Dynamic Monitoring and Assessment of Eco-Environmental Quality in Tumxuk City, 2000-2021: Postprint

Authors: Wang Jian

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Abstract

To objectively evaluate the impact of driving factors on ecological environmental quality in Tumxuk City, Xinjiang, Landsat image data from three periods (2000, 2011, and 2021) were selected, coupling four indicators: Normalized Difference Vegetation Index (NDVI), soil moisture (WET), dryness (NDSI), and land surface temperature (LST). Principal component analysis was employed to construct the Remote Sensing Ecological Index (RSEI). Combining natural and socioeconomic factors of the study area, dynamic monitoring and evaluation of the ecological environmental quality in Tumxuk City over the past 22 years were conducted. The results indicate that: (1) Over the past 22 years, the mean RSEI value in Tumxuk City increased from 0.406 to 0.476, the area with improved ecological environmental quality far exceeds the area with degraded quality, improved areas are mainly distributed in the central, southeastern, and northwestern parts of the study area, and the ecological environmental quality has been effectively improved over the past 22 years. (2) Through analysis of the driving factors in Tumxuk City, the local ecological environmental quality is influenced by factors such as population, Gross Domestic Product (GDP), cultivated land area, and climate; among the driving factors, socioeconomic factors have a significant impact on the local ecological environmental quality. (3) By constructing RSEI and analyzing the impact of its driving factors on ecological environmental quality, dynamic monitoring and objective evaluation of the local ecological environmental quality can be conducted efficiently and accurately.

Full Text

Dynamic Monitoring and Evaluation of Ecological Environment Quality in Tumshuk City from 2000 to 2021

WANG Jian[1], GUAN Yao[1], HE Xinghong[1],[2], DAI Yunhao[3], CHEN Yiwei[1], WANG Yuqiang[1], LI Huiwen[1], FAN Debao[1]

[1]College of Water Conservancy and Architecture Engineering, Tarim University, Aral 843300, Xinjiang, China
[2]South Xinjiang Geotechnical Engineering Research Center, Tarim University, Aral 843300, Xinjiang, China
[3]Beichuan Qiang Autonomous County Highway Transportation Administrative Office, Mianyang 621000, Sichuan, China

Abstract

To objectively evaluate the impact of driving factors on ecological environment quality in Tumshuk City, Xinjiang, this study selected Landsat imagery data from three periods (2000, 2011, and 2021) and coupled four indicators: Normalized Difference Vegetation Index (NDVI), soil moisture (WET), land surface temperature (LST), and normalized difference soil index (NDSI). Principal component analysis was employed to construct a Remote Sensing Ecology Index (RSEI), which was combined with natural and socioeconomic factors in the study area to dynamically monitor and evaluate the ecological environment quality of Tumshuk City over the past 22 years. The results demonstrated that: (1) The average RSEI of Tumshuk City increased from 0.406 to 0.476 during 2000–2021, with the area showing improved ecological environment quality substantially exceeding the area showing deterioration. Improved regions were mainly distributed in the central, southeastern, and northwestern parts of the study area, indicating effective ecological environment quality improvement over the 22-year period. (2) Analysis of driving factors revealed that local ecological environment quality was influenced by population, gross domestic product (GDP), cultivated land area, and climate. Among these driving factors, socioeconomic factors exerted a significant impact on local ecological environment quality. (3) By constructing RSEI and analyzing the influence of its driving factors on ecological environment quality, efficient and accurate dynamic monitoring and objective evaluation of local ecological environment quality can be achieved.

Keywords: Tumshuk City; remote sensing ecology index; ecological environment quality; driving factors; dynamic monitoring

Introduction

Xinjiang' s geographical conditions impose significant constraints, characterized by large diurnal temperature variations and low precipitation, resulting in drought and water scarcity across many regions. Tumshuk City in Xinjiang

possesses a fragile ecological environment that severely impacts agricultural production. Consequently, accurate understanding of local ecological environment quality holds great significance for agricultural production, human livelihoods, and economic development. Remote sensing technology has been widely applied in monitoring regional ecological environment quality due to its high efficiency and timeliness, providing real-time data for ecological environment quality monitoring and offering expanded possibilities for tracking regional environmental changes.

In recent years, numerous domestic and international scholars have utilized the Remote Sensing Ecology Index (RSEI) to investigate regional ecological environment quality. Research has demonstrated that RSEI is applicable to different land types and enables efficient and accurate dynamic monitoring of ecological environments in various study areas. Currently, dynamic monitoring and evaluation of regional ecological environment quality using RSEI have been extensively applied to urban areas, wetlands, arid regions, and other zones. However, most scholars have focused solely on monitoring and assessing regional ecological environment quality without conducting multi-angle objective evaluations of how natural and social factors influence ecological environment quality in their study areas.

Establishing an ecological environment quality evaluation system based on assessment indicators and analyzing the relationship between ecological quality changes and local driving factors can not only facilitate dynamic monitoring of the ecological environment but also provide reference for environmental planning and governance. This approach holds important significance for promoting ecological environmental protection and sustainable socioeconomic development in study areas. Tumshuk City represents a key development city in southern Xinjiang, where ecological environment monitoring serves as the "lifeline" of environmental protection efforts. This study selects three periods of remote sensing imagery data from Tumshuk City to construct RSEI through NDVI, WET, LST, and NDSI indicators for dynamic monitoring and objective evaluation of ecological environment quality over the past 22 years. By analyzing the relationship between local socioeconomic and natural condition driving factors and ecological environment quality, this research provides theoretical support for Tumshuk City' s future sustainable development.

1. Study Area and Data Sources

1.1 Study Area Overview

Tumshuk City (39°36 ~40°04 N, 78°38 ~79°50 E) is located on the northwestern edge of the Tarim Basin in Xinjiang. The city has a total population of 326,600 and covers an area of 1,941 km^2, with landform characteristics consisting primarily of plains and sand dunes. Tumshuk City experiences a warm temperate continental arid climate with long sunshine duration, strong solar radiation, large diurnal temperature variations, hot summers, cold winters, and distinct

four seasons. The annual average temperature ranges from 10 to 13°C, with annual precipitation between 12.3 and 30.1 mm. Cotton is the main crop, and the city is a nationally approved high-quality commercial cotton base.

[Figure 1: see original paper]

1.2 Data Sources

Landsat remote sensing imagery data for Tumshuk City from 2000, 2011, and 2021 were obtained from the Geospatial Data Cloud (http://www.gscloud.cn), selecting images with cloud cover less than 10%, including Landsat 7 ETM and Landsat 8 OLI data. Population, gross domestic product (GDP), and agricultural planting area data were sourced from the Xinjiang Production and Construction Corps Statistical Yearbook. Rainfall and temperature data were obtained from the Xihe Energy Big Data Platform (https://www.xihe-energy.com).

1.3 Methodology

1.3.1 Data Preprocessing Original imagery of the study area was preprocessed using ENVI 5.3 software, including geometric correction, radiometric calibration, and atmospheric correction. Statistical yearbook data on population, GDP, agricultural planting area, rainfall, and other variables were organized and analyzed using Origin 2018.

1.3.2 Ecological Index Factors Four ecological indices were constructed for the Remote Sensing Ecology Index (RSEI):

(1) Normalized Difference Vegetation Index (NDVI)

NDVI is commonly applied to monitor plant growth conditions and ecological environment changes, offering high monitoring sensitivity that can accurately reflect surface change patterns in the study area. The formula is:

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

(2) Soil Moisture (WET)

Soil moisture levels reflect the quality of the ecological environment in the study area, serving as an important indicator for monitoring surface environments. To effectively remove redundant data, this study employed the Tasseled Cap transformation to invert soil moisture. The formulas are:

For Landsat 7 ETM:

$$WET_{TM} = 0.0315\rho_{blue} + 0.2021\rho_{green} + 0.3102\rho_{red} + 0.1594\rho_{NIR} - 0.6806\rho_{SWIR1} - 0.6109\rho_{SWIR2}$$

For Landsat 8 OLI:

$$WET_{OLI} = 0.1511\rho_{blue} + 0.1973\rho_{green} + 0.3283\rho_{red} + 0.3407\rho_{NIR} - 0.7117\rho_{SWIR1} - 0.4559\rho_{SWIR2}$$

(3) Dryness Index (NDSI)

The dryness index was calculated using the Building Index (IBI) and Bare Soil Index (SI):

$$IBI = \frac{2\rho_{SWIR1}}{\rho_{SWIR1} + \rho_{NIR}} - \left(\frac{\rho_{NIR}}{\rho_{NIR} + \rho_{red}} + \frac{\rho_{green}}{\rho_{green} + \rho_{SWIR1}} \right)$$

$$SI = \frac{(\rho_{SWIR1} + \rho_{red}) - (\rho_{blue} + \rho_{NIR})}{(\rho_{SWIR1} + \rho_{red}) + (\rho_{blue} + \rho_{NIR})}$$

$$NDSI = \frac{IBI + SI}{2}$$

(4) Land Surface Temperature (LST)

Land surface temperature was retrieved using the atmospheric correction method. For Landsat ETM, thermal radiation intensity was converted from gray values, and surface brightness temperature was calculated from thermal radiation intensity. For Landsat OLI, the atmospheric correction method was applied with the following formulas:

For Landsat ETM:

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

For Landsat OLI:

$$LST = \frac{\gamma}{\lambda}\left\{\frac{1}{\varepsilon}\left[\psi_1 L_\lambda + \psi_2\right] + \psi_3\right\} + \delta$$

where L_λ is the radiance value received by the satellite sensor in the thermal infrared band, K_1 and K_2 are calibration constants, ε is surface emissivity, and ψ_1, ψ_2, ψ_3 are atmospheric correction parameters.

These four indicators effectively characterize the ecological environment and can comprehensively reflect the overall ecological conditions of Tumshuk City, enabling robust evaluation of the study area' s ecological environment quality.

1.3.3 Remote Sensing Ecology Index (RSEI) Considering the influence of water bodies on moisture indicators, and given that Tumshuk City contains the Xiaohaizi Reservoir (the largest in northwestern China) and the Yong' anba North-South Reservoirs, water areas within the study region were masked and excluded from analysis. To prevent weight imbalance among the four indicators, principal component analysis (PCA) was employed to integrate NDVI, WET,

NDSI, and LST. All indicators were normalized before PCA to ensure accurate results, with values ranging between [0, 1] where higher values indicate better ecological environment quality.

The normalization formula is:

$$I_i = \frac{x_i - x_{min}}{x_{max} - x_{min}}$$

The initial RSEI was constructed as:

$$RSEI_0 = 1 - PC_1(NDVI, WET, NDSI, LST)$$

The final normalized RSEI was calculated as:

$$RSEI = \frac{RSEI_0 - RSEI_{0_{min}}}{RSEI_{0_{max}} - RSEI_{0_{min}}}$$

where PC_1 represents the first principal component, and $RSEI_{0_{max}}$ and $RSEI_{0_{min}}$ are the maximum and minimum initial RSEI values, respectively.

2. Results and Analysis

2.1 RSEI Principal Component Analysis

Principal component analysis results for Tumshuk City from 2000 to 2021 showed that the first principal component contribution rates were 88.33%, 91.30%, and 93.11% for the three periods, respectively, with an average of 90.91%. All contribution rates exceeded 88%, indicating that the first principal component effectively concentrated the characteristic information of each indicator, enabling robust representation of Tumshuk City' s ecological environment quality.

2.2 Analysis of Ecological Environment Quality Changes in Tumshuk City

The ecological environment quality of Tumshuk City showed an overall improvement trend from 2000 to 2021. The area with unchanged quality was 740.483 km^2, accounting for 42.55% of the total area and widely distributed in northern and southern regions. The deteriorated area was 438.610 km^2 (25.21%), mainly distributed in northeastern and southwestern regions. The improved area was 560.994 km^2 (32.24%), primarily located in central, southeastern, and northwestern regions. The substantially larger improved area compared to deteriorated area indicates that Tumshuk City' s ecological environment quality has been effectively enhanced over the past 22 years.

[Figure 2: see original paper]

The area statistics for different ecological environment quality levels are presented in Table 3, while Table 4 shows the stochastic matrix of ecological environment quality change area. Figure 3 illustrates the changes in ecological environment quality levels from 2000 to 2021, and Table 5 provides statistics of the difference area of ecological environment quality change.

The medium-quality level area showed a decreasing trend, reducing by 71.82 km^2 (23.83%). The combined area of poor and relatively poor grades, which initially accounted for high proportions, exhibited a decreasing trend overall, with a total reduction of 8.11%. The good-quality level area increased by 66.46 km^2, showing a growth rate of 15.57%. The excellent level demonstrated a continuous increasing trend, with its proportion rising from 29.45% to 54.64%, an increase of 143.96 km^2 (23.19% growth rate).

[Figure 3: see original paper]

2.3 Driving Factor Analysis

2.3.1 Socioeconomic Factors Population and GDP in Tumshuk City showed slow growth trends from 2000 to 2009, but accelerated significantly after 2010. Agricultural planting area increased annually from 2000 to 2019, with a slight decline in 2020-2021. As ecological environment quality gradually improved, the city began enhancing agricultural production conditions in 2010 by increasing agricultural machinery, expanding mechanized cultivation, and strengthening infrastructure development. Transportation capacity was also enhanced, facilitating freight movement and promoting rapid economic development and comprehensive socioeconomic advancement during 2010-2021.

Population growth and rapid economic development increased human activity density and land use changes within the study area, impacting ecological environment quality. Analysis of planting industry, gross agricultural product, and agricultural planting area changes (Figure 5) revealed that socioeconomic factors significantly influenced local ecological environment quality.

[Figure 4: see original paper] [Figure 5: see original paper]

2.3.2 Natural Factors To investigate the impact of natural factors such as climate and precipitation on Tumshuk City' s ecological environment quality, meteorological data from 2000 to 2021 were analyzed. The annual average temperature fluctuated between 10.5°C and 13.0°C, while annual precipitation ranged from 10 to 35 mm. Both temperature and precipitation showed fluctuating patterns within these ranges over the 22-year period.

Stable annual average temperatures and increased precipitation positively contributed to ecological environment quality improvement, whereas large temperature fluctuations and reduced precipitation had negative effects. Overall, natural factors had relatively minor impacts on ecological environment quality compared to socioeconomic factors.

[Figure 6: see original paper]

3. Discussion

3.1 Trends in Ecological Environment Quality Change

Urban vegetation coverage contributes significantly to ecological environmental protection. Research on vegetation coverage in Tumshuk City showed substantial increases in vegetated area from 1993 to 2019. Changes in land use type affect ecological environment quality, with studies indicating that cultivated land and construction land areas in Tumshuk City showed increasing trends. The increase in vegetation coverage and cultivated land area has positively contributed to ecological environment quality improvement.

The continuous improvement of ecological environment quality in Tumshuk City over the past 22 years is closely related to increased vegetation coverage and cultivated land area. Future efforts should continue strengthening ecological protection measures to further enhance local environmental quality.

3.2 Driving Factors

Climate change represents a natural factor affecting the ecological environment, while the relationship between socioeconomic development and ecosystems is particularly complex. Temperature and precipitation variations influence soil moisture, with rising temperatures reducing atmospheric moisture and increased precipitation enhancing soil humidity. Population growth drives urban expansion, requiring coordination between socioeconomic development and ecological environmental protection.

Analysis of driving factors including population, GDP, climate, and agriculture revealed that socioeconomic factors significantly impacted ecological environment quality changes. Increased cultivated land area and vigorous agricultural development improved local residents' income, enhanced economic benefits, and promoted socioeconomic development, which in turn contributed to ecological environment quality improvement. These findings align with numerous previous studies. To promote sustainable development in Tumshuk City, continued attention to local ecological environmental protection remains essential.

4. Conclusion

This study constructed RSEI using Landsat imagery data from Tumshuk City for the years 2000, 2011, and 2021, dynamically monitoring and evaluating ecological environment quality changes over 22 years. The average RSEI values were 0.406, 0.447, and 0.476 for the three periods, respectively, showing an overall improvement trend. The area with improved ecological environment quality far exceeded the area with deterioration, with improvements mainly distributed in central, southeastern, and northwestern regions.

Analysis of driving factors indicated that Tumshuk City' s ecological environment quality was influenced by both natural and socioeconomic factors, with natural factors having relatively minor impacts and socioeconomic factors exerting significant effects. The RSEI approach enables efficient and accurate dynamic monitoring and objective evaluation of local ecological environment quality, providing a theoretical basis for future ecological protection and socioeconomic development in Tumshuk City.

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