were relatively large, with areas of 1831.28 km^2, 2035.42 km^2, 2107.60 km^2, and 2039.12 km^2 in the four periods, accounting for 47.54%, 52.84%, 54.71%, and 52.94% of the total area, respectively. The low remote sensing ecological index area was largest in 2011, reaching 54.71% of the total area. Since 2001, the areas of higher and high ecological index regions have increased significantly, showing an overall growth trend. In 2001, the total area of higher and high ecological index regions was 72.22 km^2, accounting for 1.87% of the total area. In 2016, the total area of such ecological index regions was 769.65 km^2, accounting for 19.98% of the total area. The spatial distribution of remote sensing ecological index grades is shown in [Figure 2: see original paper] and .

Since 2001, because large areas of the study region belong to gobi desert with almost no vegetation cover, the overall remote sensing ecological index has been low, with most areas below medium level, mainly characterized by low and lower grade remote sensing ecological indices. With the industrial transformation and upgrading of Karamay City, although the areas of higher and high remote sensing ecological indices remain relatively low, the growth trend is evident.

3.3 Grade Change Monitoring of Remote Sensing Ecological Index

Based on the classification of remote sensing ecological index grades, band operations were performed on the remote sensing ecological indices of the four years. The grade distribution maps of remote sensing ecological indices for later periods were subtracted from those of earlier periods to obtain three grade change maps of remote sensing ecological indices (2001-2006, 2006-2011, 2011-2016) ([Figure 3: see original paper]). The numerical values in the legend represent the degree of grade change, where values greater than 0 indicate upgrading, less than 0 indicate downgrading, and equal to 0 indicate no grade change.

From 2001 to 2006, grade changes in remote sensing ecological indices mainly concentrated between -1 and 1, with downgrading being the main trend, distributed relatively uniformly in space. The downgraded area was 2039.12 km^2, accounting for 52.94% of the total area. Areas with improved ecological indices were mainly concentrated in the large agricultural base. From 2006 to 2011, upgrading was the main trend, distributed relatively uniformly in space, with an upgraded area of 1858.75 km^2, accounting for 48.24% of the total area, while about half of the region' s ecological status remained unchanged. From 2011 to 2016, the areas of ecological index decline, stability, and improvement were 1889.97 km^2, 1312.67 km^2, and 1312.67 km^2, respectively, accounting for 49.06%, 34.08%, and 34.08% of the total area. During this period, remote sensing ecological indices declined significantly, with declining areas mainly located in the northern part of the study area, while ecological environments in southern areas improved noticeably.

Since 2006, areas where ecological conditions improved were mainly distributed in the main urban area of Karamay City, the large agricultural base, Xiaoguai Township, Wuwu New Town, and the 136th Regiment. These areas are venues of human activity and represent oases transformed from desert. As humans continuously optimize and beautify living conditions, the ecological environment status has improved. However, the ecological environment of surrounding areas of human activity has been damaged. Compared with the original state in 2001, ecological quality has declined significantly, especially around the road section from Wuwu New Town to Karamay City. The evolution of remote sensing ecological indices in Karamay District reflects both humans' ability to improve living conditions and the severe challenges posed to the fragile ecology. Therefore, people should fully consider actual conditions, give play to human subjective initiative, and seek coordinated and sustainable development among nature, economy, and society.

3.4 Dynamic Degree Analysis of Different Remote Sensing Ecological Index Grades

Based on the classification of remote sensing ecological index grades, the variation amounts and dynamic degrees of remote sensing ecological index regions for the three time periods were calculated using the formula (). The dynamic degree of low ecological index regions in 2001-2006 was 118.36%, indicating that low remote sensing ecological index regions were expanding. The dynamic degrees of other grades were negative, indicating that the areas of these regions decreased to varying degrees, with high ecological index regions showing a relatively large absolute dynamic degree value, indicating a greater reduction. In 2006-2011, the dynamic degree of low ecological index regions was -11.52%, indicating that such regions were decreasing year by year and transforming into higher grades. The dynamic degrees of lower and above ecological index regions were positive, reflecting the increase of these ecological index regions during this period, especially high ecological index regions with a rapid growth rate and dynamic degree up to 1510.76%. In 2011-2016, the dynamic degrees of low and high remote sensing ecological index regions were both greater than 0, at 25.31% and 44.24% respectively, indicating that both types of regions showed expansion trends, with low remote sensing ecological index regions expanding more significantly. Other grades of remote sensing ecological index regions decreased to varying degrees.

Comparing each type of remote sensing ecological index, the changes in low, lower, and medium ecological index regions showed an "increase-decrease-increase" pattern. Among them, the increase rate of low ecological index regions decreased, while the absolute dynamic degree values of lower and medium ecological index regions were small, indicating that the overall area change of these regions was not significant in recent years. Higher ecological index regions showed a "decrease-increase-decrease" inverted "V" pattern, while high ecological index regions showed a "decrease-increase-increase" "V" pattern, indicating a significant increase in the area of such regions, which is consistent with the previous analysis.

Analyzing the mean variation amounts and dynamic degrees of different grades of remote sensing ecological index regions across the three time periods revealed that in terms of quantity change, low ecological index regions changed significantly, with mean variation amounts of 1222.22 km^2 and 817.73 km^2 for low and lower ecological index regions, respectively. In terms of rate change, high remote sensing ecological index regions had obvious advantages, with mean dynamic degrees of high and higher ecological index regions at 518.28% and 46.97%, respectively. The study area was dominated by low remote sensing ecological index regions, with relatively few high remote sensing ecological index regions, so slight changes would bring high dynamic degrees.

3.5 Niche Analysis of Different Remote Sensing Ecological Index Grades

To more deeply analyze the position of different ecological index grades in the ecosystem, the ecological niche theory model was applied to analyze the niches of different remote sensing ecological indices. The ecological niche width was calculated by organically combining the state and potential of remote sensing ecological indices to reflect the variation of remote sensing ecological indices. The results are shown in .

The study results show that at the four time points, the ecological niches from low to high ecological indices in the study area fluctuated between 0.05 and 0.36, reflecting the relative stability of different grade ecological index subsystems. The changes in ecological niches from low to high ecological indices all showed an obvious upward trend, indicating a positive correlation between ecological index grade and ecological niche. The higher the ecological index grade, the higher the ecological niche, indicating that areas with better ecological environments have stronger ability to obtain resources. This is mainly because people have increasingly higher requirements for ecological environments and continuously maintain and beautify them, thus preserving their excellent status. However, the niche values of different grades of remote sensing ecological indices were all small, with a maximum value of only 0.3677, indicating that there remains much space for improving the niches of different ecological index grades in the ecosystem.

3.6 Gravity Center Transfer Analysis of Different Remote Sensing Ecological Index Grades

To explore the spatial position changes of different grades of remote sensing ecological indices, the gravity center model was used to calculate the gravity center positions and spatial variations of various ecological indices. The results are as follows.

The longitude and latitude coordinates, offset distances, azimuth angles, and offset distribution maps of the gravity centers of different remote sensing ecological indices were calculated (and , [Figure 4: see original paper]). Comparing the gravity center distance variations of each type of remote sensing ecological index, the gravity center of high ecological indices shifted the most since 2001, with an average distance of 42.60 km. The gravity center of higher ecological indices shifted the second most, with an average distance of 15.39 km. The average offset distances of low, medium, and lower ecological index gravity centers were 12.84 km, 11.18 km, and 8.21 km, respectively. In 2001-2006, the gravity center of lower ecological indices shifted the least, at 3.36 km, while that of high ecological indices shifted the most, at 47.70 km. In 2006-2011, the gravity center of high ecological indices shifted the most, at 13.07 km, followed by higher ecological indices at 11.04 km. In 2011-2016, the gravity center of high ecological indices shifted the most, at 44.62 km, followed by higher ecological indices at 32.36 km, while that of low ecological indices shifted 0.74 km. Overall, this indicates that different grades of remote sensing ecological indices in the study area exhibit spatial mobility characteristics, with high ecological index regions showing strong spatial mobility and low ecological index regions being relatively stable spatially.

Analyzing the movement directions of different grades of remote sensing ecological index gravity centers revealed that low ecological indices generally moved toward the northwest, indicating significant growth in low ecological index distribution in the northwestern part of the study area. Lower ecological indices generally moved due south, showing obvious southward directionality in space. Medium ecological indices, mainly located in the central part of the study area, generally moved toward the northeast over the 15 years, indicating an overall northeastward movement trend. The gravity center of higher ecological indices moved from near the Manas River in 2001 to the large agricultural area in 2006, and in 2011, the gravity center was located in the southwestern part of Xiaoguai Township. The gravity center of high ecological indices had the largest offset distance and showed alternating characteristics in movement direction, moving back and forth between the eastern Manas River area, the southeastern Wuwu New Town area, and the large agricultural area, reflecting the spatial distribution variation characteristics of high ecological indices in the study area.

Comprehensive analysis of movement distances and directions revealed that the gravity center of high ecological indices mainly changed around Xiaoguai Township and Wuwu New Town, where large areas of farmland are distributed. These large areas significantly influence the distribution of the gravity center of this grade, demonstrating the importance of such regions for optimizing the ecological environment of the entire study area. High ecological index regions are also sporadically distributed in the main urban area of Karamay City, mainly comprising park vegetation, residential greening, and water bodies, but their proportion in the large ecosystem is relatively small. This reflects the characteristic that ecological indices in suburban areas are higher than those in the city center, primarily due to the clustering effect of high ecological indices.

4 Conclusion

This study took Karamay City, an oasis city in an arid region, as an example and used the remote sensing ecological index model to quantitatively analyze the current status and spatial distribution characteristics of ecological indices in the study area from 2001 to 2016. The following conclusions were obtained: (1) Since 2001, the remote sensing ecological index in Karamay District has shown fluctuating changes, with an overall low level maintained at approximately 0.35, mainly characterized by low and lower grade ecological indices. (2) Grade changes in ecological indices in Karamay District mainly concentrated on one-level rises and falls, with few sudden increases. However, the areas of different grades of remote sensing ecological index domains varied significantly across different time periods. (3) The changes in ecological niches from low to high remote sensing ecological indices showed an obvious upward trend, indicating that higher ecological index grades correspond to higher ecological niches. In other words, better ecological environment quality enhances the ability to obtain resources. However, the niche values of different grades of remote sensing ecological indices were all small, with a maximum value of only 0.3677, indicating that there remains much space for improving the niches of different ecological index grades. (4) The gravity centers of different grades of remote sensing ecological indices all shifted to varying degrees. Regions with high ecological indices had strong spatial mobility, with an average distance of 42.60 km, while regions with low ecological indices were relatively stable spatially.

This study explored the temporal and spatial variation patterns of the ecological environment during human activity processes and found that farmland, park vegetation, residential greening, water bodies, and other elements in cities play significant roles in maintaining good ecological environments, reflecting humans' ability to protect the environment. However, serious ecological deterioration occurred around the G217 National Highway, reflecting the ecological damage caused by human activities. The comprehensive analysis above shows that accelerated urbanization and environmental protection implementation need not be in conflict. The key lies in properly handling the relationship between urban development and environmental protection, which significantly impacts the sustainable development of urban society, economy, and ecological environment.

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