Remote Sensing Detection of Spatiotemporal Changes in High-Altitude Urban Ecological Environment Quality Based on the Remote Sensing Ecological Index (RSEI)

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Abstract. To quantify the spatiotemporal evolution patterns of ecological quality in the core area of the Qinghai-Tibet Plateau and provide a case reference for holistic plateau ecological conservation, this study selected the densely human-activity urban center of Lhasa as the research area. Utilizing Landsat 8 Level 2 remote sensing imagery from 2016 and 2023, and leveraging Google Earth Engine (GEE) for image preprocessing, four ecological indicators—greenness (NDVI), wetness (WET), dryness (NDBSI), and heat (LST)-were employed to construct an RSEI evaluation model. Through principal component analysis, multiple factors were integrated to investigate the spatiotemporal differentiation characteristics and driving mechanisms of ecological quality in the study area from 2016 to 2023. The ecological quality in the study area is generally moderate to good, with the RSEI average increasing from 0.632 in 2016 to 0.664 in 2023, indicating a steady improvement trend. Spatial heterogeneity is pronounced, with the high-vegetation river valleys along the Lhasa River serving as high-quality ecological zones (RSEI > 0.8), accounting for 17.3% to 20.1% of the area. Correlation analysis reveals that NDVI (r=0.78) and WET (r=0.76) are positive drivers of ecological quality, while NDBSI (r=-0.71) and LST (r=-0.68) act as limiting factors. The standard deviation of the RSEI during the study period decreased from 0.118 to 0.106. This provides scientific support for the spatial planning of Lhasa and the implementation of plateau ecological restoration projects, while also offering a typical research paradigm for the construction of an ecological security barrier in the Qinghai-Tibet Plateau.

Keywords: Lhasa, remote sensing ecological index (RSEI), time and space changes, ecological evaluation.

1. Introduction

The ecological stability of the Qinghai-Tibet Plateau directly affects the water ecological security of China and even Asia. Due to the constraints of high-altitude climate and special landforms, the plateau ecosystem has weak anti-interference ability and is extremely sensitive to climate change and human disturbance, making it a key research area in global ecological geography. Lhasa, as the central urban area with the highest population concentration and the fastest development of urbanization and the cultural tourism industry on the Qinghai-Tibet Plateau, is a typical representative of the human environment coupling system in high-altitude cities. The ecological evolution law can intuitively reflect the response characteristics of alpine ecosystems under the dual drive of nature and human activities.

Traditional regional ecological quality assessment relies heavily on ground sampling and monitoring, which has shortcomings such as limited spatial coverage, poor temporal continuity, and difficulty in sampling in high-altitude and remote areas, making it difficult to meet the needs of large-scale, long-term ecological dynamic monitoring. The Remote Sensing Ecological Index (RSEI) integrates four core ecological parameters: greenness, humidity, dryness, and surface temperature. Through principal component analysis, objective weighting is achieved, effectively avoiding the subjective defects of manual weight assignment. Currently, it has been widely used in ecological evaluation of watersheds, cities, and ecologically fragile zones. However, existing RSEI-related research mostly focuses on inland plains and arid desert areas, and there is a relative lack of refined

temporal studies on high-altitude valley cities on the Qinghai-Tibet Plateau. The coupling mechanism of the four ecological factors in high-altitude environments still needs to be supplemented [1].

In recent years, the rapid expansion of urbanization and the large-scale development of the tourism industry in Lhasa have led to the continuous expansion of urban construction land. Land hardening, local vegetation degradation, and the strengthening of the urban heat island effect have gradually highlighted the contradictions between land and nature, posing a threat to the ecological security of the core area of the plateau. Therefore, this article selects the central urban area of Lhasa to conduct a dynamic evaluation of RSEI from 2016 to 2023, quantitatively analyzing the characteristics and driving factors of ecological spatiotemporal evolution. This can not only provide scientific support for the implementation of Lhasa's national spatial planning and ecological restoration projects, but also provide a typical paradigm for the assessment of the overall ecological quality of the Qinghai-Tibet Plateau and the construction of ecological security barriers.

2. Research Areas and Data Methods

2.1. Overview of the Research Area

2.1.1. Location conditions

The research scope covers the central urban area of Lhasa (E91.05°~91.20°, N29.58°~29.73°), which is located in the middle and south of the Qinghai-Tibet Plateau and the valley in the middle and lower reaches of the Lhasa River, a primary tributary of the Yarlung Zangbo River. It is the political, economic, and cultural core of the Xizang Autonomous Region, and also the urban area with the highest intensity of human activities on the Tibetan Plateau.

2.1.2. Natural environment

The terrain of the research area is high in the northeast and low in the southwest, with an altitude of 3650-7162 meters. The central part is the alluvial valley plain of the Lhasa River (3650-3800 meters), with a gentle terrain and a concentrated distribution area of urban and cultivated land; The surrounding middle and low mountainous areas have an altitude of 3800-5500 meters and a slope gradient of 15°-40°; The high-altitude mountainous areas in the north (>5500 m) are distributed with glaciers, bare rocks, and alpine meadows, and the ecology is extremely fragile.

The climate belongs to the plateau temperate semi-arid monsoon climate, with an average annual temperature of 5.8~8.2 ℃ and a daily temperature range of 15~20 ℃; The annual precipitation is 370-580 mm, with 85% of the precipitation concentrated in the rainy season from June to September, and the dry season being dry with little rainfall; The annual sunshine hours are 3000-3400 hours, with strong solar radiation, and the regional annual evaporation is 1700-2300 mm, with an overall dryness. The water system is based on the main stream of the Lhasa River, and the runoff supply is mainly from atmospheric precipitation and groundwater, with obvious seasonal differentiation. The soil is mainly composed of meadow soil, irrigated silt soil, and tidal soil. The soil layer thickness in the alluvial belt along the river is 30-80 cm, with an organic matter content of 15-40 g/kg and a pH of 7.5-8.5. It is the core land for urban greening and agriculture.

Vegetation shows significant spatial differentiation, with artificial greening (poplar, willow, pine and cypress) and farmland (barley, rapeseed) mainly in urban areas, vegetation coverage in built-up areas ranging from 30% to 50%, and urban green space coverage ranging from 60% to 75%; Natural shrubs (seabuckthorn, Jinjier) are distributed in contiguous areas along the Lhasa River, with vegetation coverage ranging from 55% to 70%.

2.1.3. Socioeconomic and ecological background

The population density of the research area is about 8500 people/km ², and the land use structure is: construction land 45%, green space 25%, water area 8%, and unused land 22%. Against the backdrop of rapid urbanization, ecological problems such as urban heat islands, fragmented green spaces, and local soil and water degradation are gradually emerging. The research area is located in

the core area of the national ecological security barrier on the Qinghai-Tibet Plateau, with ecological service functions radiating to the Three River Source and other river source areas, and a prominent strategic position in ecological protection.

2.2. Data Sources and Preprocessing

2.2.1. Data source

The LANDSAT/LC08/CO2/T1_L2 dataset (Landsat8 OLI/TIRS secondary product) was selected, which has undergone radiometric calibration, atmospheric correction, and geometric precision correction, and does not require repeated preprocessing. Filter vegetation growth season (May October) and cloud cover<10% images for 2016 and 2023, and use the GEE platform to complete batch cloud masking, band conversion, index calculation, and median synthesis.

2.2.2. GEE preprocessing process

Firstly, define the vector of the research area: construct the ROI of the research area at E91.05~91.20° and N29.58~29.73°. Then, cloud masking processing is performed to remove cloud and cloud shadow pixels based on the QA-PIXEL band. Then perform band calibration: visible light band x 0.0000275-0.2, thermal infrared band x 0.00341802+149.0 to complete radiation conversion. Next, perform surface temperature (LST) inversion, converting the thermal infrared band from the Kelvin temperature scale to Celsius temperature (℃). Finally, perform year-by-year image median synthesis and cropping, export a 30-meter-resolution GeoTIFF to the local area, and subsequently perform RSEI factor calculations in ENVI and ArcGIS.

2.3. Construction and Calculation Method of RSEI Index

RSEI is composed of four coupled indicators: greenness (NDVI), humidity (WET), dryness (NDBSI), and heat (LST) [1]. *RSEI=f(G, W, T, D)*. Its remote sensing definition is:

$$\mathrm{RSEI} = \mathrm{f}(\mathrm{NDVI}, \mathrm{Wet}, \mathrm{LST}, \mathrm{NDBSI}) \tag{1}$$

In the formula, G represents greenness, W represents humidity, T represents heat, D represents dryness, NDVI represents vegetation index, Wet represents humidity component, LST represents surface temperature, and NDBSI represents building and bare soil index.

2.3.1. Greenness index (NDVI)

Normalized Difference Vegetation Index (NDVI) can effectively reflect vegetation growth status and coverage, with high detection sensitivity, and has been widely used in regional ecological evaluation [2-4]. The calculation formula is:

$$I_{\mathrm{NDVI}} = (\rho_{\mathrm{NIR}} - \rho_{\mathrm{Red}})/(\rho_{\mathrm{NIR}} + \rho_{\mathrm{Red}}) \tag{2}$$

In the formula, ρ_{NIR} and ρ_{Red} are the spectral reflectance of the near-infrared band and the red band, respectively.

2.3.2. Humidity index (Wet)

The humidity component calculation formula based on the Landsat 8 OLI sensor is as follows [5-7]:

$$\begin{aligned} I_{\mathrm{WET,TM}} &= 0.0315\rho_{\mathrm{Blue}} + 0.2021\rho_{\mathrm{Green}} + 0.3102\rho_{\mathrm{Red}} + 0.1594\rho_{\mathrm{NIR}} - 0.6806\rho_{\mathrm{SWIR1}} - 0.6109\rho_{\mathrm{SWIR2}} \\ I_{\mathrm{WET,OLI}} &= 0.1511\rho_{\mathrm{Blue}} + 0.1972\rho_{\mathrm{Green}} + 0.3283\rho_{\mathrm{Red}} + 0.3407\rho_{\mathrm{NIR}} - 0.7117\rho_{\mathrm{SWIR1}} - 0.4559\rho_{\mathrm{SWIR2}} \end{aligned} \tag{3}$$

Among them, I is the temperature index. $\rho_{\mathrm{Blue}}, \rho_{\mathrm{Green}}, \rho_{\mathrm{SWIR1}}, \rho_{\mathrm{SWIR2}}$ representing the spectral reflectance of blue wave, green wave, shortwave infrared 1, and shortwave infrared 2, respectively.

This analysis used data from Landsat 8, so it entered the formula in Band math:

$$\textit{Wet-OLI}=(b1*0.1511+b2*0.1973+b3*0.3283+b4*0.3407+b5*(-0.7117)+b6*(-0.4559))/10000 \tag{4}$$

In the formula, b1~b6 correspond to the reflectance of the blue, green, red, near-infrared, shortwave infrared 1, and shortwave infrared 2 bands in sequence.

2.3.3. Dryness (NDBSI dryness index as a proxy variable for human activity intensity)

The dryness index is constructed by weighting the bare soil index (SI) and the building index (NDBI) [8]:

$$I_{SI} = [(\rho_{SWIR1} + \rho_{Red}) - (\rho_{Blue} + \rho_{NIR})]/[(\rho_{SWIR1} + \rho_{Red}) - (\rho_{Blue} + \rho_{NIR})], \quad (5)$$

$$I_{IB1} = \left[\frac{2\rho_{SWIR1}}{\rho_{SWIR1}+\rho_{NIR}} - \left(\frac{\rho_{NIR}}{\rho_{NIR}+\rho_{Red}} + \frac{\rho_{Green}}{\rho_{Green}+\rho_{SWIR1}}\right)\right] / \left[\frac{2\rho_{SWIR1}}{\rho_{SWIR1}+\rho_{NIR}} + \left(\frac{\rho_{NIR}}{\rho_{NIR}+\rho_{Red}} + \frac{\rho_{Green}}{\rho_{Green}+\rho_{SWIR1}}\right)\right] \quad (6)$$

$$I_{NDBSI} = (I_{SI} + I_{IBI})/2 \quad (7)$$

ρ_{Green}, ρ_{NIR}, ρ_{Red}, ρ_{SWIR1}, ρ_{SWIR2} representing the spectral reflectance of green wave, near-infrared, red wave, shortwave infrared 1, and shortwave infrared 2 respectively.

2.3.4. Heat (Lst)

The most direct indicator factor is temperature; first calculate the surface emissivity [9-10]:

$$\varepsilon = 0.004FVC - 0.986 \quad (8)$$

In the formula, FVC represents vegetation coverage. Then invert the surface temperature using Planck's formula:

$$LST = \frac{K_2}{\ln\left(\frac{K_1}{B_1}+1\right)} - 273.15 \quad (9)$$

In the formula, K1 and K2 are the calibration constants of Landsat 8 thermal infrared band, and B1 is the blackbody radiance at the same temperature.

2.3.5. Principal component analysis

Normalize the four indicators uniformly and conduct principal component analysis (PCA). Select the first principal component (PC1) as the initial RSEI value, and then normalize it to the [0,1] interval through a fuzzy membership function to obtain the RSEI value. The larger the value, the better the ecological quality [11].

3. Results and Analysis

3.1. Characteristics of Temporal Changes in Ecological Quality

As shown in Table 1, the average RSEI of the study area increased from 0.632 to 0.664 from 2016 to 2023, with a growth rate of 5.1% over 7 years, indicating a continuous improvement in the overall ecology. The RSEI standard deviation decreased from 0.118 to 0.106, indicating a decrease in regional ecological spatial dispersion and a trend towards balanced ecological development.

Table 1. Statistical Characteristics of RSEI in Lhasa City from 2016 to 2023

Year	RSEI Mean	Standard Deviation	Min	Min
2016	0.632	0.118	0.127	0.915
2023	0.664	0.106	0.153	0.938

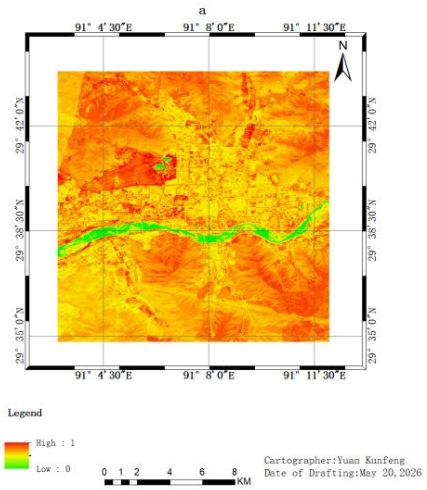
According to the RSEI value range, the ecological quality levels are divided into five levels. The changes in the proportion of each level's area in the two periods are shown in Table 2. The proportion of high-quality and good ecological land continues to rise, while the area of medium and low ecological levels has been shrinking year by year. The high-quality area (RSEI>0.8) increased from 17.3% to 20.1% (+2.8%), while the good area (0.6~0.8) increased from 35.7% to 38.9% (+3.2%). The difference level (<0.2) has decreased from 4.7% to 2.2%, with the most significant decrease. The core incentives are the improvement of bare land in built-up areas and urban greening.

Table 2. Proportion of Ecological Quality Area of Various Grades in Lhasa City from 2016 to 2023 (%)

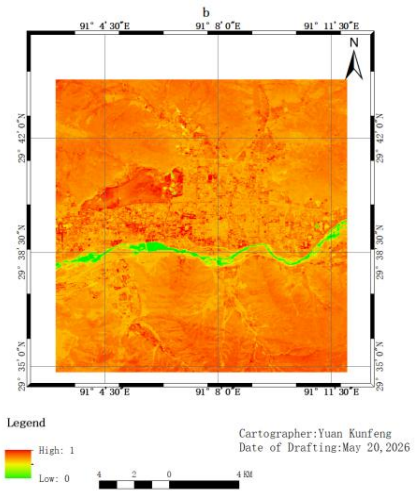
Ecological Quality Grade	2016	2023	variation range
Excellent (0.8-1)	17.3	20.1	+2.8
Good (0.6-0.8)	35.7	38.9	+3.2
Medium (0.4-0.6)	31.2	29.7	-1.5
Poor (0.2-0.4)	11.1	9.1	-2.0
Difference (0-0.2)	4.7	2.2	-2.5

3.2. Spatial Differentiation Characteristics of Ecological Quality

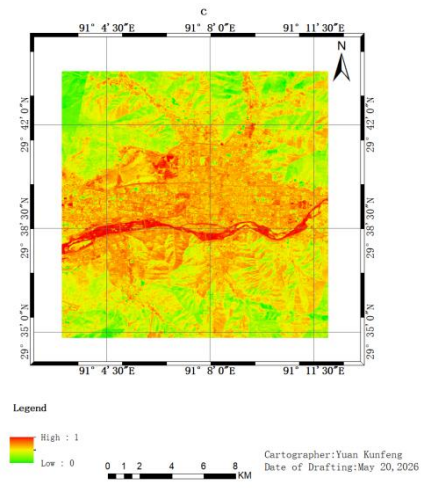
As shown in Figures a to j, the overall ecology presents a spatial pattern of optimal valley conditions, moderate suburban areas, and worst built-up areas: 1) The valleys along the Lhasa River have RSEI>0.7, NDVI>0.6, WET>-0.2, LST<20℃, and superior hydrothermal vegetation conditions, making it the ecological core advantage area of the study area. 2) Chengguan built-up area: The construction land is continuously hardened, with NDVI<0.3, WET<-0.4, NDBSI>0.5, LST>25 ℃, a prominent heat island effect, and RSEI generally<0.4. 3) Peripheral low mountains and hills: The ecological quality is between river valleys and urban areas, with vegetation decreasing and RSEI gradually decreasing as altitude rises.



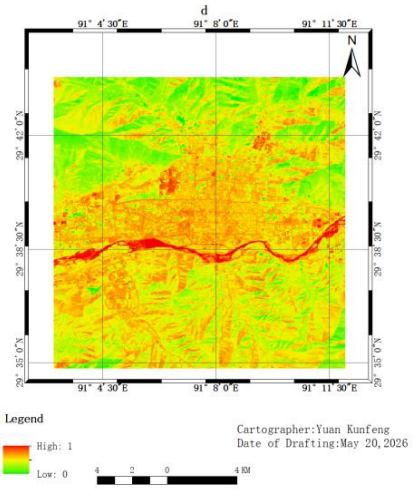
(a) Greenness Index Chart for 2023



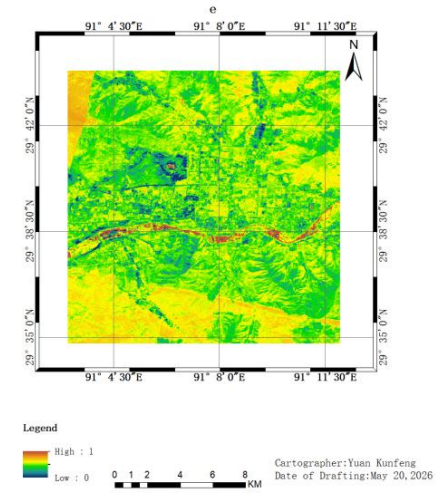
(b) Greenness Index Map in 2016



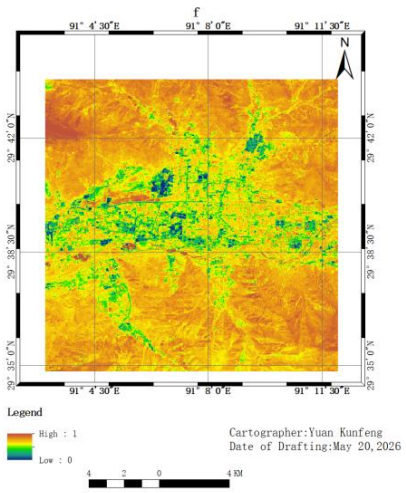
(c) Humidity index map in 2023



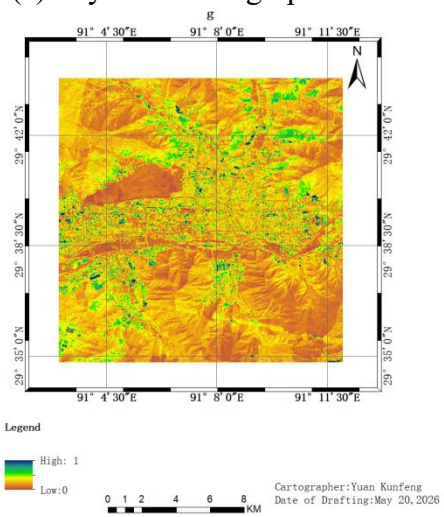
(d) Humidity index map in 2016



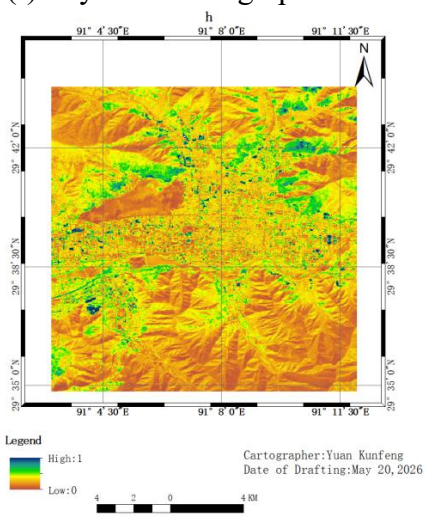
(e) Dryness index graph in 2023



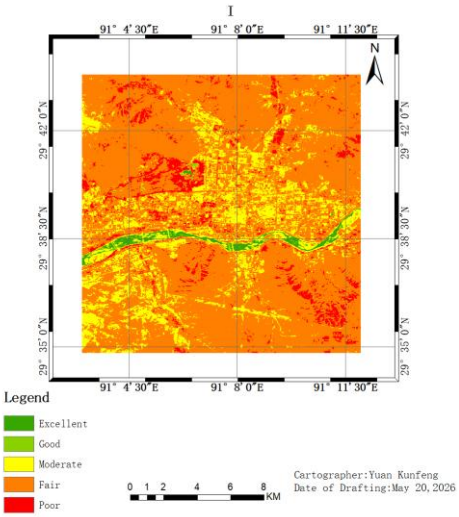
(f) Dryness index graph in2016



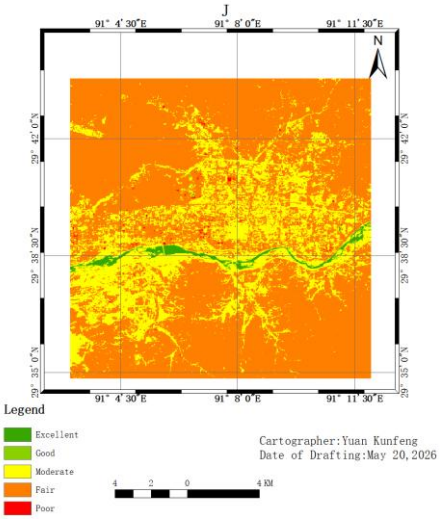
(g) Heat index chart for 2023



(h) Heat index chart for 2016



(i) Ecological quality distribution map in 2023



(j) Ecological quality distribution map in 2016

Fig. 1. Comparison of the spatiotemporal evolution of ecological indicators (greenness, wetness, dryness, and heat) and comprehensive ecological quality in the study area between 2016 and 2023 (Photo/Picture credit: Original).

Figs 1 (a) and (b) depict the spatial distribution maps of NDVI greenness for the years 2023 and 2016, respectively; Figures (c) and (d) show the humidity distribution maps for the two periods of WET; Figs (e) and (f) represent the dryness distribution maps for the two periods of NDBSI; Figures

g and h illustrate the heat distribution maps for the two periods of LST; Figs (i) and (j) are the ecological quality classification maps of RSEI for the years 2023 and 2016, respectively.

Table 3. Correlation coefficients between ecological factors and RSEI from 2016 to 2023

Ecological factor	2016	2023
NDVI	0.78	0.79
WET	0.76	0.77
NDBSI	-0.71	-0.73
LST	-0.68	-0.7
Intensity of human activities	-0.71	-0.73

NDVI and WET are the primary positive factors driving ecological improvement, while dryness and surface temperature are limiting factors (Table 3). Human activity intensity is significantly negatively correlated with RSEI. Artificial greening can effectively reverse local ecological degradation, while uncontrolled urban expansion exacerbates ecological deterioration.

4. Discussion

4.1. Analysis of the Causes of Spatiotemporal Differentiation

4.1.1. Spatial differentiation drive

Natural background is the foundation of spatial differentiation. The Lhasa River valley, with its low elevation, is rich in water and soil resources, and its hydrothermal conditions are suitable for vegetation growth. However, the mountains, with their high elevation, steep slopes, and less precipitation, have weak soil water retention capacity, limiting vegetation development. Human interference further intensifies spatial differences: the built-up areas have a high proportion of hardened surfaces, with scarce vegetation, low surface moisture content, and deteriorating thermal environment; the outskirts, with minimal human disturbance, retain well-preserved native vegetation and superior ecological quality. From the perspective of the terrain-hydrology coupling mechanism, the valley's alluvial soil layer is thick, and the Lhasa River's runoff continuously replenishes groundwater, which can sustain the growth of multi-layered vegetation communities comprising trees, shrubs, and grasses. In the high-altitude mountains, the soil is shallow and thin, with frequent freeze-thaw cycles, and the soil layer's water storage structure is unstable. Even with a slight increase in precipitation, it is difficult to form long-term stable conditions for vegetation growth. Natural background differences directly delineate the spatial gradient of ecological quality.

4.1.2. Timing improvement drive

Firstly, ecological projects have been implemented, with ongoing advancements in projects such as the restoration of the Lhasa River ecological corridor, the enhancement of urban green spaces, and the ecological management of bare lands. This has led to a significant increase in vegetation coverage and soil moisture across the entire region. Secondly, there has been refined management and control of urban areas, with strict restrictions on the disorderly expansion of construction land. Measures such as pocket parks and road greening have effectively alleviated the urban heat island effect. Thirdly, the regional climate has been favorable, influenced by the warming and wetting trend of the Qinghai-Tibet Plateau. Local precipitation in the study area has slightly increased, and the growth environment for alpine vegetation has improved. These three driving factors exhibit hierarchical differences. Artificial ecological restoration is a short-term effective active intervention method, urban spatial management and control can slow down the rate of ecological degradation, and the improvement in hydrological conditions brought about by the warming and wetting climate serves as a background condition supporting long-term vegetation recovery. The combination of these three factors has collectively driven a steady improvement in the ecological quality of the study area.

4.2. Research Comparison and Limitations

4.2.1. Comparison with similar studies

The results of this study are consistent with the research patterns of RSEI in the Yellow River Basin, Qilian Mountains, and Yangtze River Delta region: greenness and humidity are positive driving factors, while dryness and temperature are negative constraining factors, and human disturbance inhibits the improvement of ecological quality [12-14]. However, compared to the eastern plain cities (with an ecological increase of about 8.3% over 7 years), the restoration rate of the alpine ecosystem in Lhasa is only 5.1%, confirming the typical characteristics of alpine ecosystems, which are highly fragile and have a long restoration period. As an alpine valley city, Lhasa faces three core natural bottlenecks in the speed of ecological restoration. Firstly, the high altitude and low temperature stress are significant, and the low annual average temperature leads to a short annual growth cycle of vegetation, resulting in a biomass accumulation rate much lower than that in the eastern plains. Secondly, the regional evaporation is much greater than the precipitation, leading to a normalized soil moisture deficit, making it difficult for vegetation to establish and survive. Lastly, the low degree of soil development and limited organic matter content in the alpine region, coupled with seasonal freeze-thaw erosion, result in inherently weak site conditions for vegetation. Even with artificial greening, it takes a longer period for the community to stabilize and take shape.

4.2.2. Research limitations

Firstly, there are limitations in indicator selection: only four conventional remote sensing indicators are used, without incorporating field observation data such as precipitation, soil physicochemical properties, and biodiversity, making it difficult to fully reflect the complexity of the alpine ecosystem. Secondly, there is a constraint on resolution: the 30-meter resolution of Landsat 8 makes it difficult to identify scattered small green spaces in urban areas, limiting the accuracy of microscale evaluation. Lastly, there is insufficient quantification of driving mechanisms: only correlation analysis has been conducted, without constructing models such as multiple regression and geographical detectors to quantify the contribution rate of each factor. Future research can further optimize this.

5. Conclusions

Based on Landsat 8 remote sensing images from 2016 and 2023, this paper constructs an RSEI model to quantitatively analyze the spatiotemporal variation characteristics of ecological quality in the central urban area of Lhasa. The study finds that from 2016 to 2023, the overall ecological quality of the central urban area of Lhasa has been stable and improving, with the RSEI mean value increasing from 0.632 to 0.664, an increase of 5.1%. The regional ecological spatial differences continue to narrow, and ecological development tends to be balanced. The spatial pattern of ecological quality has remained stable over the long term, exhibiting a distribution characteristic of "optimal in river valleys, moderate in suburbs, and worst in built-up areas." Natural soil and water conditions and human development intensity jointly dominate the spatial differentiation pattern of regional ecology. In terms of driving factors, NDVI and WET are the core positive driving factors for ecological improvement, while NDBSI and LST are the main limiting factors. Human activity intensity shows a significant negative correlation with RSEI. Scientific artificial ecological restoration can effectively offset the negative impacts brought by urbanization, becoming a key driving force for the improvement of ecological quality in Lhasa. Combining causal analysis and regional comparison results, the ecological pattern differentiation in Lhasa is shaped by both natural background differences and human disturbances. The temporal ecological improvement relies on the superposition of three conditions: the implementation of ecological engineering, urban spatial control, and regional climate warming and wetting. Constrained by the inherent ecological bottlenecks of the alpine environment, the rate of ecological restoration is significantly slower than that of similar cities in the eastern plains. The characteristics of fragile alpine ecology and long recovery periods are

prominent. This study verifies the applicability of the RSEI model in alpine valley-type cities. The research results can provide data reference for territorial space optimization and plateau ecological barrier construction in Lhasa. Future research can combine high-resolution remote sensing data with field sampling to further improve evaluation accuracy and refine the quantitative analysis of driving mechanisms.

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