Spatio-temporal Evolution of Ecological Vulnerability in Urban Fringe Areas: A Case Study of Ganjingzi District, Dalian City (Postprint)

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Abstract

Based on multi-source data including 1998 land use data and SPOT5 remote sensing data from 2003, 2007, and 2013, this study employed the ESC model combined with spatial analysis and linear weighting methods to calculate community EVI values, classifying the ecological vulnerability of Ganjingzi District into five levels. Additionally, utilizing least squares algorithm to compute change slopes and F-values to assess change significance, both metrics were categorized into four levels to investigate the spatiotemporal differentiation of ecological vulnerability in Dalian' s Ganjingzi District from 1998 to 2013. The results indicate: (1) From the perspective of distribution characteristics of ecological vulnerability levels in urban fringe areas, the ecological environment exhibits clustering of identical levels, with communities adjacent to Shahekou District serving as the center, where neighboring levels display a pronounced radial pattern with distinct east-west disparities. (2) From the viewpoint of inter-community differences in ecological vulnerability, significant disparities exist in ecological status among communities within Ganjingzi. Communities proximal to the urban center experienced pronounced ecological vulnerability changes with rapid environmental degradation, as evidenced by average EVI increasing from 0.62 to 0.73 and a change significance index of 2.26. Certain communities distant from the urban center exhibited minimal environmental change, maintaining favorable ecological conditions. Some communities displayed negative EVI change values, indicating gradual ecological recovery. (3) Regarding the overall trend of ecological vulnerability changes in urban fringe areas, the ecological vulnerability variations in Ganjingzi District from 1998-2013 were closely associated with urbanization development rate. With 2007 as the turning point, the average change slope index was 0.51 for 1998-2007 and 0.19 for 2007-2013, manifesting a decreasing trend that was initially rapid and subsequently gradual.

Full Text

Spatio-Temporal Evolution of Ecological Vulnerability in Urban Fringe Areas: A Case Study of Ganjingzi District, Dalian

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Abstract: Based on land use data from 1998 and SPOT5 remote sensing data from 2003, 2007, and 2013, this study calculated the Ecological Vulnerability Index (EVI) for communities in Ganjingzi District using the Exposure-Susceptibility-Coping Capacity (ESC) model combined with spatial analysis and linear weighting. The ecological vulnerability of the Ganjingzi area was classified into five grades. To establish the evaluation index system, the change slope was calculated using the least squares method. When values were significant, both the change slope and significance were divided into four grades. The spatio-temporal distribution of ecological fragility in Ganjingzi District from 1998 to 2013 was also analyzed. The results were as follows: (1) From the perspective of distribution characteristics of ecological vulnerability grades in urban fringe areas, the ecological environment showed aggregation of the same vulnerability levels, with communities adjacent to Shahekou District exhibiting a distinct radial pattern and obvious differences between east and west. (2) From the perspective of inter-community differences in ecological vulnerability, communities within Ganjingzi District showed significant variation in ecological status. Communities adjacent to urban areas experienced remarkable increases in ecological vulnerability, with rapidly deteriorating environments (mean EVI increased from 0.62 to 0.73, change index 2.26). Communities distant from urban areas showed little change and maintained good ecological conditions, while some communities exhibited negative growth in EVI values, indicating gradual ecological recovery. (3) From the overall trend of ecological vulnerability change in urban fringe areas, changes in Ganjingzi District between 1998 and 2013 were closely related to urbanization speed. With 2007 as the inflection point, the average change slope index was 0.51 during 1998–2007 and 0.19 during 2007–2013, showing a trend of rapid decline followed by slowdown.

Keywords: Exposure-Susceptibility-Coping Capacity (ESC); urban fringe area; ecological vulnerability; Dalian City

1. Introduction

Ecological vulnerability represents a core issue in global environmental change and sustainable development research [1-2]. As studies on global environmental change impacts intensify, particularly regarding human-environment relationships, research on ecological vulnerability, assessment methods, and restoration of damaged ecosystems has gradually become a global hotspot, with expanding content and increasingly comprehensive, interdisciplinary applications [3-5]. With rapid socioeconomic development, urban ecological problems have become increasingly severe, making urban ecological vulnerability research a prominent concern [1]. Scholars have conducted numerous studies on ecological vulnerability [6-8], focusing on special geographical and geomorphological environments [9-13], mining cities [14-16], and agricultural cities [17]. These studies examine short-term regional ecological vulnerability changes by establishing evaluation index systems [10-11, 18-19] and employing various analytical methods to investigate formation mechanisms and change characteristics of urban ecological vulnerability [8, 21-24].

As urban ecological research deepens, rapid urbanization has led to expanding urban populations and land use into fringe areas, challenging the ecological environment of these regions [3, 16]. Research on ecological problems in urban fringe areas has gradually become popular, with literature reviews providing theoretical support for environmental protection and ecological construction [25-27]. However, current research on ecological vulnerability in urban fringe areas lacks dynamic analysis of spatial differentiation based on internal spatial units using Geographic Information Systems, as well as quantitative spatio-temporal differentiation studies. This study examines a rapidly urbanizing coastal city’ s fringe area, using multi-year time series data to reveal characteristics of urban ecological vulnerability under rapid urbanization.

Urban fringe areas represent transitional zones between urban and rural areas, where conflicts between urban development and resource environmental protection are prominent. As hinterlands for urban development, these areas face different ecological problems due to their unique characteristics and urban development stages. Scientific and rational planning of ecological environment construction in urban fringe areas holds important practical significance for urban development. Dalian, as a rapidly developing coastal city, faces geographical constraints from its peninsular environment with numerous hills and limited plains. Urban land expansion has gradually extended to fringe areas, creating representative ecological problems. This study uses the community scale as the ecological evaluation unit, selecting Ganjingzi District—where Dalian’ s urbanization has developed rapidly—and employs linear weighted comprehensive evaluation methods [28] combined with the ESC (Exposure-Susceptibility-Coping Capacity) model to calculate EVI (Ecological Vulnerability Index). The study uses change slope methods to simulate interannual variations in ecological vulnerability, regressing EVI values against time to calculate change slopes and F-values to measure significance [19], analyzing spatial distribution patterns of ecological vulnerability change significance and differences among communities in Ganjingzi District.

2. Study Area

Ganjingzi District (38°47 -39°07 N, 121°16 -121°45 E) is located in central Dalian, bordering Jinzhou District to the northeast, adjacent to Shahekou District, and connected to Lüshunkou District to the southwest. The district covers 502 km² and comprises multiple communities, serving as Dalian' s urban-rural integration zone and primary area for urban expansion. Its special geographical location makes Ganjingzi District' s urbanization and ecological vulnerability issues representative of Dalian' s overall urbanization process, giving this research practical significance.

3. Data Sources and Processing

The study utilized diverse data including land use data, SPOT5 remote sensing imagery (2.5 m resolution) from 2003, 2007, and 2013, and socio-ecological environmental data from the Ganjingzi Statistical Yearbook.

Table 1 Data sources and description

Data Type	Source	Processing Description
Land use data	Dalian Land Bureau	Land use/cover current situation
SPOT5 imagery	Geographic Spatial Data Cloud	Human activities interference intensity
Water resources	Ganjingzi Statistical Yearbook	Water resources condition
DEM	Digital Elevation Model	Topographic condition extraction
Industrial data	Dalian Statistical Yearbook	Secondary industry proportion
Environmental data	Ganjingzi Statistical Yearbook	Compliance rates for wastewater, 废气, and solid waste

4. Ecological Vulnerability Assessment Methods

Based on previous research and expert consultation, this study processed data using ArcGIS and established an evaluation index system. The ESC assessment framework was combined with linear weighted comprehensive evaluation to calculate EVI. Least squares algorithm analyzed change slopes of ecological vulnerability indices, while F-values measured significance indices.

[Figure 2: see original paper]

Figure 2 Technology roadmap

4.1 ESC Model Framework The ESC model decomposes ecological vulnerability into three components: exposure, susceptibility, and coping capacity, each with distinct connotations and representations [8, 30]. Rapid urbanization changes various elements in urban ecosystems. Since evaluation indicators may overlap and excessive indicators increase analytical complexity, and different indicators respond differently to ecological vulnerability, this study introduced weight values to calculate EVI, yielding more realistic results. Using Yaahp Version software for weight calculation, the study obtained weight values for each indicator.

4.2 Data Standardization As measurement units varied across indicators, original data required standardization. Considering that positive and negative indicators differently impact ecological vulnerability, different standardization methods were applied. Range standardization processed positive and negative indicators, while fuzzy membership functions handled moderate indicators [21].

For positive/negative indicators:

$$X_{ij} = \frac{x_{ij} - x_{min}}{x_{max} - x_{min}}$$

For moderate indicators:

$$X_{ij} = \begin{cases} \frac{x_{ij}-\lambda_j}{x_{max}-\lambda_j} & \text{if } x_{ij} \geq \lambda_j \\ \frac{\lambda_j-x_{ij}}{\lambda_j-x_{min}} & \text{if } x_{ij} < \lambda_j \end{cases}$$

Where x_{ij} is the original vulnerability indicator data, x_{min} and x_{max} are minimum and maximum values, and λ_j is the moderate value.

4.3 EVI Calculation and Classification Ecosystem vulnerability assessment requires integrated evaluation. Using linear weighting:

$$EVI = \sum_{i=1}^{n} W_i \times I_i$$

Where W_i is the weight of evaluation indicator i and I_i is the standardized value.

Table 2 Ecological vulnerability evaluation index system based on ESC framework

Factor Level	Weight	Target Level	Weight	Indicator Level	Property	Weight
Exposure	0.424	Population/industry distribution	0.054	Population density	+	0.138
		Human activity interference intensity	0.120	Wastewater discharge per unit	+	0.181
		Climate condition	0.067	废气 emission per unit	+	0.084
Susceptibility	0.247	Land use/cover status	0.162	Solid waste per unit	+	0.194
		Water resources condition	0.043	Annual precipitation	+	0.033
		Topographic condition	0.034	Green space coverage	-	0.042
Coping Capacity	0.329	Socio-economic development level	0.062	Construction land proportion	+	0.064
		Environmental protection/ecological construction willingness and ability	0.053	Cultivated land proportion	+	0.048

Note: "+" indicates positive correlation, "-" indicates negative correlation, "*" indicates moderate indicators.

Referencing existing ecological vulnerability evaluation standards [8, 31] and considering local conditions, Ganjingzi District' s ecological vulnerability was classified into five grades:

Table 3 Urban ecological vulnerability state evaluation standards

Vulnerability Level	EVI Range
Good ecology	EVI 0.35
Slight vulnerability	0.35 < EVI 0.50
Medium vulnerability	0.50 < EVI 0.65

Vulnerability Level	EVI Range
Intensity vulnerability	0.65 < EVI 0.80
Ultimate vulnerability	EVI > 0.80

4.4 Change Slope Analysis Change slope method regresses time-series variables to predict trends. Using least squares, EVI values were regressed against time for each community. The slope calculation formula:

$$\text{slope} = \frac{n\sum_{i=1}^{n}(i \times EVI_i) - \sum_{i=1}^{n} i \sum_{i=1}^{n} EVI_i}{n\sum_{i=1}^{n} i^2 - (\sum_{i=1}^{n} i)^2}$$

Where n is the number of years and EVI_i is the index value for year i.

Based on calculated slopes and referencing relevant research [19], slopes were classified into four grades:

Table 4 Change slope classification evaluation standard

Slope Grade	Slope Index
Slight change	< 0.15
Medium change	0.15 slope < 0.30
Significant change	0.30 slope < 0.45
Rapid change	0.45 slope < 0.60

4.5 Significance Testing F-test assessed change significance:

$$F = \frac{U/1}{Q/(n-2)}$$

Where U is regression sum of squares and Q is error sum of squares. Based on F-values, change significance was classified:

Table 5 Change significance grading evaluation standards

Significance Level	F Index
No significant change	< 0.15
Slight deterioration	0.15 < F 0.20
Medium deterioration	0.20 < F 0.25
Significant deterioration	0.25 < F 0.30

5. Results and Analysis

5.1 Spatial Distribution Evolution of Ecological Vulnerability Calculated community EVI values and vulnerability grades revealed that Ganjingzi communities exhibited characteristics of small-scale aggregation of same grades and interspersion of adjacent grades. Ecologically good areas were mainly distributed in western forest parks, theme parks, and northern golf clubs. Slight vulnerability communities were relatively dispersed, concentrating in central Ganjingzi. Intense vulnerability areas were centrally distributed in communities near Shahekou District in central Ganjingzi.

[Figure 3: see original paper]

Figure 3 Urban ecological vulnerability grade distribution map, 1998–2013

[Figure 4: see original paper]

Figure 4 Community urban ecological vulnerability discrepancy distribution map, 1998–2013

5.2 Inter-Community Differences From a community perspective, Ganjingzi' s internal communities showed significant differences in ecological status. Communities near urban areas experienced remarkable ecological vulnerability changes, with rapid environmental deterioration. The mean EVI increased from 0.62 to 0.73, with a change significance index of 2.26. Communities distant from urban areas showed little environmental change and maintained good conditions. Some communities exhibited negative EVI growth, indicating gradual ecological recovery.

Between 1998–2013, Ganjingzi' s average ecological vulnerability index showed a "rapid then slow" increasing trend: 0.2645 in 1998, 0.425 in 2007, and 0.6136 in 2013. The ecological state shifted from primarily "good" to primarily "medium vulnerability," indicating transition from low-exposure, high-adaptability states to high-exposure, low-adaptability states. This situation has gradually been alleviated and controlled.

Community-level changes showed different characteristics. During 1998–2003, inter-community ecological vulnerability differences remained at nearly unchanged levels (maximum difference: 0.1201). During 2003–2007, differences increased (maximum: 0.150887), with rapid deterioration in some communities. During 2007–2013, the number and scope of communities with negative growth (ecological recovery) gradually decreased.

[Figure 5: see original paper]

Figure 5 Urban ecological vulnerability index change distribution map, 1998–2013

5.3 Change Trend Analysis Integrating multi-year community EVI data through change slope models revealed spatial patterns of ecological vulnerability change in Ganjingzi. The highest slope value was 0.0122, average slope was 0.0443, and the lowest was 0.0976. Western and southwestern communities showed negative slopes (ecological improvement), while central and eastern communities showed positive slopes (rapid deterioration).

Significance analysis showed that northwestern and central communities had no significant change, while southwestern ecologically good areas and central-eastern highly vulnerable areas showed significant changes during 1998–2013.

[Figure 6: see original paper]

Figure 6 Urban ecological vulnerability change slope map

[Figure 7: see original paper]

Figure 7 Urban ecological vulnerability change significance map

6. Conclusions

Based on urban ecological vulnerability theory, this study combined linear weighting to evaluate community-level ecological vulnerability and used change slope methods to simulate interannual variations. Taking Ganjingzi District as an example, the ESC framework was adapted to local conditions to calculate change slopes and analyze spatio-temporal patterns.

1. **Spatial distribution characteristics:** Urban fringe ecological environments showed same-grade aggregation, with communities near Shahekou District displaying radial patterns of adjacent grades. Western areas maintained good ecological states, while east-west differences were pronounced, with eastern areas showing intense vulnerability.

2. **Inter-community differences:** Ganjingzi' s communities exhibited significant vulnerability variation. Urban-adjacent communities showed remarkable vulnerability increases and rapid environmental deterioration, while distant communities maintained stable, good conditions. Some communities showed negative EVI growth, indicating ecological recovery.

3. **Overall trends:** Changes in Ganjingzi' s ecological vulnerability (1998–2013) closely correlated with urbanization speed, showing a rapid-then-slow decline trend. Change slope and significance values reflected spatial characteristics of ecological conditions during 1998–2013, with southwestern communities gradually improving while most others deteriorated.

7. Discussion

This study examined urban fringe ecological vulnerability at the community scale during urbanization, aiming to provide insights for Dalian' s development and ecological improvement. However, data for environmental protection investment and education investment were difficult to obtain, requiring proxy data that may affect accuracy. Future research should focus on ecological state prediction and protection recommendations.

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