Ecological Security Assessment of Coastal Saline-Alkali Land in Hebei (Postprint)

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Abstract

Coastal saline-alkali lands exhibit severe salinization and possess fragile land ecological environments. Understanding the land ecological security status of coastal saline-alkali zones and investigating their driving mechanisms can provide a scientific basis for land structure adjustment and land function enhancement in these regions. This study selects Huanghua City, Hebei Province as the research area, and based on land use types, designs a classification standard for Land Use Ecological Security (LUES) in Huanghua City. LUES values for the study period were calculated, the land use ecological security status of Huanghua City was elucidated, and the key land use types exerting primary influences were identified. Building upon this foundation, utilizing TM remote sensing imagery data and socioeconomic data from 2000 to 2010, and employing the Erdas, ArcGIS, and Fragstats software platforms, 16 indicators including LUES were selected to construct a P-S-R land ecological security assessment model for Huanghua City, thereby exploring the land ecological security status of Huanghua City. The results indicate: (1) During 2000–2010, LUES values in Huanghua City ranged from 0.458 to 0.466, with land use ecological security existing in a critical safety state; areas of construction land, salt pans, and severely saline-alkali land should be controlled; (2) The improvement in land use ecological security in Huanghua City was primarily attributable to reduced soil salinization; the positive ecological effects resulting from decreased areas of moderately and severely saline-alkali land and increased area of lightly saline-alkali land exceeded the negative ecological effects caused by increased construction land area, representing the main reason for LUES improvement; (3) The Land Ecological Security Index (LESI) in Huanghua City demonstrated a year-by-year upward trend, with the security status improving from relatively unsafe in 2000 (LESI of 0.431) to relatively safe in 2010 (LESI of 0.666); (4) The Pressure index (P) decreased annually, while the Response index (R) increased annually; in 2010, the Response index contributed most significantly to LESI,

with a contribution rate of 45.3%, demonstrating that anthropogenic measures mitigated land ecological risk. The findings of this study can provide a scientific basis for land ecological utilization in Huanghua City.

Full Text

Evaluation of Ecological Security of Coastal Saline Land in Hebei

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Abstract: Severe soil salinization and fragile ecological environments characterize coastal saline land. Analyzing the state of ecological security in coastal saline areas and exploring its driving mechanisms provides a basis for structural land adjustment and functional land improvement. This study developed a classification standard for Land Use Ecological Security (LUES) in Huanghua City, Hebei Province, based on land use types. LUES values were calculated for the study period to clarify the land use ecological security status and identify key land use types. Using TM remote sensing imagery and socio-economic data from 2000–2010, and employing Erdas, ArcGIS, and Fragstats platforms, we selected 16 indicators (including LUES) to construct a P-S-R (Pressure-State-Response) land ecological security evaluation model for Huanghua City. Results showed: (1) LUES values ranged from 0.458–0.466 during 2000–2010, indicating a critical security state, requiring control of construction land, salt fields, and heavily saline land areas; (2) LUES improvement primarily resulted from reduced soil salinization, where positive ecological effects from decreased moderate and severe saline land and increased light saline land exceeded negative effects from construction land expansion; (3) The Land Ecological Security Index (LESI) increased annually, improving from less secure (LESI = 0.431) in 2000 to secure (LESI = 0.666) in 2010; (4) The pressure index (P) decreased annually while the response index (R) increased, with R contributing most to LESI in 2010 (45.3%), demonstrating that anthropogenic measures reduced land ecological risk. These results provide a scientific basis for ecological land utilization in Huanghua City.

Keywords: Land ecological security; P-S-R model; Ecological security of land use; Coastal saline land; Huanghua City

Introduction

The concept of ecological security emerged in the 1980s, with Chinese research beginning in the late 1990s, emphasizing ecosystem sustainability. International research focuses on ecological health, GMO risks, ecological invasion, environmental pollution, and food safety, typically at global or national scales. Domestic studies emphasize ecological health diagnosis and ecological risk assessment, employing diverse methods including P-S-R models, attribute recognition models, and landscape analysis. The P-S-R framework, which illustrates human-environment interactions from a socio-economic and environmental unity perspective, provides a logical foundation for indicator construction and is widely applied.

Land systems, as essential habitats for human survival, face increasing problems of irrational land use structure and deteriorating ecological environments. With the Global Land Project (GLP) initiative, land system ecological security has attracted significant scholarly attention. Researchers have applied principal component analysis to assess land ecological security in Harbin and constructed "natural-social-economic" indicator systems for Jinan. The P-S-R model's ability to demonstrate human-environment interactions has led to its widespread adoption and modification for land ecological security evaluation.

Land use structure and function constitute the basic elements of land systems, with structure determining function and being closely related to human activities. Integrating land use and ecological security analysis can reveal regional security status and driving mechanisms. Previous studies have evaluated ecological security at the pixel scale in the Huangfuchuan watershed, analyzed spatiotemporal land use changes in Jining using an improved TOPSIS model, and assessed ecological security in the Tumen River region using the P-S-R framework with land use types as indicators.

The eastern coastal region of Hebei represents an ecologically fragile zone at the land-water interface, characterized by shallow groundwater, severe soil salinization, sparse vegetation, and aquaculture impacts on water environments. This study focuses on Huanghua City in the Hebei coastal zone, designing an LUES classification standard based on land use types, calculating LUES values, and incorporating them into a P-S-R model to evaluate land ecological security dynamics and provide a reliable basis for ecological security management in coastal saline areas.

1. Materials and Methods

1.1 Study Area

Huanghua City is located on the western coast of Bohai Bay in southeastern Hebei Province (117°05 –117°40 E, 38°09 –38°39 N), covering 221,900 hm². The area features marine depositional plains with flat terrain at 1–7.5 m elevation and muddy coastlines formed through marine transgression and regression. Groundwater quality is poor, with mineralization exceeding 3 $g \cdot L^{-1}$ in most areas, exhibiting Cl-Na or Cl-Na · Mg hydrochemical types. Soils are impoverished with high salinization (exceeding 3% in some areas). Six soil types exist: clayey loam, loamy, sandy loam, chloride-salinized loam, coastal saline soil, and salinized swamp soil, with loam covering 88,800 hm^2 as the primary agricultural soil type.

1.2 Data Sources and Processing

1.2.1 Data Sources This study utilized three-phase remote sensing data and statistical data from 2000, 2005, and 2010 (Table 1). Socio-economic statistics were obtained from the *Cangzhou Yearbook*. Remote sensing data comprised Landsat imagery (30 m spatial resolution). Image preprocessing was completed using ERDAS IMAGINE 9.2 with cubic convolution resampling, UTM projection, and WGS84 datum.

1.2.2 Remote Sensing Data Processing **Image Interpretation.** Based on China's *Current Land Use Classification Standard* and extensive field surveys, land use types were initially classified into construction land, marshland, salt fields, aquaculture water, water bodies, and agricultural land. Given Huanghua's coastal alluvial-marine plain characteristics and severe salinization, agricultural land was further subdivided into light, moderate, and severe saline land based on salinization degree, which is crucial for ecological security assessment. The classification system ultimately comprised eight types: construction land, salt fields, aquaculture water, water bodies, light saline land, moderate saline land, severe saline land, and other land. Aquaculture water was distinguished from natural water bodies by its regular square grid structure in imagery.

Spatial Analysis. Using ArcGIS 10.2, interpreted images were clipped with Huanghua's administrative boundary vector data to generate land use maps, and area statistics were calculated for each category.

1.3 Construction of the Land Ecological Security Evaluation Model

This study employed the widely used P-S-R model for land ecological security evaluation.

1.3.1 Establishment of the Evaluation Indicator System **Indicator Selection.** The P-S-R framework comprises pressure indicators (human activity loads), state indicators (ecosystem conditions), and response indicators (countermeasures). Drawing from existing research and data availability, 16 representative indicators were selected (Table 2). Landscape metrics comprehensively reflect land system security status, so edge density and contagion index were included as state indicators to represent system stability and connectivity. Edge density reflects landscape fragmentation (higher values indicate greater fragmentation), while contagion index measures patch adjacency (higher values indicate better connectivity). Land Use Ecological Security (LUES) was also included as a state indicator reflecting land use versatility and environmental impact. The system comprises three hierarchical levels: target, criterion, and indicator layers.

LUES Evaluation. Referencing relevant studies and coastal saline area characteristics, an LUES classification standard was developed based on land use types from the perspective of land use versatility, convertibility, and environmental damage (Table 3). To quantify LUES, security levels were assigned corresponding standard values ($LUES_0$) from high to low security.

The LUES calculation formula is:

$$X_{11} = \sum_{i=1}^{5} LUES_{0i} \times W_i \quad (1)$$

where $LUES_{0i}$ represents the standard value for security level i (see Table 3), and W_i is the area weight for level i, calculated as:

$$W_i = \frac{A_i}{\sum_{i=1}^{5} A_i} \quad (2)$$

where A_i is the area (hm²) of security level i.

1.3.2 Standardization of Evaluation Indicators The extremum method was used to standardize indicators to a [0,1] range:

For positive indicators:

$$Z_{ij} = \frac{X_{ij} - \min\{X_{ij}\}}{\max\{X_{ij}\} - \min\{X_{ij}\}} \quad (3)$$

For negative indicators:

$$Z_{ij} = \frac{\max\{X_{ij}\} - X_{ij}}{\max\{X_{ij}\} - \min\{X_{ij}\}} \quad (4)$$

where Z_{ij} is the normalized value, and X_{ij} is the original value of indicator j in year i.

1.3.3 Weight Determination Using Mean Square Deviation Method The mean square deviation method derives weights from actual data, offering strong objectivity. Weights reflect the relative dispersion degree of indicators—greater dispersion yields larger weights. The weight calculation formula is:

$$W_j = \frac{\sigma_j}{\sum_{j=1}^{n} \sigma_j} \quad (5)$$

where σ_j is the mean square deviation of indicator j:

$$\sigma_j = \sqrt{\frac{1}{m}\sum_{i=1}^{m}(Z_{ij} - \bar{Z}_j)^2} \quad (6)$$

Results are shown in the "Weight" column of Table 2.

1.3.4 Land Ecological Security Index Calculation and Classification
The comprehensive index method was used to calculate the Land Ecological Security Index (LESI):

$$LESI_i = \sum_{j=1}^{16} Z_{ij} \times W_j \quad (7)$$

where $LESI_i$ represents the index for year i, Z_{ij} is the standardized value, and W_j is the weight.

Based on existing research, LESI was divided into five security levels (Table 4).

2. Results

2.1 Land Use Ecological Security Assessment Based on Land Use Types

Table 5 shows LUES values of 0.458, 0.459, and 0.466 for 2000, 2005, and 2010, respectively—all indicating critical security status. This suggests problems in the current land use structure requiring control of Class IV and V lands with poor convertibility. Security Class II occupied the largest area (32.23%–38.52%) and contributed most to the composite LUES value (exceeding 50%, up to 57.9%). Temporally, Classes I and V showed annual increases, Classes II and IV decreased then increased, while Class III increased then decreased with the highest change rate reaching 47.8%.

2.2 Dynamic Land Use Changes in Huanghua City

Land use type forms the basis for ecological security evaluation. This section analyzes dynamic changes during the study period (Figure 1) to identify key land use types for targeted regulation.

During 2000–2005, construction land expansion exceeded other land reduction, increasing insecure areas. However, severe saline land reduction (13,500 hm²) far exceeded salt field increases, decreasing less secure areas. Aquaculture water and moderate saline land expansion increased critically secure areas, while light saline land (more secure) decreased and water bodies (secure) increased. Overall, construction land increased by 11,200 hm², but the negative effects were offset by severe saline land reduction, leaving LUES largely unchanged.

During 2005–2010, construction land and other land increases expanded insecure areas, while slight increases in severe saline land and salt fields expanded less secure areas. Moderate saline land reduction (30,500 hm^2) was the main reason for decreased critically secure areas. Light saline land and water body expansion increased more secure and secure areas. Overall, light saline land increase (13,700 hm^2) buffered ecological risks from insecure area expansion (9,900 hm^2), while moderate saline land reduction significantly improved LUES.

Over the entire 2000–2010 period, except for decreased less secure areas from severe saline land reduction, patterns matched the 2005–2010 period. Construction land continuously expanded, while moderate and severe saline land reduction was key to LUES improvement. With economic development and urbanization, construction land expansion reduced multi-purpose land use potential. However, scientific management of saline land as reserve cultivated land resources substantially reduced salinization in Cangzhou's coastal areas, improving ecological utilization. Overall, positive effects from salinization reduction exceeded negative effects from construction land expansion, gradually improving Huanghua's land use ecological security.

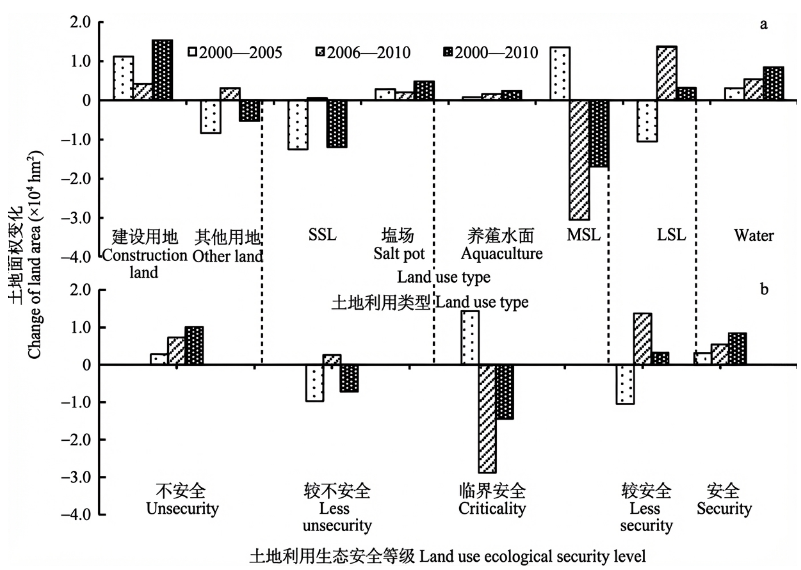

Figure 1: Figure 1

2.3 Comprehensive Land Ecological Security Evaluation Based on the P-S-R Model

Table 6 presents P-S-R model results. Overall, LESI increased annually, improving from Level IV (less secure) in 2000 to Level II (secure) in 2010. In the P-S-R framework, "Pressure" (P) represents negative impacts from human activities, "State" (S) reflects land system conditions, and "Response" (R) represents human countermeasures. In 2000, security indices ranked P > S > R; in 2005, P > R > S; and in 2010, R > S > P. This demonstrates decreasing pressure and increasing response over time, with the 2010 response index exceeding pressure, indicating growing awareness and effective measures to reduce ecological risk.

3. Conclusions and Discussion

3.1 Main Conclusions

1) During 2000–2010, Huanghua's land use ecological security remained at a critical state, requiring control of Class IV and V areas with poor convertibility. Class II land exceeded 30% of total area, contributing over 50% to LUES, with other classes contributing in descending order: III > IV > V $\approx$ I.

2) LUES improvement primarily resulted from reduced soil salinization. Positive ecological effects from decreased moderate and severe saline land and increased light saline land exceeded negative effects from construction land expansion. During 2000–2005, construction land increase was offset by severe saline land reduction. During 2005–2010, light saline land increase buffered risks from construction and severe saline land expansion, while moderate saline land reduction significantly improved security.

3) LESI increased annually, improving from Level IV (less secure, 0.431) in 2000 to Level II (secure, 0.666) in 2010. Temporally, pressure index P decreased while response index R increased, with R contributing most (45.3%) to LESI in 2010, demonstrating that anthropogenic measures reduced land ecological risk.

3.2 Discussion

3.2.1 Incorporating Ecosystem Service Values to Improve the P-S-R Indicator System This study subdivided saline land into three classes and combined them with five other land use types to create eight categories with corresponding security levels, quantifying LUES as an indicator in the P-S-R model. However, agricultural land was only divided by salinization degree without distinguishing cultivated land, orchards, and forests, which have different ecological functions regarding vegetation cover and water retention. Ecosystem service value quantifies ecological well-being provided to humans. Future research should incorporate ecosystem service values as state indicators to improve P-S-R model comprehensiveness. He et al. calculated Huanghua's ecological security baseline using ecosystem service values, projecting a 4.244 billion yuan baseline by 2081. However, ecosystem services alone cannot quantify negative human impacts or positive restoration effects, necessitating integration with the P-S-R framework for more scientific assessment.

3.2.2 Enhancing Land Ecological Security Through Land Use Pattern Optimization This analysis indicates that Huanghua's security improvement mainly resulted from reduced moderate and severe saline land areas. Located on the Bohai Bay coast with shallow, saline groundwater, Huanghua experiences severe salinization. Engineering measures like open ditch drainage and subsurface pipe installation have lowered groundwater tables and reduced salinization, but coastal location constraints make complete desalinization unlikely. Therefore, future security improvements should focus on efficient utilization of saline groundwater and precipitation resources to increase vegetation cover, land use efficiency, and crop yields. Niu et al. summarized agricultural regulation techniques for safe saline water use, Zhang et al. studied multi-source water utilization mechanisms in the Bohai low plain, and Kong et al. demonstrated that mixed irrigation with diverted water and shallow groundwater significantly improves saline-fresh water use efficiency. These studies provide technical references for optimizing Huanghua's land use pattern through water-land coupling to enhance ecological security.

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