Research on Spatiotemporal Evolution Characteristics of Production-Living-Ecological Space Resilience in Yichang City Based on AHP-GIS

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Abstract: The production-living-ecological space (three-function spaces) constitutes an essential foundation for the territorial spatial planning system and regional sustainable development evaluation. Amid rapid urbanization, most municipal-level regions are confronted with problems including unbalanced spatial layout and disordered land-use structure. To identify the evolution patterns of three-function spaces at the municipal scale, optimize spatial structure, and reconcile ecological conservation with urban-rural construction, this paper takes Yichang City, Hubei Province as the research object. Based on three-phase land-use data of 2015, 2020 and 2023, a classification system is established following the concept of three-function spaces. The analytic hierarchy process (AHP) is adopted to construct a comprehensive evaluation indicator system for territorial space, and GIS technology is applied to analyze the spatial evolution characteristics of Yichang City over the past eight years. The research findings can provide data support and theoretical reference for the high-quality development planning of Yichang City.

Keywords: Three Types of Territorial Spaces; Analytic Hierarchy Process; GIS Spatial Analysis; Spatio-Temporal Evolution; Territorial Spatial Pattern

1. Introduction

Against the backdrop of the comprehensive implementation of the territorial spatial planning system, "intensive and efficient production space, livable and moderate living space, and picturesque ecological space" have become important directions for territorial spatial governance and high-quality development [1]. The structural characteristics and spatial differences of PLE spaces reflect the trade-off between industrial development and ecological protection, serving as the core carrier for territorial spatial optimization and sustainable development research.

Domestic scholarship has formed a relatively complete research framework around PLE spaces, achieving functional zoning of production, living, and ecological areas based on the dominant functions of land use, and realizing a research shift from land-use statistics to functional integration [2]. Methodologically, studies employ weighting models, spatial overlay, transfer matrix, and other methods to analyze spatio-temporal evolution characteristics [3]. Relevant findings mostly take the Yangtze River Economic Belt and urban agglomerations as cases, focusing on spatial competition, functional restructuring, and pattern optimization paths under ecological bottom-line constraints [4].

Existing studies have largely focused on the long-term, full-sequence evolution patterns of PLE spaces and ecological security assessment across the entire Yangtze River Economic Belt [5]. However, there remain areas for expansion: first, there is a relative scarcity of long-term, high-frequency evolution analyses at the municipal scale, especially for key node cities in the middle and upper reaches of the Yangtze River [6]; second, quantitative studies that combine PLE spatial functional evaluation with spatial resilience are relatively limited [7]; third, for composite cities with excellent ecological backgrounds, strong industrial transformation demands, and rapid urban expansion, the coupling mechanisms and differentiation patterns of PLE spaces still require typical case support [8].

Based on this, this paper takes Yichang City as the study area, selects remote sensing and land-use data from three periods (2015, 2020, and 2023), constructs a PLE space classification and comprehensive evaluation system, and adopts the AHP-GIS coupling method to quantitatively reveal the spatio-temporal evolution, resilience differentiation, and driving characteristics of Yichang's PLE spaces over the past eight years. The aim is to provide data support and decision-making reference for Yichang's territorial spatial planning, ecological protection, industrial layout, and urban-rural livable construction, as well as to offer methodological reference for PLE space research in similar cities along the Yangtze River Economic Belt.

2. Methods for PLE Space Evaluation

Evaluation of production-living-ecological (PLE) spaces is a key quantitative means for identifying territorial spatial patterns, assessing functional quality, and analyzing spatio-temporal evolution. It enables the quantification of regional PLE functional development levels, spatial differences, and dynamic changes, thereby providing a quantitative basis for territorial spatial optimization. The evaluation targets functional identification, quality assessment, and spatio-temporal analysis. The process encompasses indicator screening, standardization, weight assignment, comprehensive calculation, and spatial visualization. Each step is coherently linked and coordinated, forming a complete evaluation system that ensures objective and accurate analytical results.

Indicator selection closely follows the core connotations of PLE spaces, screening typical, quantifiable, and temporally and spatially comparable positive and negative indicators to establish a hierarchical evaluation foundation. The extremum method is used to standardize multi-source heterogeneous data, completing normalization to avoid calculation errors caused by numerical disparities and unify comparison benchmarks across indicators. Weight determination adopts the Analytic Hierarchy Process (AHP) [4], constructing a multi-level evaluation structure and conducting consistency tests to combine subjective experience with objective logic, thereby enhancing weight rationality. The study employs a linear weighted model, combining standardized indicators with weights to calculate comprehensive scores and quantify PLE space development levels. Using ArcGIS, GIS spatial analysis is conducted to complete data processing, raster overlay, and visualization mapping, intuitively presenting the spatio-temporal differentiation and evolution characteristics of PLE spaces.

Through the above technical framework, the study can systematically reveal the development levels, pattern characteristics, and evolution rules of PLE spaces in the study area, providing reliable methodological support for subsequent spatio-temporal evolution analysis and optimization strategy formulation.

3. Data Sources

The data used in this study mainly include two types: socio-economic statistical data and GIS spatial remote sensing vector and raster data. Among them, socio-economic statistics related to socio-economy, land use, and ecological environment are compiled from the Yichang Statistical Yearbook, Yichang National Economic and Social Development Statistical Bulletins, Yichang Ecological Environment Bureau Annual Environmental Quality Reports, and Natural Resources Bureau Land Use Statistical Annual Reports [9]. Specialized ecological indicators such as per capita water resources and days with good air quality are sourced from publicly available monitoring statistical results of Yichang City [10].

For GIS spatial remote sensing data, nighttime light data are obtained from the National Geographic Information Center and public data platforms [11]; the Normalized Difference Vegetation Index (NDVI) is acquired from the Resource and Environmental Science Data Center of the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, with annual vegetation coverage data retrieved through the pixel dichotomy method; water system, road network, and water network vector data are integrated from existing vector results of open-source map data; industrial enterprises and facility services are extracted from open platforms of electronic maps and converted into corresponding raster data using ArcGIS kernel density analysis; administrative boundary vector data for Yichang's municipal and county-level divisions are sourced from the standard administrative division vector dataset released by the Hubei Provincial Department of Natural Resources [12]. All data undergo unified coordinate transformation and spatial registration.

4. Study Area Overview

Yichang is located in the southwestern part of Hubei Province, with overall terrain higher in the west and lower in the east, presenting a geomorphic pattern of "70% mountains, 20% hills, and 10% plains." Plains are mainly distributed in strips along the main stream of the Yangtze River [13]. The region has a subtropical monsoon humid climate with a superior ecological foundation. Ecological space accounts for over 70% of the municipal area, and ecological red lines occupy 21.82% of the territory, making it a key ecological barrier and water conservation area in the middle and upper reaches of the Yangtze River, with prominent ecological control constraints.

Spatially, it forms a pattern of ecology in the west, living in the middle, and production in the east. Production and living lands are concentrated along the river, while ecological lands are concentrated in the northwestern mountainous areas. As a port-based industrial city, it previously experienced conflicts between chemical industries along the river and production-ecological spaces [9]. In recent years, driven by initiatives such as Yangtze River conservation and green transformation, the city's PLE spaces have been continuously restructured and optimized. Its territorial spatial evolution reflects the typical relationship between development and protection in river basin cities [14].

5. Construction of the PLE Space Evaluation System Based on AHP

5.1 Evaluation System Construction and Indicator Selection

With the comprehensive development level of Yichang's territorial space as the overall objective, and following the principles of scientificity, systematicity, operability, and regional adaptability, a PLE space evaluation system is constructed comprising three objective layers—production space, living space, and ecological space—with a total of 27 specific indicators. The living space layer selects 12 indicators, including permanent population density, urban and rural resident income, total retail sales of consumer goods, and public service facilities, reflecting livability and service support capacity. The production space layer selects 9 indicators, including industrial structure, GDP growth rate, number of industrial enterprises, fiscal revenue, and road network density, representing economic development and industrial intensification levels. The ecological space layer selects 6 indicators, including air quality, water resources, vegetation coverage, and water network density, reflecting ecological background and ecosystem service functions. Indicators are classified as positive or negative. Permanent population density, primary industry proportion, secondary industry proportion, and comprehensive air quality index are negative indicators; the rest are positive indicators (see Table 1).

5.2 Weight Determination and Consistency Testing

The Analytic Hierarchy Process (AHP) is used to determine indicator weights. A 1–9 scale method is applied to construct pairwise comparison judgment matrices. The square root method is used to calculate eigenvectors, which are then normalized to obtain local weights for each indicator. Combined with objective layer weights, global weights are derived. The consistency index (CI) and random consistency ratio (CR) are calculated. All judgment matrices have CR < 0.1, passing the consistency test, confirming the scientific validity of the weight results.6. Optimization Pathways for Hubei's Resilient City Policies

Based on the empirical analysis of policy tools, planning content, regional differences, and tool-content coupling relationships, and considering Hubei's natural endowments, disaster characteristics, and local development realities, this paper proposes systematic and implementable optimization pathways from four dimensions: policy tools, planning content, regional coordination, and supply-demand coupling, to comprehensively improve the provincial resilience policy system.

Table 1. Indicator System for PLE Space Resilience Assessment in Yichang City

Objective Layer	Indicator Layer	Indicator Nature
Living Space	Permanent population density	-
	Per capita disposable income of urban residents	+
	Per capita disposable income of rural residents	+
	Total retail sales of consumer goods	+

	Year-on-year growth of total retail sales of consumer goods	+
	Growth rate of actual foreign direct investment	+
	Growth rate of urban fixed asset investment	+
	Accommodation facilities per 1,000 people	+
	Healthcare services per 1,000 people	+
	Transportation facilities per 1,000 people	+
	Number of mobile phone subscribers	+
Production Space	Primary industry proportion	-
	Secondary industry proportion	-
	Tertiary industry proportion	+
	GDP growth rate	+
	Number of industrial enterprises above designated size	+
	Sales rate of industrial enterprises above designated size	+
	Local general public budget revenue	+
	Road network density	+
Ecological Space	Days with good air quality	+
	Comprehensive air quality index	-
	Total per capita water resources	-
	Surface water resources	+
	Fractional Vegetation Coverage (FVC)	+
	Water network density	+
	Year-on-year growth of total retail sales of consumer goods	+
	Growth rate of actual foreign direct investment	+
	Growth rate of urban fixed asset investment	+
	Accommodation facilities per 1,000 people	+
	Healthcare services per 1,000 people	+
	Transportation facilities per 1,000 people	+
	Number of mobile phone subscribers	+
	Primary industry proportion	-

5.3 Data Standardization

The extremum standardization method is applied to the indicator data for 2015, 2020, and 2023 for dimensionless processing, eliminating differences in units and magnitudes and uniformly mapping data to the [0, 1] interval.

Formula for positive indicators:

$$X'_{ij} = \frac{X_{ij} - X_{min}}{X_{max} - X_{min}} \quad (1)$$

Formula for negative indicators:

$$X'_{ij} = \frac{X_{max} - X_{ij}}{X_{max} - X_{min}} \quad (2)$$

Where X'_{ij} is the standardized value, X_{ij} is the original value, and X_{max} and X_{min} are the maximum and minimum values of the indicator, respectively. Standardized data can be directly used for weighted calculations.

5.4 Comprehensive Evaluation Model

The linear weighted summation method is used to construct the comprehensive evaluation model for PLE spaces. The calculation formula is:

$$S = \sum_{i=1}^{n} W_i \times X'_i \quad (3)$$

Where S is the comprehensive score, W_i is the global weight of indicator i, X'_i is the standardized value, and n is the total number of indicators.

Sub-scores for living, production, and ecological spaces, as well as the comprehensive territorial space score, are calculated separately. Scores closer to 1 indicate higher development levels of the corresponding space, quantitatively revealing temporal changes and development differences in Yichang's PLE spaces.

5.5 Raster Synthesis of PLE Space Resilience Index

Based on the linear weighted comprehensive evaluation model, standardized indicator rasters are overlaid and calculated layer by layer according to corresponding weights to generate a continuously distributed PLE space resilience index raster for the entire Yichang area. The resilience index ranges from 0 to 1, with higher values indicating stronger resilience, system stability, and self-recovery capacity of the corresponding space; lower values indicate weaker resilience and poorer anti-interference ability.

Through raster calculation and zonal statistics, three-phase PLE space resilience index spatial datasets are formed, providing quantitative support for spatio-temporal evolution analysis.

6. GIS-Based Spatio-Temporal Evolution Analysis of PLE Spaces in Yichang City

From 2015 to 2023, the resilience of Yichang's PLE spaces exhibited pronounced differentiation characteristics over time (see Figures 1–6). Ecological space resilience showed a continuous and steady improvement, with the high-value area index rising from 0.607 in 2015 to 0.756 in 2020, and marginally increasing to 0.757 in 2023. Driven by policies such as the Yangtze River Conservation and the Three Gorges ecological barrier construction, the city's ecological background quality and protection resilience have been continuously enhanced [9] (see Figure 7).

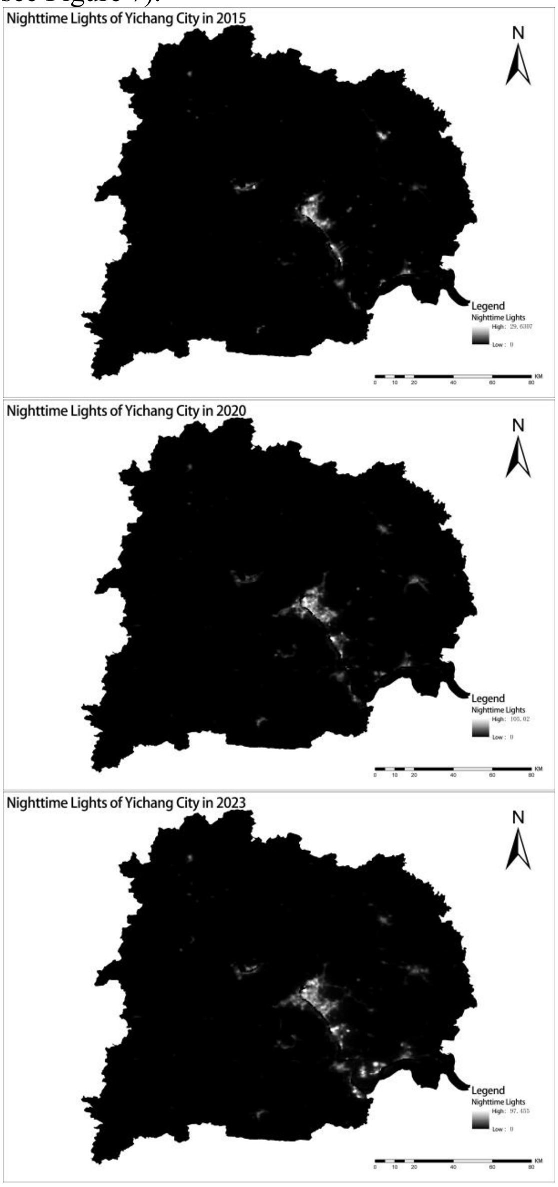


Figure 1. Nighttime Lights

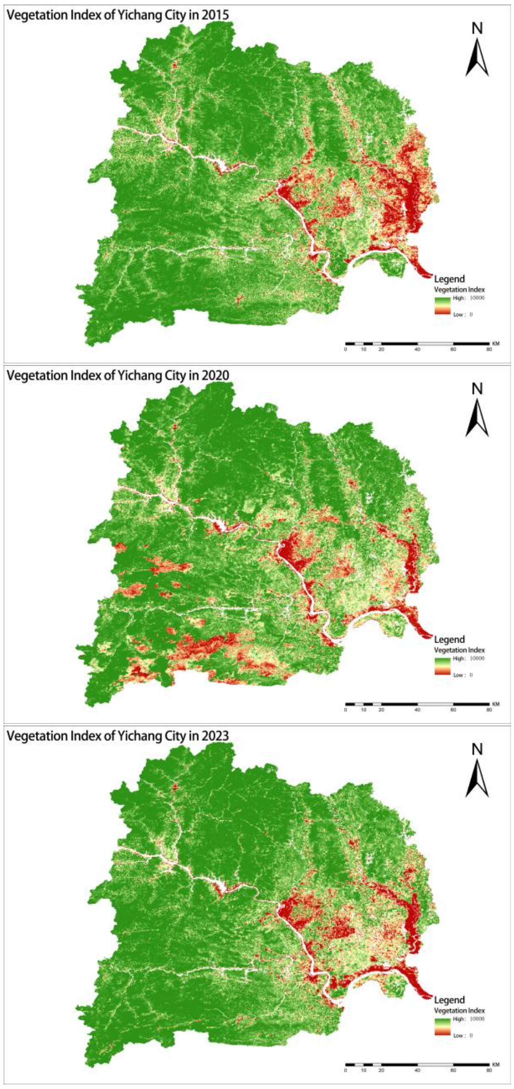
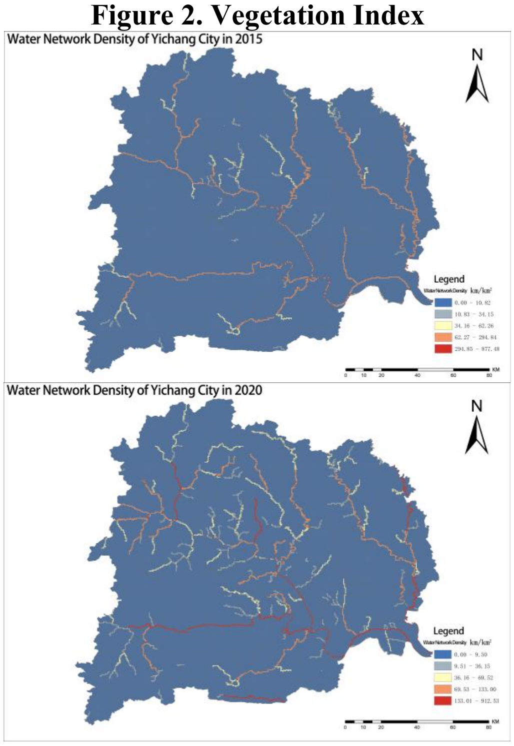


Figure 2. Vegetation Index



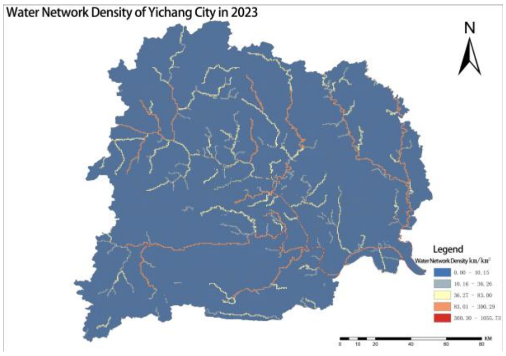


Figure 3. Water Network Density

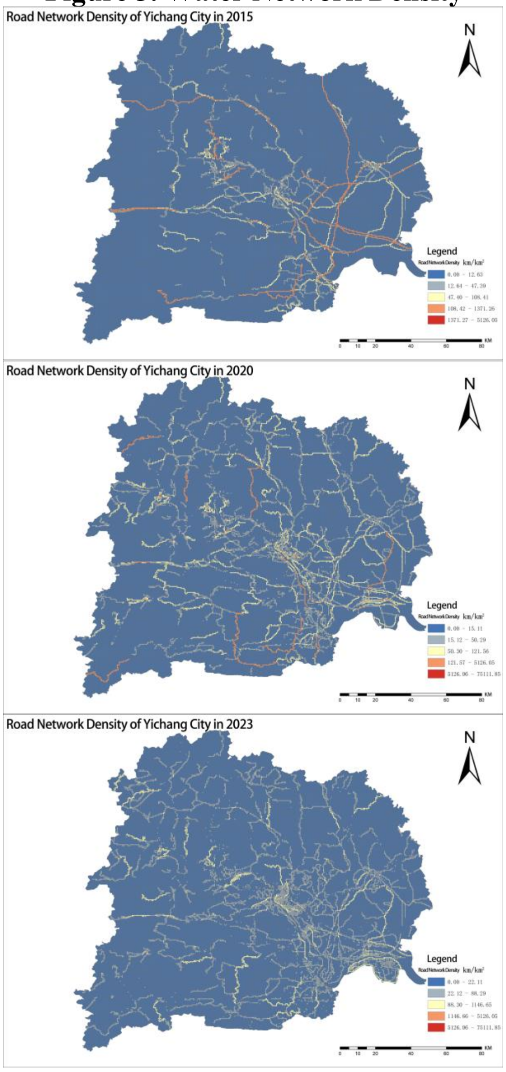
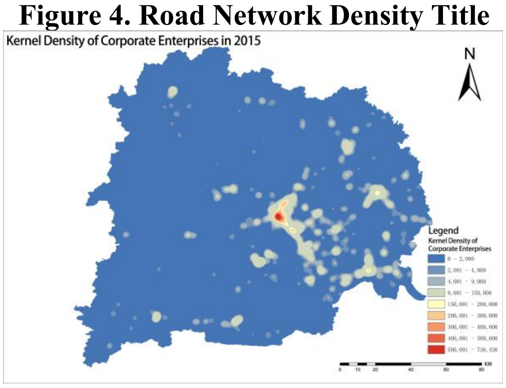


Figure 4. Road Network Density Title



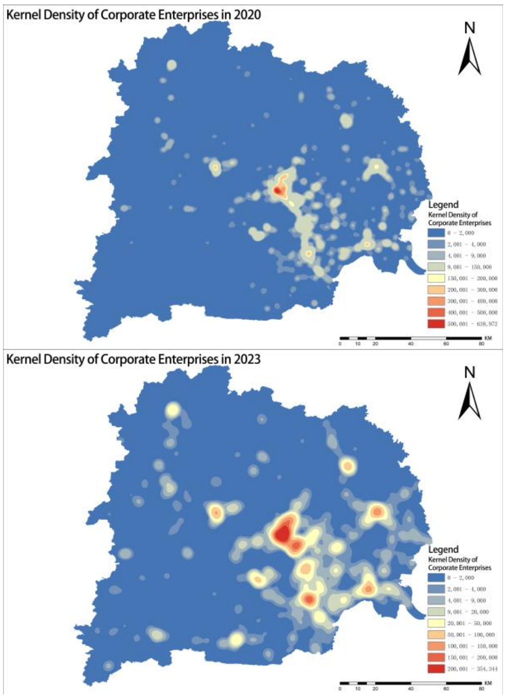


Figure 5. Kernel Density of Enterprises

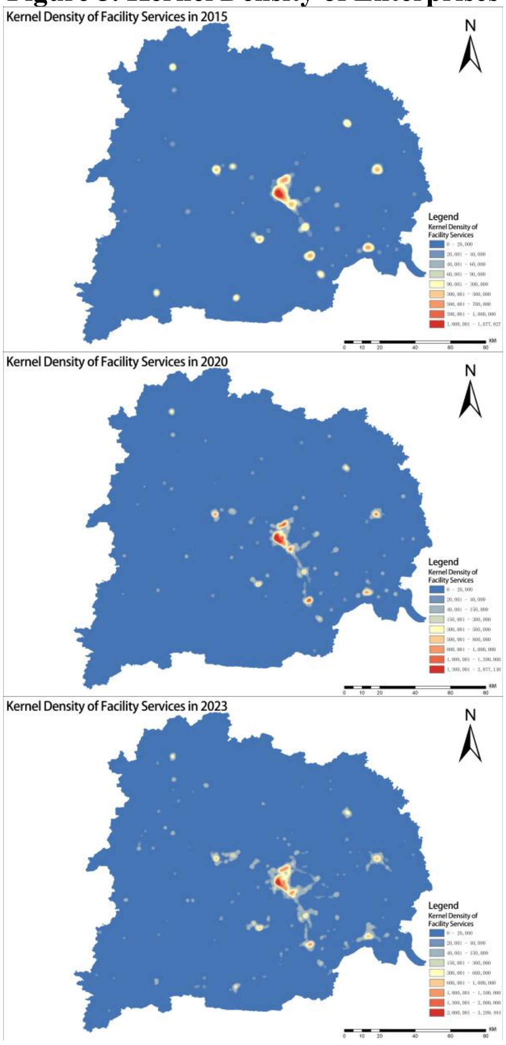


Figure 6. Kernel Density of Public Service Facilities

Production space resilience exhibited a phased decline, with the high-value area index decreasing from 0.662 in 2015 to 0.575 in 2020, and further to 0.554 in 2023. This trend is highly consistent with the phased adjustment characteristics of traditional industry remediation and green transformation [4] (see Figure 8). Living space resilience declined first and then stabilized, with gradual recovery. The high-value area index decreased from 0.656 in 2015 to 0.573 in 2020, and slightly rebounded to 0.558 in 2023. The matching between urban expansion and public service supply gradually improved, and livability resilience tended to stabilize [13] (see Figure 9).

Spatially, constrained by the geomorphic pattern and functional layout, the resilience of PLE spaces exhibited a differentiated pattern of concentric agglomeration and corridor-style extension [14]. High-value areas of ecological space were stably distributed in the western and northern mountainous areas, forming continuous ecological corridors along river basins, with the scope continuously expanding.

High-value areas of production space were concentrated in industrial parks along the Yangtze River, showing a trend of core contraction and corridor diffusion, reflecting the characteristics of intensive transformation. High-value areas of living space radiated outward from the central urban area in concentric circles and gradually extended to county towns, indicating a shift from single-center agglomeration to multi-center coordination in urbanization, with steady improvement in the balance of urban-rural living spaces.

From 2015 to 2023, the spatio-temporal differentiation characteristics of Yichang's PLE space resilience were significant. Ecological space resilience continued to optimize; production space resilience underwent phased adjustments with industrial transformation; and living space resilience gradually stabilized through urban quality improvement.

The spatial pattern was highly coupled with landforms and functional zoning, forming a stable structure of ecology strong in the west, production along the river, and living spaces expanding in concentric circles. The overall evolution is the result of the synergistic promotion of ecological protection priority, industrial green transformation, and new urbanization, consistent with the general orientation of ecological priority and green development in the Yangtze River Economic Belt [11].

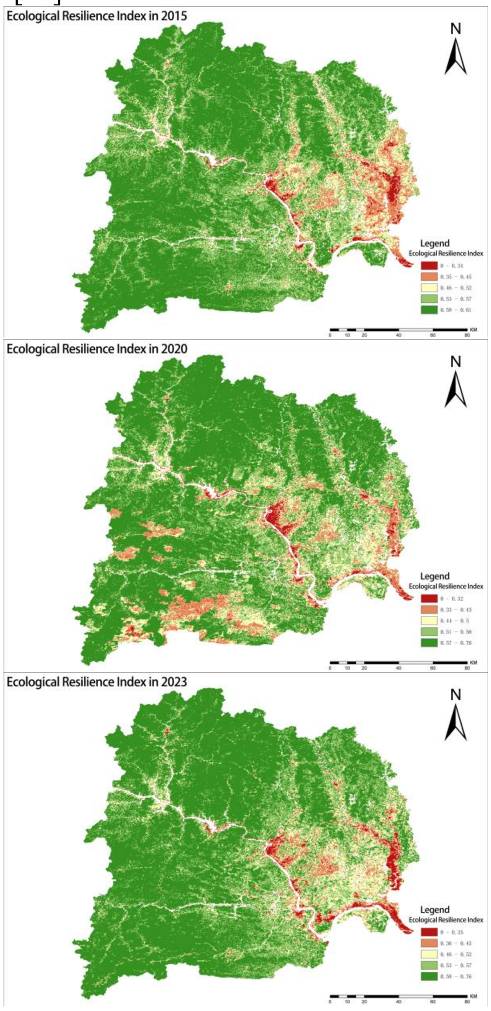
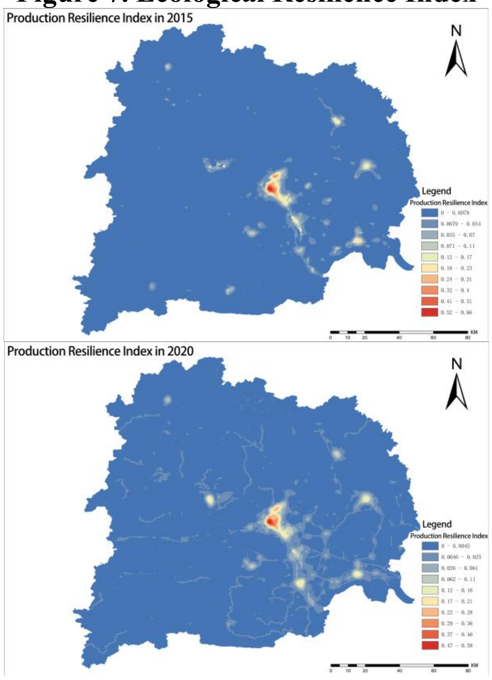


Figure 7. Ecological Resilience Index



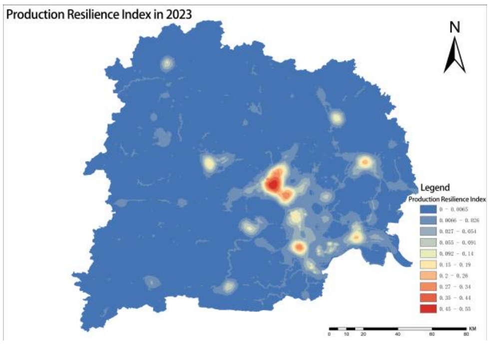


Figure 8. Production Resilience Index

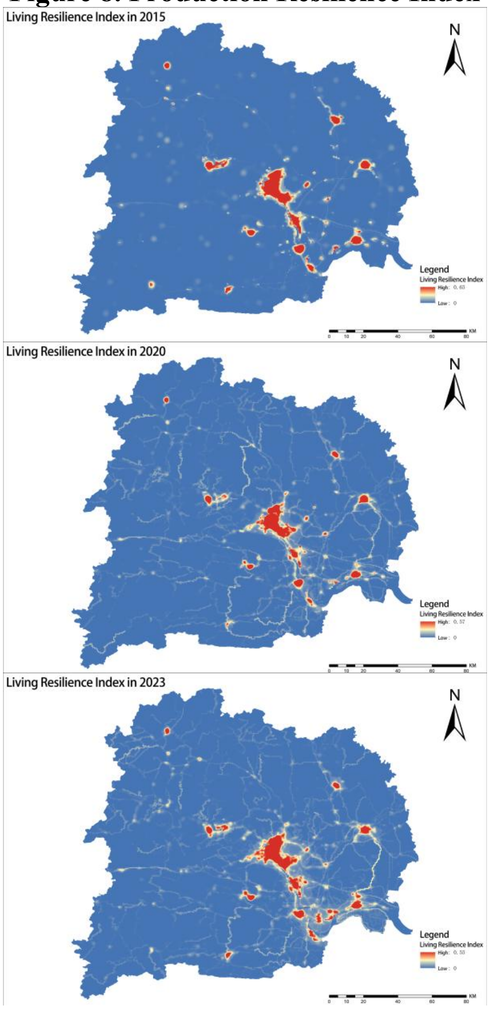


Figure 9. Living Resilience Index

7. Research Conclusions

This study takes Yichang City as the research area, based on three-phase spatio-temporal data from 2015, 2020, and 2023, and couples the theory of production-living-ecological (PLE) spaces, the Analytic Hierarchy Process (AHP), and GIS spatial analysis technology. It systematically reveals the spatio-temporal evolution characteristics and resilience differentiation patterns of municipal production, living, and ecological spaces over the past eight years. The research findings can provide quantitative support and scientific reference for regional territorial spatial planning, ecological protection and restoration, industrial layout optimization, and urban-rural livable construction.

This study constructs a comprehensive PLE space evaluation system comprising three major dimensions—production, living, and ecology—with a total of 27 indicators. The AHP method is used for weight assignment, passing consistency tests. The weight distribution is highly consistent with Yichang's dual positioning as an industrial city and an ecological barrier. Temporally, the resilience of the municipal PLE spaces exhibits pronounced differentiation characteristics: ecological space resilience shows a continuous and steady improvement, with ecological background and protection capacity constantly enhanced; production space resilience shows phased declines with industrial remediation and green transformation, reflecting the staged effects of intensive and efficient transformation; living space resilience declines first and then stabilizes, with urban expansion and public service supply gradually matching, and livability levels tending to stabilize.

Spatially, the distribution of PLE spaces is highly coupled with the "70% mountains, 20% hills, 10% plains" landform and the functional layout of "ecology in the west, living in the middle, production in the east," presenting characteristics of ecological space agglomeration in the west, production space distribution along the river, and living space radiating in concentric circles from the central urban area. The overall evolution process is the result of the combined effects of ecological protection policies, industrial structure adjustment, and new urbanization promotion, fully reflecting the strategic orientation of ecological priority and green development in the Yangtze River Economic Belt.

This study provides data support for the high-quality development of Yichang's territorial space and offers a transferable technical framework and practical ideas for similar cities in the Yangtze River basin to conduct PLE space evaluation, spatio-temporal evolution analysis, and pattern optimization. Future work still needs to further coordinate the layout of production, living, and ecological spaces, strengthen spatial resilience improvement, and continuously promote the synergistic progress of regional ecological protection and high-quality socio-economic development.

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