Evaluation of Spatiotemporal Patterns of Land Ecological Security at the Township Scale: A Case Study of Bortala Mongol Autonomous Prefecture (postprint)

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Abstract

In recent years, scholars both domestically and internationally have conducted extensive research on regional land ecological security assessment; however, most studies have targeted watersheds or administrative units at the county level and above, with very few investigations focusing on the township scale. Therefore, this study selects the Bortala Mongol Autonomous Prefecture, located in the arid and ecologically fragile region of northwestern China, as the research area. Supported by "3S" technology and mathematical statistical methods, and integrating the natural geographical characteristics and socio-economic conditions of the study area, we constructed a township-level Pressure-State-Response (P-S-R) land ecological security assessment model for the Bortala Mongol Autonomous Prefecture, and conducted a diagnostic analysis of the spatial pattern characteristics and underlying causes of its land ecological security. The results indicate: (1) Land ecological security in Bortala Prefecture deteriorated from 2011 to 2014, with the largest conversion area being from Level III to Level IV, reaching 2555.33 km², primarily within Wenquan County, followed by conversion from Level V to Level IV covering 1356.53 km², mainly occurring in Mangding Township and Tuotuo Township of Jinghe County; (2) The land ecological security status of most townships in Bortala Prefecture is at Level III, indicating an unstable regional ecological structure that requires urgent adjustment; (3) The land ecological security status of Bortala Prefecture exhibits distinct regional distribution characteristics, with low-value areas concentrated primarily in the desert regions of eastern Bortala, and high-value areas concentrated mainly in the oasis and lake regions of central Bortala. These research findings can provide references for township-level land ecological security assessment and theoretical guidance for coordinated regional ecological protection and sustainable township development.

Full Text

Preamble

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Spatiotemporal Pattern Evaluation of Land Ecological Security at the Township Scale: A Case Study of Bortala Mongolian Autonomous Prefecture

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Abstract

Regional land ecosystems are facing deterioration due to rapid urbanization. To promote sustainable development of land ecosystems, evaluating regional land ecological security is essential. While numerous studies have assessed land ecological security, most have focused on watershed or county-level administrative units, with few examining the township scale. This study selected Bortala Mongolian Autonomous Prefecture (hereafter "Bortala") in Xinjiang Uyghur Autonomous Region—a drought-prone and ecologically vulnerable area in northwestern China—as the research area. Integrating "3S" technologies (Remote Sensing, Geographic Information Systems, and Global Positioning Systems) with mathematical statistical methods, we constructed a township-level Pressure-State-Response (P-S-R) land ecological security evaluation model tailored to Bortala's natural geographic features and socioeconomic conditions. Using data from statistical yearbooks and remote sensing imagery for 2011 and 2014, we established an index system comprising 25 indicators reflecting regional P-S-R characteristics. The entropy weight method and analytic hierarchy process were employed to determine indicator weights. Land ecological security indices were then calculated for each township using GIS Grid analysis.

The results show: (1) Land ecological security in Bortala deteriorated from 2011 to 2014. Between these years, 2,555.33 km² of Level III (security grade) areas transitioned to Level IV, with degraded areas concentrated primarily in Wenquan County. Meanwhile, 1,356.53 km² of Level V areas improved to Level

IV, concentrated in Mangding Township and Tuotuo Township of Jinghe County. (2) Most townships exhibited Level III security, indicating unstable ecological structures. (3) Spatial distribution of land ecological security was distinctly regional: low-value areas clustered in eastern desert regions, while high-value areas concentrated in central oasis zones and lake areas. These findings provide references for township-level land ecological security evaluation and theoretical guidance for coordinated regional ecological protection and sustainable township development.

Keywords: township scale; land ecological security; P-S-R model; Bortala Mongolian Autonomous Prefecture

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1. Study Area Overview

Bortala is located in the northwestern border region of Xinjiang Uyghur Autonomous Region, covering 24,896 km². The terrain forms an inclined valley, 380 km long, surrounded by mountains on three sides (north, west, and south) with elevation decreasing from west to east. The landscape comprises mid-mountain forests, desert steppe at the southern and northern piedmonts, and the Gobi desert around Ebinur Lake. The Bortala River in the west and the Jinghe River in the east nurture oases along their banks. Bortala features a typical north temperate continental arid climate, though the western and northern piedmonts receive abundant precipitation during summer. The prefecture administers Bole City, Jinghe County, and Wenquan County. [Figure 1: see original paper] shows the study area.

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2. Data Sources

Digital imagery data included: Landsat 5 TM and Landsat 8 OLI (30 m × 30 m resolution), MODIS NDVI monthly composite products (500 m × 500 m resolution), and ASTER GDEM (30 m × 30 m resolution). Socioeconomic data were obtained from the Bortala Statistical Yearbook, Bole City Statistical Yearbook, Wenquan County Statistical Yearbook, and relevant government departments. Field survey data included 96 spatial information points with location data and landscape photos. Analogous standard reference data were selected to establish evaluation criteria. Detailed data types and sources are listed in .

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3. Digital Image Data Preprocessing

3.1 Remote Sensing Image Preprocessing and Classification

Landsat images were preprocessed using ENVI 4.8 software. Radiometric correction was performed using the FLAASH model [31]. Geometric precision correction employed control point polynomial fitting based on 1:100,000 topographic maps, with ground control point errors maintained below 0.5 pixels. Cubic convolution resampling and Krueger projection were applied. Cloud and snow-affected images were excluded to ensure quality.

Supervised classification was conducted using decision tree rules derived from training samples. Land use/land cover (LULC) was classified into six categories: cropland, forest, grassland, water, salinized land, and other. Classification accuracy exceeded 94% for both years (2011: 96.07%, Kappa coefficient 0.9507; 2014: 94.05%, Kappa coefficient 0.9302), meeting research requirements. Manual visual interpretation refinement was performed where needed.

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4. Evaluation Indicator Standardization

4.1 Evaluation Units

Most land ecological security studies use administrative units as data carriers due to data availability. However, county-level units lack spatial visualization and practical guidance. Considering Xinjiang' s vast county-level administrative areas, this study selected townships as the minimum evaluation units. Multi-source data were resampled to 30 m × 30 m resolution, enabling fine-grained raster data to reflect spatial heterogeneity within evaluation units.

4.2 Indicator System and Weights

The P-S-R framework, established by the United Nations Economic Cooperation and Development Organization [33], systematically organizes environmental indicators from human-environment interaction perspectives. Pressure indicators reflect human activities' burden on resources and ecosystems [34]. State indicators describe current natural resource and environmental quality conditions [35-36]. Response indicators represent optimization measures and feedback for sustainable ecosystem development [37]. The framework demonstrates strong systematicity [38].

Based on literature review and Bortala' s actual conditions, we constructed a township-level P-S-R evaluation model. Following scientific, practical, and dynamic principles, 25 indicators closely related to land ecological security were selected. Pearson correlation analysis screened indicators, retaining those with correlation coefficients <0.9 with criteria or objective layers and intra-layer correlations <0.8. The entropy weight method and analytic hierarchy process were combined to determine weights, balancing regional characteristics and data mathematical features. The final indicator system is shown in .

4.3 Indicator Definitions and Standardization

Given diverse indicator types, direct comparison of measured values is challenging. Standardization prioritized international or national standards, followed by local ecological civilization standards. For indicators without explicit standards, range normalization was applied.

Standardization formulas: - For positive indicators: $Y_{ij} = \frac{X_{ij} - X_j^{min}}{X_j^{max} - X_j^{min}}$ - For negative indicators: $Y_{ij} = \frac{X_j^{max} - X_{ij}}{X_j^{max} - X_j^{min}}$

Where X_{ij} is the original value of indicator j in year i, and X_j^{max} and X_j^{min} are the maximum and minimum values for indicator j.

Key indicators include: - **Fertilizer use per unit cropland**: Inverse indicator; higher values indicate greater pressure. - **Pesticide use per unit cropland**: Inverse indicator; reflects pesticide pollution severity. - **Plastic film use per unit cropland**: Inverse indicator; reflects plastic pollution severity. - **Grassland livestock carrying capacity**: Inverse indicator; calculates livestock number per unit grassland area. - **Population density**: Inverse indicator; reflects population pressure on land. - **Natural growth rate**: Inverse indicator; ratio of natural population increase. - **GDP per unit land area**: Positive indicator; reflects economic development level. - **Grain yield per capita**: Positive indicator; reflects cropland' s population support capacity. - **Forest coverage rate**: Positive indicator; percentage of forest area. - **Water network density**: Positive indicator; total river length per unit area. - **Shannon diversity index**: Positive indicator; $SHDI = -\sum_{i=1}^{m} P_i \ln(P_i)$, where P_i is the proportion of landscape type i. - **Landscape fragmentation**: Inverse indicator; number of patches per unit area. - **Desertification rate**: Inverse indicator; change in desertified area between periods. - **Cropland irrigation ratio**: Positive indicator; ratio of effectively irrigated cropland.

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5. Land Ecological Security Model

The Land Ecological Security (LES) index measures regional land ecological security degree:

$$LES = \sum_{i=1}^{n} P_i \times w_i$$

Where P_i is the standardized value of indicator i, and w_i is its weight.

5.1 Evaluation Criteria

Traditional studies often use absolute thresholds (0.2, 0.4, 0.6, 0.8, 1.0) corresponding to five security levels, which may cause deviations. This study analyzed Bortala's ecosystem conditions and referenced relevant literature [22,28,38] to establish classification standards using ArcGIS natural breaks classification, adjusted based on 96 field survey points and expert interpretation. The final five-level standard is shown in .

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6. Spatial Autocorrelation Analysis

6.1 Global Spatial Autocorrelation

Spatial autocorrelation explains spatial dependency relationships. Global Moran' s I verifies overall spatial correlation, while local indicators (LISA) reflect correlation between local units and neighbors.

Global Moran' s I formula:

$$I = \frac{n}{S_0} \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^{n} (x_i - \bar{x})^2}$$

Where n is sample size, x_i is the statistical value of region i, $\bar{x}$ is the mean, and W_{ij} is the spatial weight matrix (1 for adjacent regions, 0 otherwise). Moran' s I ranges from -1 to 1, with larger absolute values indicating stronger spatial correlation.

Bortala' s land ecological security showed strong positive spatial correlation, with Moran' s I values of 0.5990 (2011) and 0.6763 (2014), indicating significant spatial clustering.

6.2 Local Spatial Autocorrelation

Local Moran' s I identifies spatial clusters: - **H-H clusters**: High values surrounded by high values (spatial homogeneity) - **L-L clusters**: Low values surrounded by low values - **H-L clusters**: High values surrounded by low values (spatial heterogeneity) - **L-H clusters**: Low values surrounded by high values

Significance testing used Z-scores:

$$Z(I_i) = \frac{I_i - E(I_i)}{\sqrt{Var(I_i)}}$$

Local spatial autocorrelation analysis revealed distinct spatial patterns: low-value clusters concentrated in eastern desert areas, while high-value clusters were found in oasis and lake regions. [Figure 4: see original paper] and [Figure 5: see original paper] show Moran scatter plots and local spatial autocorrelation cluster maps for 2011 and 2014.

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7. Results

7.1 Structural Characteristics of Bortala' s Land Ecological Security

Analysis of township P-S-R subsystems revealed: - **Pressure subsystem**: Most townships were at Level III. Administrative centers (Bole City, Jinghe Town, Bogdaer Town) faced Levels IV-V due to intense environmental, resource, and social pressures. Non-administrative townships showed lower pressure levels. - **State subsystem**: Most townships were at Level III. Xiao Yingpan Town and Wenquan County townships reached Level II due to abundant water resources and stable ecosystems. Jinghe County and Bole City townships were at Level IV, with vulnerable ecological structures due to extensive desert/bare land areas. - **Response subsystem**: Administrative centers were at Levels I-II, demonstrating effective policy implementation and good feedback. Other townships were mostly at Level III, indicating lower policy execution efficiency due to geographical constraints.

7.2 Spatiotemporal Patterns of Bortala' s Land Ecological Security

Spatial distribution analysis using ArcGIS overlay calculations showed: - **2011**: Level V areas were mainly Ebinur Lake, Jinghe Oasis, and Wenquan County. Level I areas concentrated in eastern Ebinur Lake and southeastern desert regions. The spatial distribution was extremely unbalanced. - **2014**: Eastern areas showed improvement, but Level I areas remained extensive. The central region (Wutubulage Town) showed significant deterioration. Level V areas decreased in oasis-desert ecotones but increased in mountainous areas.

Area transfer matrix () revealed: - 2,555.33 km² transitioned from Level III to Level IV (mainly in Wenquan County), representing the largest degradation area (29.99% of total area). - 1,356.53 km² improved from Level V to Level IV (concentrated in Mangding and Tuotuo townships). - Overall, degraded area (5,512.82 km²) exceeded improved area (1,819.73 km²), indicating worsening ecological security.

The spatial pattern showed strong regional characteristics: low-value areas in eastern desert regions, high-value areas in central oases and lake regions, with fewer high-value areas in mountainous river valleys.

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8. Discussion

The pressure and state subsystems showed higher security levels than the response subsystem, indicating inadequate township-level responses. The 25-indicator system, incorporating sensitive indices like NDVI and landscape metrics, effectively captured regional variations. However, Bortala' s fragile arid ecosystem, combined with increasing agricultural water use and cropland expansion, posed significant challenges.

Key findings: 1. **Water resource constraints**: Limited water data (only water network density and irrigation ratio) hindered quantitative analysis of upstream agricultural impacts on downstream ecosystems. Most water originates from glacier melt; increased agricultural water consumption in upstream areas is the primary cause of downstream ecological degradation. 2. **Desert tourism development**: The Mutar Desert and Dandagai Desert tourism zones offer economic opportunities while controlling desert expansion, representing a sustainable development strategy. 3. **Policy effectiveness**: Administrative centers showed better ecological security due to higher urbanization, technology levels, and policy implementation efficiency. Non-administrative centers need improved policy execution and resource allocation. 4. **Indicator sensitivity**: NDVI, landscape fragmentation, and land use type effectively reflected ecosystem degradation, with decreasing NDVI and Shannon diversity and increasing fragmentation indicating deteriorating conditions.

The P-S-R framework proved effective for township-scale assessment, though indicator refinement is needed due to data acquisition limitations at this scale.

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9. Conclusions

1. Most Bortala townships were at critical security levels (Level III) in 2011, with Xiao Yingpan Town, Angrige Township, and Chagantunge Township reaching relatively safe levels (Level II), while Tuotuo Township was relatively unsafe (Level IV).
2. From 2011-2014, only Bole City' s urban street, Bailinghari Modong Township, and Bogdaer Town showed improvement; other townships deteriorated. Degraded areas primarily suffered from poor vegetation growth and inadequate human response measures.
3. Spatial distribution was distinctly regional: low-value areas clustered in eastern desert regions with simple ecosystems; high-value areas concentrated in oases and lake regions. This pattern reflects the fragile ecological structure of arid regions.
4. The evaluation objectively reflected Bortala' s land ecological security changes, demonstrating the feasibility of the P-S-R indicator system at the township scale. Results provide theoretical guidance for coordinated ecological protection and sustainable development.

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