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Ecological Vulnerability Assessment of the Changjitu Region

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Abstract: To safeguard the ecological security of the Changjitu Pilot Zone (a core cross-border cooperation area in Northeast Asia) and address ecological stress from industrialization, urbanization, and agricultural intensification, this study assessed its ecological vulnerability. Using 2009 (Strategy launch year) and 2019 as time nodes, six environmental variables (NDVI, NDWI, LC, Slope, Surface Runoff, Sub-basin) from Landsat and ASTER GDEM data were selected. An Ecological Index (EI) was built via GIS overlay analysis, with the 5km-radius average EI used to classify areas into five categories (fragile to high-quality). Results showed: areas below the ecological red line (≤0.6) dropped from 40% to 25%, high-quality areas doubled (0.04%→0.08%); fragile areas concentrated in Changchun/Jilin urban centers (>30% of urban area); Nong'an, Dehui, Dunhua, and Hunchun improved significantly; natural deterioration (2.25% of total area) near Changbai Mountains linked to 2019 humidity decline. This study clarifies the "structure-function-stress" mechanism, providing a basis for territorial space optimization and cross-border ecological security in Northeast Asia.

Keywords: Changjitu Region; Ecological Vulnerability Assessment; GIS/RS Technology; Ecological Index (EI).

1. Introduction

As a pilot zone for cross-border cooperative development and opening-up in Northeast Asia and a core growth pole for the revitalization of Northeast China, the Changjitu Region features a complex geographical pattern of "mountain-plain-wetland-river valley". It undertakes key ecological functions such as water conservation in the Changbai Mountains, black soil conservation in the Songliao Plain, and connectivity of cross-border wetlands in the Tumen River Basin. Thus, ecological security is crucial for the implementation of regional strategies [1-3]. Currently, the overlapping of regional industrialization (automotive/chemical industry), urbanization (with an annual growth rate of 1.2%), and agricultural intensification has led to a 23% increase in the area of construction land from 2010 to 2020, making it urgent to accurately identify the core of ecological issues [4].

Most existing studies are limited to the assessment of single ecological elements. Ground-based monitoring results in incomplete spatial coverage, and Geographic Information System (GIS)/Remote Sensing (RS) technologies only remain at the stage of data visualization, failing to achieve multi-source data assimilation and spatial correlation analysis of stress-effects. This makes it difficult to support systematic management and control [5-8]. Relying on the advantages of GIS spatial analysis and dynamic simulation, this study aims to clarify the coupling mechanism of "structure-function-stress" in the complex ecosystem. It provides precise spatial decision-making basis for the optimization of regional territorial space development and the protection of cross-border ecological security in Northeast Asia, directly serving the sustainable development of the pilot zone and the ecological security of border areas.

2. Study Area

The full name of the Changjitu Region is the Changjitu Pilot Zone for Development and Opening-up. It is located in the eastern part of Northeast China and the central-eastern part of Jilin Province, with geographical coordinates ranging from 124°00′ to 131°19′ E longitude and 42°06′ to 46°40′ N latitude. Centered on the two cities of Changchun and Jilin, the region extends eastward along the Tumen River Basin. It covers the urban areas of Changchun and Jilin, 9 counties/cities (including Yanji, Tumen, Dunhua, etc.) in Yanbian Korean Autonomous Prefecture, and the Changbai Mountain Protection and Development Zone, with a total area of approximately 33,000 km^2. It is an important gateway for China's opening-up to Northeast Asia [9].

The terrain presents a gradient distribution of "low in the west and high in the east". The western part is the eastern section of the Songliao Plain, with an altitude of 150-280 m. It has a flat and open terrain, dominated by chernozem and meadow soil with deep soil layers. The eastern part is a mountainous and hilly area, belonging to the branch of the Changbai Mountain system, including Laoye Ridge, Zhangguangcai Ridge, and Haerba Ridge. The altitude ranges from 500 to 1200 m, with the highest point (Mudan Peak) reaching 1638 meters. The mountains mainly extend in the northeast-southwest direction, with large topographic undulations, forming diverse microhabitats.

3. Data and Methods

To obtain an objective assessment result of the ecological environment in the Changjitu Region, this study set six objective environmental variables. These include the Normalized Difference Vegetation Index (NDVI) representing vegetation growth status, the Normalized Difference Water Index (NDWI) representing environmental humidity, Land Cover (LC) representing human activities, Slope (Sl) representing topographic factors, Surface Runoff (Str) representing hydrological characteristics, and Sub-basin (Sb) also representing hydrological characteristics. The simplified operation process is shown in Fig. 1.

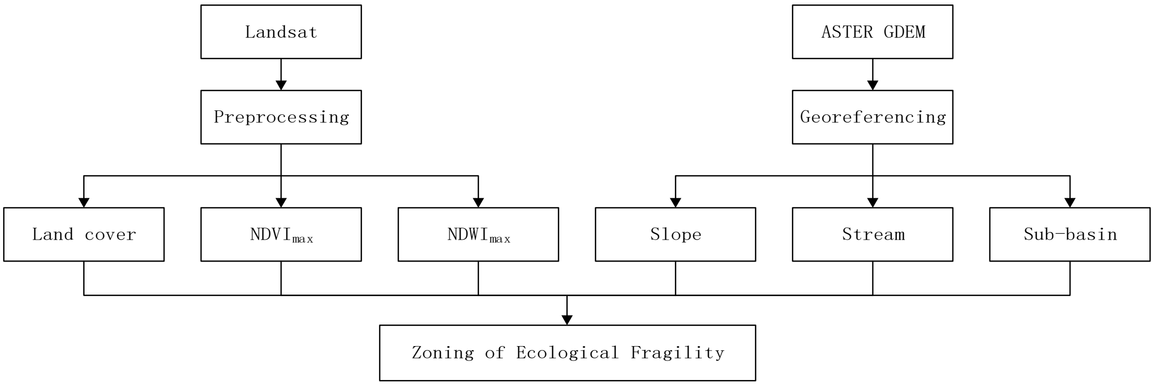

Fig 1. Ecological Assessment Process

In this study, the overlay analysis method of GIS was used to combine the six factors as ecological environment variables into an evaluation equation for assessing the ecological environment of the Changjitu Region. Among them, Slope, Surface Runoff, and Sub-basin were calculated using ASTER Global Digital Elevation Model (GDEM) data (a typical RS-derived geospatial dataset).

Among the six environmental factors, Land Cover, NDVI, and NDWI were all obtained through the analysis of Landsat series satellite remote sensing data. However, these three factors are greatly affected by human activities and change significantly over a certain time span. Meanwhile, to capture the changes in the ecological environment of the Changjitu Region, the research team collected 244 annual scenes of Landsat 7 ETM+ remote sensing images in 2009 (the official launch year of the Changjitu Strategy) and 270 annual scenes of Landsat 8 OLI remote sensing images in 2019 for analysis. Landsat 7 ETM+ and Landsat 8 OLI data have basically the same parameters, both being visible - near - infrared - medium - infrared remote sensing observation images with a 30-meter spatial resolution. The overall accuracy of the 2009 classification results was 86.91%, and the Kappa coefficient was 0.84.

3.1. Calculation of Ecological Index Data

1. NDVI

As an important component of the ecological environment, vegetation is widely discussed in ecological environment assessment. NDVI is calculated using the red edge effect of vegetation spectral reflectance (Equation 1, where ρ_{NIR} is the near-infrared spectral reflectance and ρ_R is the red band spectral reflectance). Before formal calculation, radiometric calibration was performed on the downloaded Landsat remote sensing images to restore the spectral reflectance in each band. NDVI can well indicate the growth status of vegetation.

$$NDVI = \frac{\rho_{NIR}-\rho_R}{\rho_{NIR}+\rho_R} \quad (1)$$

In addition, to reduce the impact of clouds on the calculation results and minimize the differences in vegetation growth status across different seasons (time), this study used the annual maximum NDVI values (denoted as $NDVI_{max}$) of 2009 and 2019 as the final indicators for ecological environment assessment.

There are slight differences in the wavelengths of the same bands between ETM+ and OLI, resulting in different reflectances of the same ground objects in the two RS sensors. To ensure the comparability of results between 2009 and 2019, a normalization process was performed on the $NDVI_{max}$ data of the two years before the evaluation modeling.

2. NDWI

This study adopted the NDWI calculation method proposed by Gao (1995) [10] (Equation 2, where ρ_{NIR} and ρ_{MIR} are the near-infrared reflectance and medium-infrared reflectance, respectively, which can be obtained through radiometric correction of the downloaded remote sensing images).

$$NDWI = \frac{\rho_{NIR}-\rho_{MIR}}{\rho_{NIR}+\rho_{MIR}} \quad (2)$$

The NDWI calculated by this equation is not only sensitive to water bodies but also highly sensitive to the water content of vegetation. Considering that the degree of vegetation dryness is closely related to soil water content and even environmental humidity, this study used this data as an indicator for evaluating environmental humidity. Consistent with the use of the NDVI indicator, the annual maximum NDWI values (denoted as $NDWI_{max}$) of the two years were extracted as variables for evaluation, and a normalization process was conducted on $NDWI_{max}$ to facilitate the comparison of results between the two years.

3.2. Estimation of the Impact of Surface Hydrological Environment

A sub-basin refers to a runoff-converging area surrounded by water divides. To assess the impact of surface hydrological characteristics on the ecosystem, this study conducted analysis with sub-basins as the basic unit. The impact of the surface hydrological structure in the Changjitu Region was evaluated based on the distribution of distances from surface runoff within each sub-basin.

Using the hydrological analysis tools in ArcMap 10.5 (a professional GIS software platform), and based on DEM data, surface water runoff and sub-basins were extracted step by step in the order of "data filling → flow direction calculation → confluence calculation → river network extraction → sub-basin calculation". Evaluation weights were set according to the conditions of distances from surface runoff within each sub-basin: 200m, 500m, 1000m, 2000m, and more than 2000m.

3.3. Ecological Environment Characterization and Vulnerability Assessment

3.3.1. Ecological Environment Characterization

This study established an ecological environment characterization function (denoted as EI) using six objective environmental factors, which were integrated into five calculation indicators: vegetation growth status ($NDVI_{max}$), environmental humidity ($NDWI_{max}$), human impact (LC), topographic factor (Sl), and hydrological characteristics (Str & Sb).

$$EI = f(NDVI_{max}, NDWI_{max}, LC, Sl, (Str \& Sb)) \quad (3)$$

In Equation 3, $NDVI_{max}$ and $NDWI_{max}$ were normalized before the function calculation. Meanwhile, to unify the calculation dimensions, the evaluation results of the three indicators (LC, Sl, and Str & Sb) were also normalized.

In addition, the weight setting for the three indicators in the evaluation process was as follows:

1. For LC: Buffers were created based on distances from water bodies (200m, 500m, 1000m, 2000m, and more than 2000m), with weights set from high to low as the distance increases. Then, evaluations were conducted in sequence according to the water-loving order of vegetation within different distance ranges from water bodies. The weights in descending order were: "water body + forest cover", "water body + wetland cover", "water body + grassland cover", forest cover, wetland cover, grassland cover, water body cover, cultivated land cover, artificial surface cover, and bare land cover.

2. For the Sl indicator: Weights were set from high to low as the slope increases.

3. For the Str & Sb indicators: Weights were set from high to low as the distance from runoff within each sub-basin decreases.

Considering that the five indicators are equally important in the ecological environment, equal weights were assigned to each of the five indicators in the weighted calculation of the function, with each given a weight of "0.2".

3.3.2. Vulnerability Assessment

The EI values calculated through the above process range between [0, 1]. Since the EI values are composed of objective environmental factors, they have a certain indicative effect on the ecological environment of the locations corresponding to the pixel points. To evaluate the ecological vulnerability of the Changjitu Region, this study used the average value of the Ecological Index (EI) within a 5km evaluation radius as the indicator for statistics.

Based on the statistical results, the areas where the statistical EI value within 5 km was lower than "0.6" were defined as the red line for ecological vulnerability (areas with EI < 0.6 were classified as ecologically vulnerable areas, and areas with EI > 0.6 were classified as ecological areas). The ecologically vulnerable areas were further subdivided into fragile areas and risk areas, while the ecological areas were subdivided into qualified areas, good areas, and high-quality areas. The classification criteria are as follows:

1. Ecologically fragile areas: "EI average/25km²" ≤ 0.5
2. Ecological risk areas: 0.5 < "EI average/25km²" ≤ 0.6
3. Ecological qualified areas: 0.6 < "EI average/25km²" ≤ 0.7
4. Ecological good areas: 0.7 < "EI average/25km²" ≤ 0.8
5. Ecological high-quality areas: "EI average/25km²" > 0.8

4. Results and Discussion

4.1. Ecological Vulnerability Assessment of the Changjitu Region

At the initial stage of the implementation of the Changjitu Plan Outline, the spatial distribution of the ecological environment is shown in Fig. 2. The area below the ecological red line accounted for approximately 40% of the total area of the Changjitu Region. The western and southeastern ends of the region faced severe ecological vulnerability, especially the western part, where most of the "fragile areas" were distributed. In contrast, the central region had a better ecological environment.

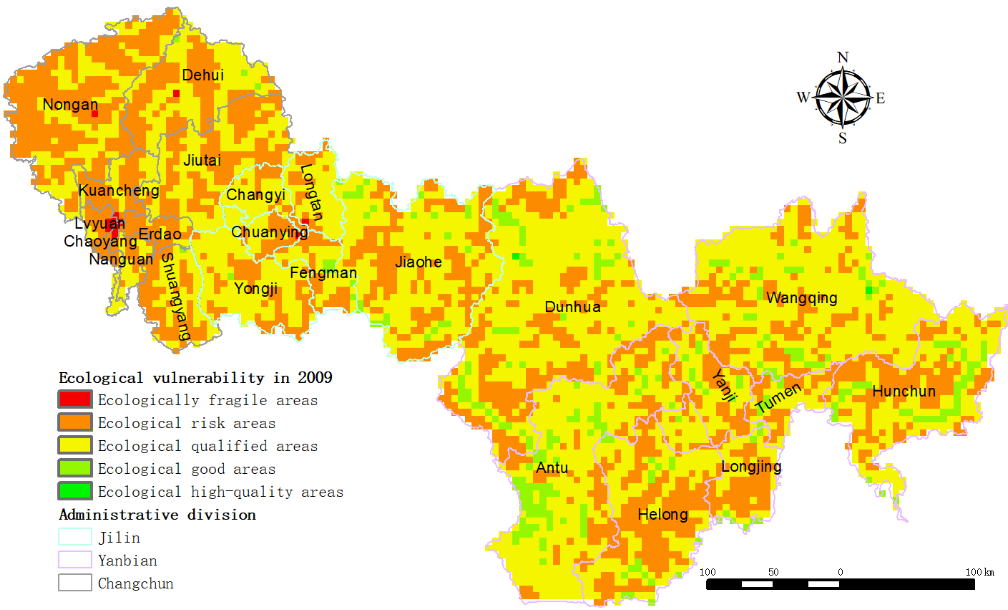

Fig 2. Ecological Vulnerability Assessment of the Changjitu Region in 2009

The specific distribution of areas below the ecological red line was as follows: Most areas within the administrative jurisdiction of Changchun, Chuanying District and Fengman District (the main urban areas of Jilin City), and Longjing City and Helong City (southeastern Yanbian Prefecture) had a wide distribution of "risk areas". The total area of "fragile areas" in the entire region was approximately 285.66 km², accounting for 0.21% of the total area. These areas were mainly distributed in the central urban areas of Changchun and Jilin, as well as the central areas of Nong'an County and

Dehui City under the jurisdiction of Changchun.

The "qualified areas" and "good areas" of the ecological environment accounted for 55.65% and 5.69% of the Changjitu area, respectively. The central part of the Changjitu Region (extending north-south) had a relatively good ecological environment. The area below the red line in Antu County was relatively small, and the western part of the county had a good ecological environment. In 2009, the area of ecological "high-quality areas" in the Changjitu Region was approximately 51.94 km², accounting for only 0.04% of the total area, distributed in the northwest corner of Dunhua City and the northeast corner of Wangqing County.

After more than a decade of development and opening-up, the ecological environment of the Changjitu Region is shown in Fig. 3.

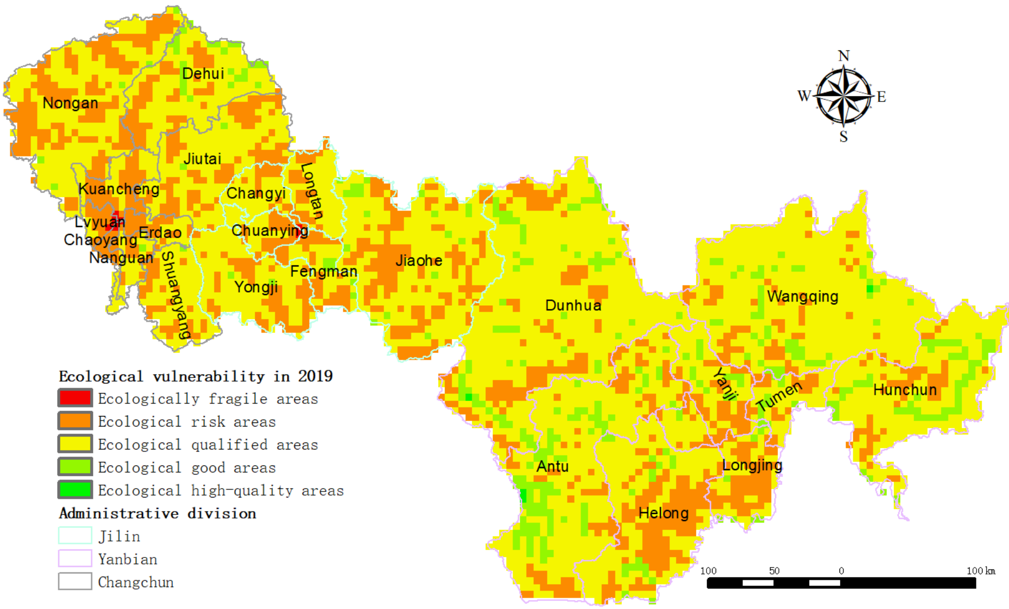

Fig 3. Ecological Vulnerability Assessment of the Changjitu Region in 2019

The area below the ecological red line accounted for approximately 25% of the total area of the Changjitu Region, showing a 15% improvement compared to the ecological condition a decade ago. The environmental improvement was visually obvious in Nong'an County, Dehui City, Jiutai District, and Shuangyang District (under the jurisdiction of Changchun), as well as Dunhua City and Hunchun City (under the jurisdiction of Yanbian Prefecture).

The specific ecological changes were as follows: The areas below the red line were mainly at the "risk area" level, accounting for 25.72%. The area proportions of ecological "qualified areas", "good areas", and "high-quality areas" reached 66.83%, 7.24%, and 0.08% respectively, all increasing compared to a decade ago. The area of "high-quality areas" nearly doubled. The central part (Antu County, Dunhua City) and northeastern part (Wangqing County) of the Changjitu Region had a high proportion of areas above the red line indicator. These areas had a high altitude, and were rich in forest resources and hydrological environment. The "fragile areas" accounted for 0.14% of the total area, mainly concentrated in the central urban areas of Changchun and Jilin. The "fragile areas" in the urban areas of Changchun and Jilin accounted for more than 30% of the urban area.

A comparison of data over the past decade shows that although the ecological environment in most areas has improved, the areas below the red line in Chaoyang District, Kuancheng District, Erdao District, and Lvyuan District of Changchun, as well as Chuanying District and Fengman District of Jilin, still accounted for more than 40% of their administrative areas. This was positively correlated with the level of regional economic development. Nong'an County, Helong City, and Longjing City had a relatively high proportion of ecological "risk areas" within their administrative jurisdictions. As one of the top five grain-producing counties in China, Nong'an County is dominated by cultivated land. Although it has a good hydrological environment, its ecological environment still faces vulnerability risks. Although Helong City and Longjing City are rich in forest resources, the topographic undulations in the ecological risk areas are too obvious, and geological risks make the ecological environment relatively fragile.

4.2. Ecological Environment Changes in the Changjitu Region

The deteriorating environment slightly increased in Longtan District and Fengman District; there was no change in Chaoyang District, Changyi District, and Longjing City. To better observe the spatial distribution of ecological environment changes, the research team examined the spatial distribution of areas with improved and deteriorated ecological environment over more than a decade, as shown in Fig. 4.

Within the Changjitu Region, the area with improved ecological environment was 22,389.33 km², accounting for 16.73% of the total area. Most of the improved areas were concentrated within the administrative jurisdictions of Changchun City and Yanbian Prefecture. In particular, the overall environment of Erdao District, Shuangyang District, Nong'an County, and Dehui City improved, with no deteriorated areas. From the perspective of numerical values and spatial distribution, there was no change in the ecological environment of Changyi District. Although there were scattered deteriorated areas in Jiutai District, Hunchun City, Wangqing County, Helong City, Antu County, and Dunhua City, the overall environment showed signs of improvement.

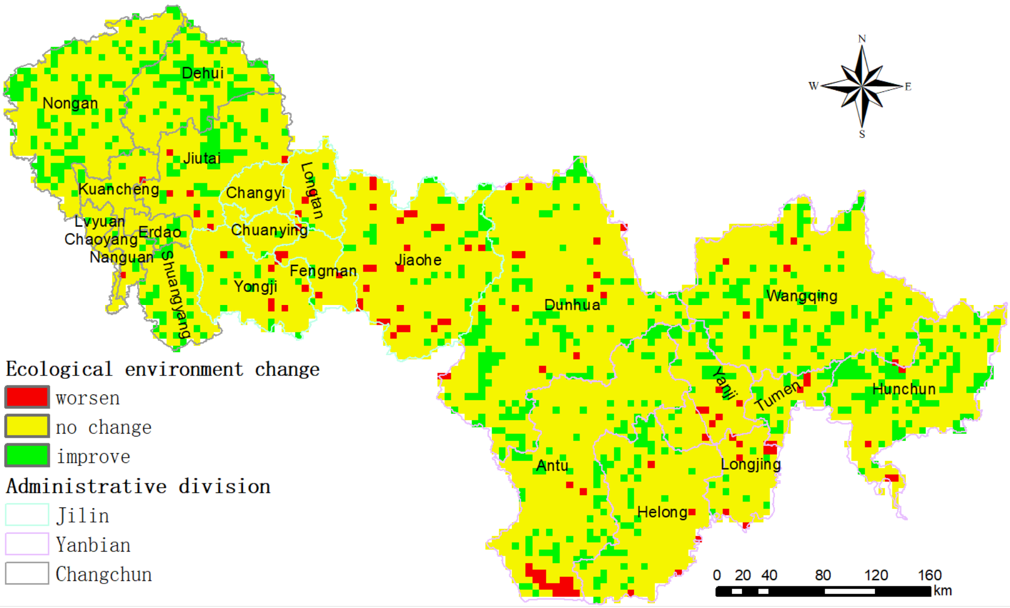

Fig 4. Spatial Distribution of Ecological Environment Changes in the Changjitu Region over a Decade of Development and Opening-up

There was a relatively concentrated area of deteriorating environment near the Changbai Mountains in the southern part of the Changjitu Region, which was related to the decrease in environmental humidity in 2019. Since changes in environmental humidity are greatly affected by meteorological factors, the environmental deterioration in this area was attributed to natural factors rather than human factors.

The area with deteriorated environment in the Changjitu Region was approximately 3,012.43 km², accounting for 2.25% of the total area. Most of the deteriorated areas were concentrated in the central part of the Changjitu Region and the border area between Yanji City and Longjing City in the eastern part of the Changjitu Region.

After more than a decade of development and opening-up, although some areas in the Changjitu Region still experienced environmental deterioration, the overall environment has improved under the background of comprehensive economic revitalization. This is inseparable from the good policy advocated by the Party Central Committee that "lucid waters and lush mountains are invaluable assets, and ice and snow are also invaluable assets", as well as the active implementation by the CPC Jilin Provincial Committee and the People's Government of Jilin Province.

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