Postprint: Eco-environmental Changes in the Tuha Region Based on the Remote Sensing Ecological Index

Authors: Wang Jinjie

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Abstract

This study takes Turpan City and Hami City (collectively referred to as the Turpan-Hami region) as the research area. Based on remote sensing data from the MODIS multispectral sensor for the years 2000, 2006, 2012, and 2018, four indices characterizing wetness, dryness, heat, and greenness were employed to establish and map the Remote Sensing Ecology Index (RSEI) for multiple periods in the Turpan-Hami region. Quantitative analysis was conducted on the ecological environment quality and land use conversion in this region.

The results indicate that over the past 20 years, the greenness index in the Turpan-Hami region increased by an average of 0.0244, the heat index decreased by an average of 0.0241, while the overall changes in wetness and dryness indices were close to zero. Among these, the heat index exhibits a negative correlation with RSEI.

Overall, the ecological environment quality in the Turpan-Hami region showed a slight declining trend from 2000 to 2018. Specifically, Shanshan County in Turpan City experienced the largest RSEI change magnitude, ranking first in the region in terms of environmental quality decline, while Barkol Kazakh Autonomous County in Hami City showed the smallest decrease in environmental quality.

Over the past 20 years, grassland area in the Turpan-Hami region has increased significantly; however, it is necessary to control grassland reclamation and overgrazing to prevent regional ecological environment deterioration.

Full Text

Study on Ecological Environment Changes in the Turpan-Hami Region Based on the Remote Sensing Ecology Index

WANG Jinjie[1,2,3], DING Jianli[1,2,3], ZHANG Zipeng[1,2,3]

[1]College of Geography and Remote Sensing Sciences, Xinjiang University, Urumqi 830017, Xinjiang, China
[2]Xinjiang Key Laboratory of Oasis Ecology, Xinjiang University, Urumqi 830017, Xinjiang, China
[3]Key Laboratory of Smart City and Environment Modeling of Higher Education Institute, Urumqi 830017, Xinjiang, China

Abstract: This study examines Turpan City and Hami City (collectively referred to as the Turpan-Hami region) as the research area. Based on four indices representing humidity, dryness, heat, and greenness derived from MODIS multispectral sensor data, we established and mapped the Remote Sensing Ecology Index (RSEI) for multiple periods from 2000 to 2018. The ecological environment quality and land use conversion in the region were quantitatively analyzed. Results indicate that over the past two decades, the greenness index in the Turpan-Hami region increased by an average of 0.0244, the heat index decreased by an average of 0.0241, while humidity and dryness indices showed minimal overall change near zero. The heat index exhibited the strongest negative correlation with RSEI. Overall, the ecological environment quality of the Turpan-Hami region showed a slight declining trend from 2000 to 2018. Shanshan County in Turpan City experienced the most significant changes and the greatest environmental quality decline, whereas Barkol Kazakh Autonomous County in Hami City showed the smallest decline. Although grassland area increased substantially during this period, controlling grassland reclamation and overgrazing remains essential to prevent further ecological degradation.

Keywords: Remote sensing ecology index; MODIS data; spatio-temporal variation; Turpan City; Hami City

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Introduction

Natural ecosystems constitute the foundation of human survival and development [1]. In recent years, increasingly intensive human economic activities have altered surrounding ecological environments and land use patterns, exerting tremendous pressure on ecosystem stability [2]. Consequently, objective and effective evaluation of spatio-temporal changes in regional ecological environment quality serves as an essential guide for sustainable development pathways. Remote sensing information technology has become an indispensable tool in environmental monitoring and quality assessment research due to its advantages of rapid, non-destructive, timely, and high-resolution observations [3].

For instance, Gu Liwan et al. [4] monitored vegetation coverage by combining vegetation indices with a pixel dichotomy model to comprehensively evaluate the ecological environment of Anhui Province. Qi Zhao et al. [5] used Landsat imagery as the research foundation and employed differential analysis to quantitatively assess ecological environment restoration in the Shennongjia region. However, these studies focused on single environmental factors and lacked multi-dimensional objective evaluation.

To address this limitation, researchers have integrated four environmental variables most readily perceived by humans—dryness, humidity, heat, and greenness indices—through Principal Component Analysis (PCA) to construct a Remote Sensing Ecology Index (RSEI) suitable for regional assessment [6]. The information contained in this index derives from remote sensing imagery and its derivative products, ensuring calculation objectivity. This evaluation model has been widely applied [7]. For example, Zhou Meng et al. [8] evaluated ecological environment changes in the Dongjiang River headwaters region, finding that urban construction land expansion caused by human activity was the key factor driving environmental quality changes. Xu Min et al. [9] analyzed spatio-temporal changes in the ecological environment of the Chuzhou region based on Sentinel-2A imagery, revealing an overall slight decline in environmental quality.

In-depth analysis reveals that RSEI application research has primarily concentrated in central and eastern China, with relatively limited attention to northwestern regions. However, northwestern China serves as a crucial ecological barrier, making ecological environment index monitoring essential. Turpan and Hami cities (hereinafter referred to as the Turpan-Hami region) are located in the hinterland of the Eurasian continent, surrounded by mountains, with an area of approximately 1.2×10^{5} km^2. The region features a mid-early Jurassic coal-bearing basin with abundant coal, oil, and other mineral resources, providing inherent advantages for large-scale industrial development. The area also boasts promising prospects for characteristic agriculture and tourism development, while serving as an important transportation hub and core zone of the Silk Road Economic Belt.

Since 2000, continuous economic and social development has severely strained water resources in the Turpan-Hami region. Natural water availability is extremely limited, and increasing water exploitation has led to surface water extraction rates far exceeding typical river thresholds, with severe groundwater over-exploitation. These dual natural and anthropogenic factors have caused a series of ecological problems, including land desertification, wetland degradation, and frequent salt-dust storms, resulting in continuous ecological environment deterioration [10]. Therefore, this study conducts a comprehensive assessment of the region's ecological environment conditions and land use changes over the past two decades through quantitative analysis of RSEI spatio-temporal variations.

1 Study Area Overview

The Turpan-Hami region (41°18 –43°43 N, 86°40 –96°04 E) comprises Turpan City (including Gaochang District, Shanshan County, and Toksun County) and Hami City (including Yizhou District, Barkol Kazakh Autonomous County, and Yiwu County). Located in the interior of the Eurasian continent and surrounded by mountains, the region covers approximately 1.2$×10^{5}$ km^{2}. The climate is characterized by high temperatures and drought in summer, scarce precipitation (annual average <50 mm), and strong evaporation (annual average 2000 mm), resulting in extreme water shortage, sparse vegetation, severe land desertification, and an extremely fragile ecosystem [11].

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2 Data and Methods

2.1 Data Sources

MODIS data were obtained from LAADS DAAC (https://ladsweb.modaps.eosdis.nasa.gov/). Land use data for different periods were derived from the 30 m resolution land use dataset (https://zenodo.org/record/5210928#.YdJoJci4z9h), which is based on Landsat imagery and manual visual interpretation [12].

2.2.1 Establishment and Evaluation of the Remote Sensing Ecology Index (RSEI)

Numerous studies demonstrate that heat, greenness, humidity, and dryness indices are four key indicators directly related to ecological environment quality [13]. RSEI is constructed using these four indicators to characterize environmental quality changes. Literature review reveals that the humidity index can be obtained through Tasseled Cap Transformation of remote sensing imagery. Heat and greenness indices are represented by Land Surface Temperature (LST) and Normalized Difference Vegetation Index (NDVI), respectively. The dryness index is constructed using the Normalized Difference Built-up and Bare Soil Index (NDBSI) [14].

RSEI can be expressed as a function of these four indices:

$$RSEI = f(G, W, T, D)$$

The specific expression is:

$$RSEI = (NDVI, Wetness, LST, NDBSI)$$

where G represents the greenness index, W the humidity index, T the heat index, and D the dryness index. Wetness is the humidity component obtained from Tasseled Cap Transformation, LST is land surface temperature, and NDBSI is the built-up and bare soil index.

Humidity Index: Tasseled Cap Transformation effectively reduces remote sensing data dimensionality [15]. The transformed components exhibit strong interpretability for ecological environmental parameters (humidity, brightness, and greenness). The humidity component correlates closely with vegetation and soil moisture, so this study uses the Wetness component to represent the humidity index:

$$Wetness = 0.26\rho_1 + 0.21\rho_2 + 0.09\rho_3 + 0.05\rho_4 - 0.07\rho_5 - 0.15\rho_6 - 0.24\rho_7$$

where ρ_i (i=1, 2, …, 7) are the reflectance values of MODIS image bands.

Greenness Index: NDVI is a widely used vegetation index closely related to leaf area, biomass, and vegetation coverage [16]. Therefore, this study selects NDVI to characterize the greenness index:

$$NDVI = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$$

where ρ_1 and ρ_2 are the reflectance values of MODIS multispectral sensor's red and near-infrared bands, respectively.

Heat Index: Land surface temperature is calculated using the thermal infrared band:

$$T_6 = gain \times DN + bias$$

$$LST = \frac{K_2}{\ln\left(\frac{K_1}{T_6} + 1\right)}$$

where DN is the dimensionless pixel brightness value, *gain* and *bias* are the gain and offset values for band 6, T_6 is the sensor temperature, and K_1 and K_2 are calibration parameters. To obtain accurate LST, emissivity correction is required:

$$LST = \frac{T_6}{\varepsilon^{1/4}}$$

where λ is the central wavelength of the MODIS band, ρ is a constant, and ε is the emissivity.

Dryness Index: NDBSI is constructed by combining the Index of Built-up Index (IBI) and Soil Index (SI):

$$NDBSI = IBI + SI$$

After calculating the four indices, Principal Component Analysis (PCA) is performed. Since these indices have different dimensions, direct PCA would significantly affect RSEI results. Therefore, all indices were normalized before analysis. The first principal component (PC1) was selected to represent regional ecological environment quality, as its variance contribution rate exceeded 80% in all periods. For inter-study comparison, RSEI was further standardized:

$$RSEI = 1 - PC1$$

All calculations were implemented in MATLAB2021a (The MathWorks, Natick, MA, USA), with PCA and normalization performed using the `mapminmax` function.

2.2.2 Land Use and Transfer Matrix Calculation

Given the 30 m resolution of land use data [17], data were resampled to 1000 m to match MODIS resolution. The transition matrix, a common technique for quantifying land use change [18], was calculated in MATLAB2021a to analyze land use transfer patterns in the Turpan-Hami region from 2000 to 2018.

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3 Results and Analysis

3.1 Spatio-Temporal Distribution of Ecological Environment in the Turpan-Hami Region

The greenness index distribution (Fig. 2) reveals low vegetation coverage in the Turpan-Hami region, with only small patches concentrated in Yizhou District and Yiwu County of Hami City, and mountainous areas north of Turpan City. Temporal comparison shows gradually increasing ecosystem greenness from 2000 to 2018, with mean greenness index rising to 0.0244. Overall, Turpan City's greenness index remains lower than Hami City's.

Humidity index distribution (Fig. 3) shows high values concentrated in Turpan's mountainous areas and northern Hami, while low values appear in southern desert regions and their ecotones. Statistical analysis yields average humidity indices of 0.0021, 0.0023, 0.0025, and 0.0024 for 2000, 2006, 2012, and 2018, respectively, indicating an overall increasing trend (Table 1). The 2012 average humidity is relatively high, likely related to increased snowmelt runoff.

Dryness index distribution (Fig. 4) demonstrates generally high values across the region, with only localized low values near city and county centers. Average dryness indices are 0.0018, 0.0017, 0.0019, and 0.0019 for the four periods, showing fluctuating but slightly increasing trends, with 2012 recording the highest average dryness value. This suggests certain soil erosion conditions related to internal land use patterns.

Heat index distribution (Fig. 5) reveals high-temperature zones mainly in southern desert areas and low-temperature zones in northern mountains. Temporal analysis shows a decreasing trend, with average heat index declining from 0.0241. Overall, high-value areas (RSEI>0.5) are concentrated near farmland oases and mountainous regions (Fig. 6). The region's ecological environment quality initially declined (2000–2006), then improved (2006–2012), before declining again (2012–2018). No significant differences exist between regions, with changes remaining small (approximately 0.02). Further statistical analysis (Table 2) shows the most significant improvement in central Hami City (increase of 0.2–0.3), while most areas of Barkol Kazakh Autonomous County show slight increases (0–0.2).

3.2 Correlation Analysis Between RSEI and Individual Indices

Global correlation analysis between RSEI and individual indices (Table 3) reveals significant positive correlations with greenness and humidity indices ($P<0.001$) and negative correlations with heat and dryness indices. Greenness shows stronger positive correlation than humidity. Across all periods, heat index exhibits the strongest correlation with RSEI in the Turpan-Hami region, indicating it is the dominant factor controlling ecological environment quality.

3.3 Spatio-Temporal Changes in Ecological Environment Quality

Greenness index changes (Fig. 7) show 60% of the region exhibiting increasing trends, with only minor decreases in northern areas. Notable increases occur in northern Turpan and around Hami City, with 增幅为 0.2–0.3. Average greenness index increased by 0.0244, with 增幅次之达到 0.2–0.3.

Humidity index changes (Fig. 8) reveal increasing trends in 65% of the region from 2000 to 2018, particularly in southeastern Barkol Kazakh Autonomous County (增幅 0.2–0.3). Decreasing trends appear in 35% of the region, but overall, the 近 20 年变化 shows a net increase, with central Hami showing relatively high 增幅 (0.2–0.3). The overall change is offset by the general decline in the 2006–2012 period.

Dryness index changes (Fig. 9) show opposite trends to humidity. From 2000–2006, 55% of the region exhibited decreasing trends, while 2012–2018 showed overall increases (45% area). Overall, 近 20 年来 60% of the region shows increasing dryness, most notably in southern Yiwu County (增幅 0.2–0.3), while central Hami shows significant decreases (dryness index reduction of 0.15–0.2).

Heat index changes (Fig. 10) also show opposite trends. During 2000–2006, heat index decreased across most of Turpan and southern Hami, while northern Hami showed increases. The area proportions of change are similar across periods. Overall, 近 20 年来 65% of the region shows decreasing heat index, particularly in central Hami and Yiwu County (reduction of 0.15–0.2).

RSEI changes (Fig. 11) show that 近 20 年来 55% of the region experienced slight ecological environment quality decline (change mean 接近-0.02), while 45% showed improvement. Central Hami exhibited the most significant quality improvement (增幅 0.2–0.3), whereas most of Barkol Kazakh Autonomous County showed slight increases (0–0.2). The 2006–2012 period showed opposite trends to dryness (Fig. 9) and heat index (Fig. 10) changes.

3.4 Land Use Changes Across Periods

Analysis of land use across three periods reveals that unused land dominates the Turpan-Hami region, followed by grassland concentrated in northern Turpan and central Hami (Fig. 12). Statistical analysis shows cultivated land and grassland areas increased from 2000 to 2018, while Barkol Lake area significantly shrank.

Land use transition matrix analysis indicates that grassland increased most substantially (5142 km^2), followed by cultivated land (869 km^2) and urban/rural land (594 km^2). Conversely, unused land decreased most dramatically (9085 km^2), followed by forest land (310 km^2) and water bodies (112 km^2) (Table 5). Changes were more dramatic during 2000–2006, with relatively stable changes in subsequent periods.

Further analysis of land use transfers reveals that despite 1348 km^2 of grassland degrading to unused land, 8044 km^2 of unused land was converted to grassland. Additionally, 682 km^2 of unused land was reclaimed as cultivated land, and 543 km^2 of grassland was converted to cultivated land (Table 6). These results indicate an overall greening trend in the Turpan-Hami region over the past two decades, consistent with RSEI analysis results. However, future efforts must reduce grassland reclamation and overgrazing while preventing cultivated land abandonment.

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4 Conclusions

This study utilized MODIS remote sensing data to invert four indices representing temperature, greenness, humidity, and dryness in the Turpan-Hami region. Through multiple calculation methods, RSEI was constructed and various spatio-temporal change analyses were conducted to comprehensively explore ecological environment and land use changes, providing an effective basis for high-quality regional development. The main conclusions are:

1) The RSEI constructed using four covariates (surface temperature, vegetation greenness, environmental humidity, and dryness) better reflects ecological environment changes from 2000 to 2018 than single indices. Overall, the greenness index increased by 0.0244, heat index decreased by 0.0241, while humidity and dryness indices showed minimal change near zero. Dryness and heat indices decreased most significantly in central Hami City.

2) The ecological environment quality of the Turpan-Hami region showed a slight overall decline (change mean of -0.02). Shanshan County in Turpan City exhibited the largest change magnitude and greatest environmental quality decline, while Barkol Kazakh Autonomous County in Hami City showed the smallest decline.

3) Over the past two decades, grassland (5142 km^2) and cultivated land (869 km^2) areas increased significantly. However, controlling grassland reclamation and overgrazing remains crucial to prevent regional ecological environment deterioration.

4) The heat index is the dominant factor controlling ecological environment quality changes in the Turpan-Hami region. Although the region shows an overall greening trend, continued control of grassland reclamation and overgrazing is necessary.

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