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Ecological zoning identification and optimization strategies of Wuhan based on ecosystem service value and landscape ecological risk

Abstract

This study takes Wuhan as an example, based on the comprehensive assessment of ecosystem service value (ESV) and landscape ecological risk index (ERI), combined with remote sensing technology, geographic information models, landscape ecology, and GIS grid analysis methods, analyzes the spatiotemporal evolution of land use change, ESV, and ERI from 2002 to 2022. The Z-score standardization method was used to determine four types of ecological zones. The research results show that: ① In 2002, 2012, and 2022, the ecosystem service value (ESV) of Wuhan was 5.021 billion yuan, 4.772 billion yuan, and 4.296 billion yuan, respectively, with a unit area ESV of 1.6433 million yuan/km². ② During this period, the landscape ecological risk index (ERI) was 0.0029, 0.0027, and 0.0025, respectively, with low ecological risk areas accounting for about 75.05% of the total area, among which the risk levels of cultivated land and water areas were higher. ③ Combining ESV and ERI, Wuhan was divided into four ecological zones: ecological restoration area (I), ecological reconstruction area (II), ecological development area (III), and ecological protection area (IV), and differentiated management strategies were proposed.

Keywords: ecosystem services, ecological risk, ecological zoning identification, control scheme

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Foreword

Amidst the accelerating process of global urbanization, intensive anthropogenic disturbances and rapid climate change have triggered drastic land-use and land-cover changes. This has disrupted the balance of regional ecosystems, leading to a degradation of ecosystem service capacity and an amplification of ecological risks. These factors pose a severe threat to sustainable development and significantly impede urban sustainability.[1,2] As a pivotal hub within the Yangtze River Economic Belt, Wuhan leverages its unique aquatic resources and geographical location, yet faces ecological conflicts stemming from rapid urban expansion. The establishment of an ecological identification zoning system serves as a core instrument for advancing ecological civilization. A central challenge for Wuhan's ecological planning lies in implementing systematic spatial governance to ensure robust economic development while achieving sustainable ecosystem management.

Current research has achieved notable progress in the fields of Ecosystem Service Value (ESV) and the Ecological Risk Index (ERI). Regarding ESV assessment, Costanza et al. developed an evaluation model based on economic value parameters per unit area for the global ecosystem.[3] The Millennium Ecosystem Assessment, spearheaded by the United Nations, underscored the critical linkages between ecosystem services and human well-being.[4,5] Under the framework of the Millennium Ecosystem Assessment, Xie Gaodi and his research team developed a set of equivalent value factors for ecosystem services tailored to China's specific conditions. This work significantly enhanced the applicability and accuracy of value-based assessment methodologies within the country.[6] In the domain of ecological risk, Yang Xu investigated the impacts of mining and metallurgical activities on regional ecological security by developing an exposure-response model specific to mining areas.[7] In a case study of Xining City, Bin Qiao analyzed the spatiotemporal heterogeneity of land-use evolution and landscape ecological risk. Based on this analysis, he proposed an optimal pathway for the allocation of regional land resources.[8] Jun Hao constructed a landscape ecological risk assessment model to identify the spatiotemporal patterns of ecological risk in the Nenjiang River Basin of Mongolia. The study revealed that paddy fields and reservoirs/ponds were the primary land use types driving the increase in landscape ecological risk within the watershed. This analysis provides a scientific basis for constructing regional ecological security patterns.[9] However, existing research has predominantly focused on a single dimension, while studies that integrate ESV and ERI remain relatively scarce.

As a typical waterfront city, Wuhan features a high proportion of water surface area, which exerts a significant influence on its ecosystem service functions. Issues such as the decline of cultivated land and the expansion of construction land have intensified landscape fragmentation, thereby aggravating landscape ecological risks. Based on multi-temporal land use data, this study comprehensively employed remote sensing technology, geographic information modeling, and landscape ecology methods to quantitatively assess the spatiotemporal evolution of ESV and ERI. From the dual perspectives of ecosystem services and ecological risk, a "value-risk" assessment model was constructed to propose zoning optimization strategies. This research provides a scientific basis for ecological planning and sustainable development in Wuhan, while also establishing a research paradigm for similar cities. The findings hold significant practical value for constructing ecological security patterns in Wuhan and other comparable urban areas.

Description of the study area and data sources

Description of the study area

Wuhan Municipality, the capital of Hubei Province, is situated in eastern China on the Jianghan Plain. The city covers a total area

of approximately 8,572.91 square kilometers and has a resident population of about 13.774 million. Wuhan experiences a typical subtropical monsoon climate, characterized by distinct seasonal variations, abundant sunshine, and substantial precipitation. The multi-year average annual temperature is 16.7°C, with an average annual rainfall of 1,203 millimeters.[9] The city is dotted with numerous lakes and ponds, with water bodies accounting for 15.86% of its total area. Its complex network of rivers and dense concentration of lakes and harbors establish it as a crucial shipping hub in the middle reaches of the Yangtze River (Figure 1).

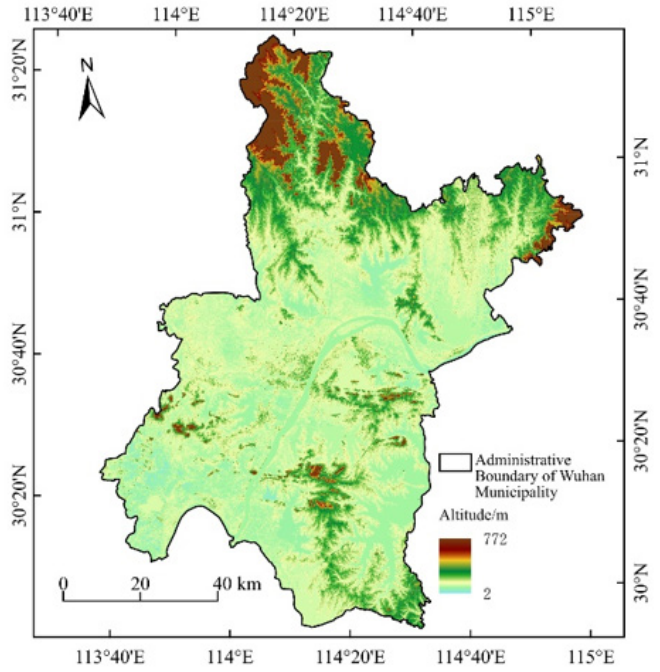

Figure 1 Location and profile of Wuhan municipality.

Wuhan Municipality was selected as the study area primarily due to its unique representativeness as a rapidly urbanizing megacity characterized by an extensive water network. As a pivotal hub within the Yangtze River Economic Belt, Wuhan exhibits pronounced human-land conflicts. Its distinctive geographical identity as the "City of a Hundred Lakes" renders its ecosystem service value highly dependent on sensitive water resources, making it an ideal case study for investigating the interplay between intensive human activities and critical natural ecosystems. Furthermore, the presence of all key landscape elements—mountains, rivers, forests, farmland, lakes, and grassland—within its administrative boundaries forms a complete composite ecosystem. This configuration allows for clear identification of spatiotemporal heterogeneity in ecosystem services and landscape ecological risks. Thus, research conducted here not only provides direct evidence to inform ecological planning in Wuhan but also establishes a "value-risk" dual-perspective assessment and zoning framework with significant paradigmatic value for guiding sustainable development in similar waterfront megacities.

Description of the data sources

This study collected national land cover data for the years 2002, 2012, and 2022, with a spatial resolution of 30 meters, sourced from the ZENODO repository (http://www.zenodo.org). With reference to the national land use/cover classification system for remote sensing monitoring and the specific land use characteristics of the study area, the land use data for Wuhan were reclassified through categorization and manual interpretation into six types: cropland, forest land, grassland, water bodies, bare land, and construction land. Data on grain prices were obtained from the Compilation of Cost-Benefit Data of National Agricultural Products (2002-2022), while total grain output and sown area were sourced from the *Wuhan Statistical Yearbook (2002-2022).[10]

The selection of the years 2002, 2012, and 2022 for this study was based on comprehensive considerations. This 20-year time span is sufficient to effectively capture the long-term ecological evolution trends of Wuhan City during its rapid urbanization process. The three time points form two balanced decade-long intervals, which are conducive to analyzing the rate and trajectory of changes. Specifically, 2002 can be regarded as the ecological "baseline" state before the acceleration of urbanization, 2012 represents a transitional mid-term developmental stage, while 2022 reflects the most recent conditions.

Concurrently, these years correspond to significant policy and planning milestones. In 2002, China was in a period of rapid development following its accession to the WTO, and national-level ecological policies had already begun implementation. The year 2012 marked the middle of the "12th Five-Year Plan" period, a time when ecological civilization construction was elevated to new heights. Master plans for Wuhan City, including its ecological framework planning, had profound impacts during this phase. The year 2022 represents a critical juncture at the conclusion of the "13th Five-Year Plan" and the commencement of the "14th Five-Year Plan," enabling an assessment of the effectiveness of the series of ecological protection and restoration policies implemented previously.

The selection of these three years ensures the availability of multi-temporal land use remote sensing data with consistent spatial resolution and classification systems. This guarantees the scientific rigor and comparability of the temporal analysis, while also providing practical guidance significance.

Methodology

Delineation of assessment units

Grid-based analysis is a spatial analysis method that involves partitioning the study area into a series of regular or irregular grid cells. Subsequent processing, statistical computation, and analysis are then performed on the data within each individual cell.[11,12] Based on a comprehensive consideration of Wuhan's land use planning, the implementation of ecological compensation mechanisms, and practical guidance value, the study area was delineated into a grid of 0.3 km × 0.3 km cells. This grid-based approach was employed to analyze the spatiotemporal changes in the Landscape Ecological Risk Index (ERI) and Ecosystem Service Value (ESV) within Wuhan.

Assessment of ecosystem service value

Based on the biomass factor table for farmland ecosystems in different provinces of China, established by Xie Gaodi et al.,[6] this study calculated the per-unit-area ecosystem service value for each land use type in Wuhan (Table 1). The ecosystem service value for cropland was determined with reference to farmland ecosystem types and their mean equivalent values. For forest land, the calculation was based on the ecosystem types of coniferous forest, broad-leaved forest, and mixed coniferous-broadleaved forest along with their respective mean equivalents. Grassland values were derived from the ecosystem types of shrub-grassland, meadow, and steppe and their mean equivalents. The value for water bodies was referenced from the ecosystem types of rivers/canals and wetlands and their mean

equivalents. Shrubland and bare land retained their original baseline values. When considering only the value of natural ecosystem services, the ecosystem service value of construction land was assigned a value of zero.[13] Thus, a table of per-unit-area ecosystem service value (ESV) equivalent factors for the study area spanning the period 2002–2022 was derived (Table 1).

Table 1 Table of equivalent factors for ecosystem service value per unit area in Wuhan municipality (yuan/km²)

Ecosystem service functions		Cultivated land	Forest land	Grass land	Waters	Unused land	Impervious Land
Provisioning Services	Food Production	20264.50	5012.64	4630.57	24023.97	0.00	0.00
	Production of material	4493.03	11553.51	10636.57	13387.40	0.00	0.00
	Water Supply	-23932.28	5990.71	5501.67	199527.35	0.00	0.00
Regulating Services	Gas conditioning	16321.63	38022.68	34981.47	48964.89	366.78	0.00
	Climate regulation	8527.59	113701.25	104669.33	108016.18	0.00	0.00
	Environmental purification	2475.75	33071.17	30671.83	167801.03	1833.89	0.00
	Water Regulation	27416.67	70849.33	68495.83	2319322.05	550.17	0.00
Supporting Services	Soil Conservation	9536.23	46275.18	42592.12	59418.07	366.78	0.00
	Nutrient Cycling	1742.20	3545.52	3255.16	4584.73	0.00	0.00
	Biodiversity	3117.61	42118.37	38786.80	191091.45	366.78	0.00
Cultural Services	Landscape Aesthetics	1375.42	18461.17	17009.34	121403.59	183.39	0.00

The formula for calculating the Ecosystem Service Value (ESV) is as follows:

$$ESV_i = \sum A_i VC_i$$

$$ESV = \sum_{i=1}^{n} ESV_i$$

Where ESV_i represents the ecosystem service value of the *i*-th land use type. A_i denotes the area of the *i*-th land use type. VC_i is the value coefficient of ecosystem services for the *i*-th land use type. *ESV* refers to the total ecosystem service value.

This study determined the economic value of one standard equivalent factor for the year 2022, used as the baseline, to be 18,338.91 yuan/km². This calculation was based on data including grain yield, sown area, and grain price obtained from the *Wuhan Statistical Yearbook*[10] and the *Compilation of Cost-Benefit Data of National Agricultural Products*.

The Landscape Ecological Risk Index (ERI) reflects the susceptibility of landscape patterns to external disturbances. It serves as a tool to analyze the stability of landscape types and estimate potential ecological issues that may arise when they are subjected to uncertainties and threats. This study builds upon prior research findings[14,15] A comprehensive ecological risk index was constructed by integrating three key indicators: the landscape disturbance index, the vulnerability index, and the loss index.[16,17] This framework allows for the analysis of the magnitude and spatiotemporal changes of landscape ecological risk within the study area. The specific formulas are as follows:

$$ERI_i = \sum_{i=1}^{N} \frac{A_{ki}}{A_k} (aC_i + bV_i + cL_i) \times F_i$$

In the equation, ERI_i represents the ecological risk index of the *i*-th risk grid unit. A_{ki} denotes the area of landscape type *i* within the *k*-th grid unit. A_k is the total area of the *k*-th grid unit. C_i indicates the landscape fragmentation index, V_i signifies the landscape separation index, L_i points to the landscape dominance index. *a*, *b* and *c* are the weights assigned to C_i, V_i and L_i, with the constraint $a+b+c=1$. Based on relevant literature, the values of *a*、*b* and *c* were set to 0.5、0.3 and 0.2.[18] F_i is the landscape vulnerability index, referenced from prior studies.[19,20] A vulnerability index was assigned to each of the seven land use types within the study area (Table 2). The assigned values were then normalized to yield the vulnerability index (F_i) for each landscape type. The normalization results are presented in the table (Table 3).

Table 2 Vulnerability index by land use type

Land use type	Cultivated land	Forest land	Grass land	Waters	Unused land	Impervious land
Landscape vulnerability index	4	2	3	5	6	1

Table 3 Normalized vulnerability index by land use type

Land use type	Cultivated land	Forest land	Grass land	Waters	Unused land	Impervious land
Landscape vulnerability index	0.1905	0.0952	0.1429	0.2381	0.2857	0.0476

Delineation of ecological zones based on ESV and ERI

The ecosystem service value (ESV) and landscape ecological risk index (ERI) of each assessment unit within the study area were standardized using the Z-score method. Based on the standardized results, a "value-risk" coordinate system was established, where the x-axis represents the ESV and the y-axis represents the ERI. Quadrant I represents areas with high ESV and high ecological risk. Quadrant II represents areas with low ESV and high ecological risk. Quadrant III represents areas with low ESV and low ecological risk. Quadrant IV represents areas with high ESV and low ecological risk. Assessment

units falling into different quadrants correspond to distinct ecological zones.[16] The formula for Z-score standardization is given as follows:

$$Z = \frac{X_n - \bar{x}}{\sigma}$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(X_n - \bar{x})^2}{n-1}}$$

In the equation, Z is the standardized value of the assessment unit, X_n represents the ecosystem service value or landscape ecological risk index of the n-th assessment unit, $\bar{x}$ is the mean value of the ecosystem service value or landscape ecological risk index for all assessment units in the same period, σ denotes the sample standard deviation of the ecosystem service value or landscape ecological risk index for all assessment units in the same period, n refers to the total number of assessment units in the study area.

Results and Analysis

Spatiotemporal evolution of ecosystem service value (ESV)

Assessment of ecosystem service value: As shown in the table (Table 4), the total ecosystem service value (ESV) in the study area was 5.021 billion yuan, 4.772 billion yuan, and 4.296 billion yuan in 2002, 2012, and 2022, respectively, indicating a general declining trend during the period 2002-2022. In terms of the contribution of different land resources, water bodies contributed the most to the total ESV, accounting for approximately 85.00%. The ESV provided by water bodies was 4.380 billion yuan, 4.151 billion yuan, and 3.644 billion yuan in 2002, 2012, and 2022, constituting 87.24%, 86.99%, and 84.84% of the total ESV in their respective years. Cropland also represented a significant component of the ESV, with contributions of 438 million yuan, 417 million yuan, and 398 million yuan, accounting for 8.72% to 9.26% of the total ESV. The ESV from forest land ranged between 202 million yuan and 253 million yuan, representing 4.01% to 5.90% of the total. Grassland contributed an ESV ranging from 0.03 million yuan to 0.12 million yuan, accounting for about 0.01% of the total ESV. The Unused land was minimal, varying between 904.48 yuan and 3,149.16 yuan. When considering only the value of natural ecosystem services, the ESV of construction land was zero.

Table 4 Ecosystem service value by land use type in Wuhan from 2002 to 2022

Land use type	2002 ESV/ Yuan	Proportion/%	2012 ESV/ Yuan	Proportion/%	2022 ESV/ Yuan	Proportion/%
Cultivated land	4.38×10^8	8.72	4.17×10^8	8.73	3.98×10^8	9.26
Forest land	2.02×10^8	4.01	2.03×10^8	4.26	2.53×10^8	5.90
Grass land	1.16×10^6	0.02	9.95×10^5	0.02	2.83×10^5	0.01
Waters	4.38×10^9	87.24	4.15×10^9	86.99	3.64×10^9	84.84
Unused land	3.15×10^3	0.00	9.04×10^2	0.00	1.41×10^3	0.00
Impervious Land	0.00	0.00	0.00	0.00	0.00	0.00
Total	5.02×10^9	100	4.77×10^9	100	4.30×10^9	100

Regarding individual ecosystem service functions, water regulation contributed the most, accounting for 60.91% of the total ESV. Its value was 3.058 billion yuan, 2.907 billion yuan, and 2.617 billion yuan in 2002, 2012, and 2022, respectively. The contributions of landscape aesthetics, biodiversity, soil conservation, climate regulation, gas regulation, water supply, and waste treatment were relatively lower, collectively accounting for 36.46% of the total ESV. Their individual contributions, listed in descending order, were: climate regulation > biodiversity > waste treatment > water supply > landscape aesthetics > soil conservation > gas regulation. The contributions of food production, raw material production, and nutrient cycling were the lowest, with a combined ESV of approximately 132 million yuan, accounting for less than 3.00% of the total. The values of individual ecosystem services in Wuhan from 2002 to 2022 are presented in the table below (Table 5)

In terms of ESV per unit area, the value for the entire study area was 1.6433 million yuan/km² in 2002, 2012, and 2022. Water bodies exhibited the highest ESV per unit area at 3.2575 million yuan/km², followed by forest land (388,600 yuan/km²), grassland (361,230 yuan/km²), and cropland (71,300 yuan/km²). Unused land had the lowest value, at 3,667.78 yuan/km².

Spatial visualization of ecosystem service value: Using the natural breaks classification method, the ecosystem service values of the assessment units were categorized into five levels: low-value zones (ESV ≤ 2.29×10^7 yuan), relatively low-value zones (2.29×10^7 < ESV ≤ 7.04×10^7), medium-value zones (7.04×10^7 < ESV ≤ 1.40×10^8), relatively high-value zones (1.40×10^8 < ESV ≤ 2.19×10^8), and high-value zones (ESV > 2.19×10^8). This process yielded spatial distribution maps of ESV for different time periods (Figure 2). As shown in Figure 2, the high-value zones primarily consist of water bodies, followed by cropland and forest land, accounting for 86.36%, 8.90%, and 4.72% of the high-value zone area, respectively. The relatively high-value zones are predominantly cropland, constituting 99.50% of their area. Medium-value zones are also mainly composed of cropland, covering 99.57% of the area within this value range. Relatively low-value zones are primarily distributed in the northern part of the study area, with cropland making up the vast majority (99.89% of the area). Low-value zones consist almost entirely of unused land, accounting for 100.00% of their area.

According to the formula calculation, the Landscape Ecological Risk Index (ERI) for the study area in the three periods was 0.0029, 0.0027, and 0.0025, respectively. The risk indices for various land use types are shown in Table 6. From the perspective of land use types, cropland had an ERI above 0.020, indicating the highest ecological risk level and classifying it as a high-risk area, which is significantly influenced by anthropogenic production and living activities. Water bodies, construction land, and forest land had ERI values of approximately 0.0095, 0.0022, and 0.0021, respectively, representing relatively lower ecological risk levels with less impact from natural disturbances and human interference. However, both water bodies and forest land exhibit poor vulnerability and stability. Grassland is considerably affected by construction land expansion. As construction

land gradually expands, most natural grassland has been converted to artificial grassland, leading to a yearly decrease in its ecological vulnerability and a low ERI ranging from 0.0004 to 0.0008. Unused land, characterized by highly fragmented patch distribution, weak self-recovery capacity, and low resistance to disturbance, has an ERI of 0.0005, classifying it as a low-risk area in terms of landscape ecological risk.

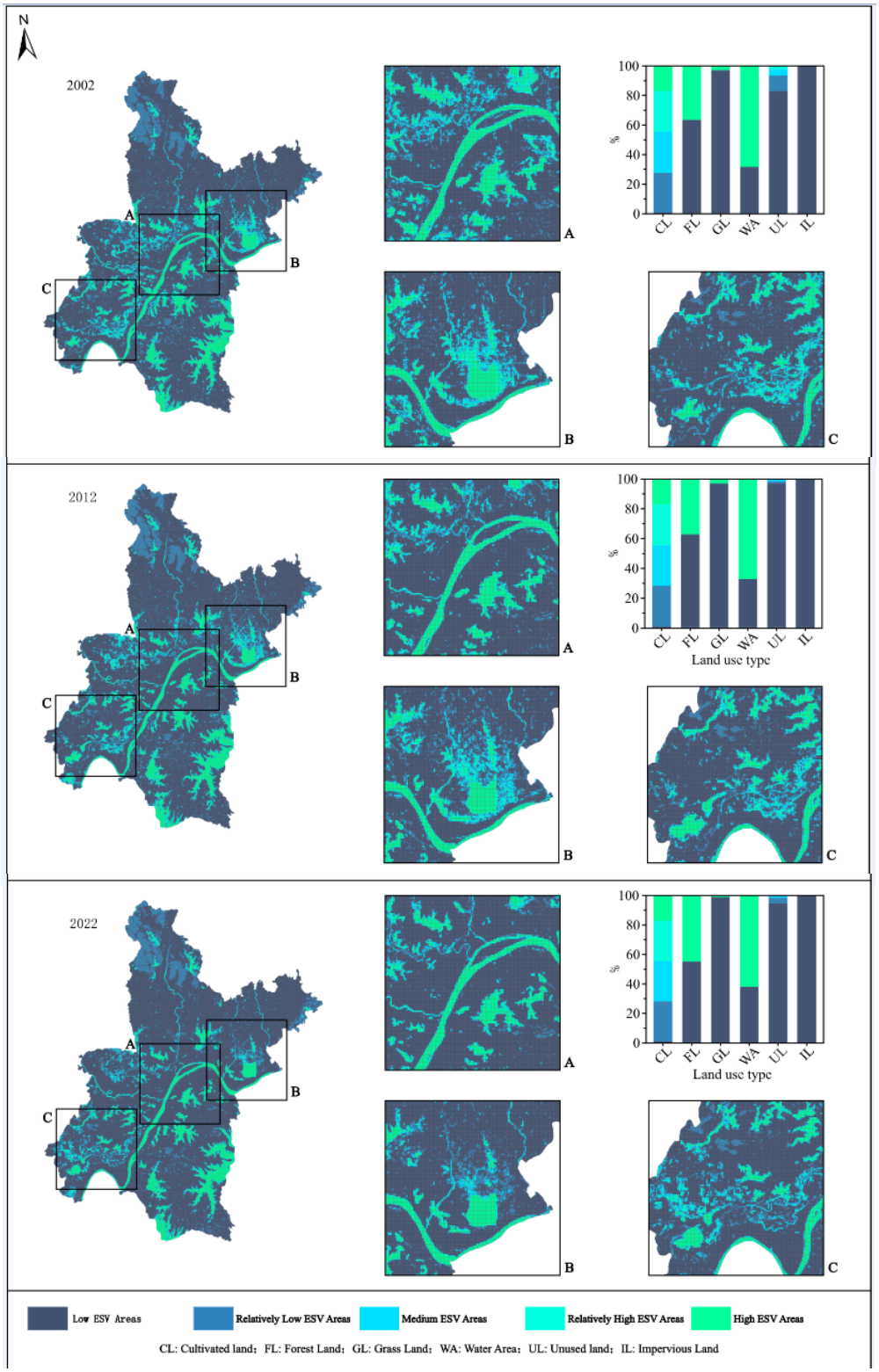

Figure 2 Spatial distribution of ecosystem service value levels in Wuhan from 2002 to 2022.

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Table 6 Landscape ecological risk index of Wuhan from 2002 to 2022

Land use type	Ecological Risk Index（ERI）		
	2002	2012	2022
Cultivated land	0.0220	0.0215	0.0207
Forest land	0.0020	0.0020	0.0023
Grass land	0.0008	0.0008	0.0004
Waters	0.0099	0.0097	0.0090
Unused land	0.0006	0.0004	0.0005
Impervious Land	0.0021	0.0022	0.0024
Comprehensive Ecological Risk Index	0.0029	0.0027	0.0025

Spatiotemporal analysis of landscape ecological risk: Using the natural breaks classification method, the landscape ecological risk of the assessment units was classified into five levels: low-risk (ERI ≤ 0.0341), relatively low-risk (0.0341 < ERI ≤ 0.0412), medium-risk (0.0412 < ERI ≤ 0.0506), relatively high-risk (0.0506 < ERI ≤ 0.0610), and high-risk (ERI > 0.0610). As shown in Table 7, over the 20-year period, the area of low-risk zones showed an increasing trend. The smallest area was recorded in 2002, accounting for 73.22% of the total study area in that year. The area of relatively low-risk zones exhibited a gradual decreasing trend, declining by 1.85% over the two decades. Both medium-risk and relatively high-risk zones also showed decreasing trends, reaching their smallest areas in 2022, accounting for 3.89% and 2.92% of the total area in that year, respectively. The area of high-risk zones demonstrated a gradually moderating upward trend, increasing from 692.37 km² in 2002 to 764.37 km² in 2022, representing an increase of 0.83%.

Table 7 Area and proportion of landscape ecological risk levels in Wuhan from 2002 to 2022

Ecological risk category	Area /km²			Proportion /%		
	2002	2012	2022	2002	2012	2022
Low-risk	6367.05	6436.08	6775.38	73.22	74.02	77.92
Relatively Low-risk	723.96	695.43	563.4	8.33	8.00	6.48
Medium-risk	480.42	447.57	338.49	5.52	5.15	3.89
Relatively High-risk	431.73	363.33	253.89	4.96	4.18	2.92
High-risk	692.37	753.12	764.37	7.96	8.66	8.79

In terms of the structure of landscape ecological risk levels, the ERI in the study area over the 20-year period was dominated by the low-risk level, accounting for approximately 75.05% of the total area. The relatively low-risk and high-risk areas followed, constituting about 7.60% and 8.47% respectively. The decrease in relatively low-risk areas coupled with the increase in high-risk areas suggests a potential upward trend in the overall ERI of the study area, representing a potential concern for regional optimization strategies. The medium-risk and relatively high-risk areas accounted for smaller proportions, at 4.85% and 4.02% respectively, and could serve as key focal points for optimization strategies.

Spatial visualization of the landscape ecological risk index: Spatial patterns of landscape ecological risk over the 20-year period were derived based on the five risk levels. As shown in Figure 3, the study area is predominantly characterized by low-risk zones, with relatively low-risk zones scattered sporadically. Medium-risk zones are widely and contiguously distributed, while relatively high-risk zones are sporadically interspersed among low- and medium-risk areas. High-risk zones exhibit a clustered distribution pattern. In terms of land use types, cropland, forest land, and construction land primarily fall within low-risk zones. Grassland is mainly classified as low-risk (accounting for 99.49% of its total area), with minor portions classified as medium- and high-risk. Water bodies are predominantly low-risk, but include a portion of high-risk areas (approximately 7.28%). The remaining area is relatively evenly distributed among the other three risk levels, accounting for about 1.51%, 1.83%, and 1.99%, respectively. Unused land is almost exclusively low-risk (approximately 99.89% of its area), with minimal, sporadic distribution in relatively high-risk and high-risk zones.

Characteristics of ecological space zoning: Z-score standardization was conducted on the ecosystem service value (ESV) and landscape ecological risk index (ERI), yielding a value-risk quadrant distribution map (Figure 4), a statistical table of ecological zoning (Table 8), and a spatial map of ecological zones (Figure 5) for the study area. The results indicate that:

1) The area of Zone I (High ESV - High Ecological Risk) showed a decreasing trend, with areas of 1,827.00 km², 1,807.02 km², and 1,622.34 km² in the three respective periods. The ESV per unit area was 2.26×10^5 yuan/km², 9.65×10^4 yuan/km², and 1.12×10^6 yuan/km², showing an increasing trend. The ERI values were 0.0537, 0.0542, and 0.0559. This zone exhibited the highest spatial overlap with water bodies, which accounted for over 50.00% of its area, followed by cropland at approximately 33.71%.

2) The area of Zone II (Low ESV - High Ecological Risk) exhibited an upward trend, accounting for 0.96%, 1.08%, and 1.79% of the study area's total area in the three periods, respectively. The ESV per unit area demonstrated a decreasing trend, with values of 5.41×10^5 yuan/km², 1.68×10^5 yuan/km², and 4.11×10^3 yuan/km². The corresponding ERI values were 0.1609, 0.1381, and 0.0869. Cropland constituted the primary component of this ecological zone, accounting for approximately 32.00% of its area. Notable changes were observed in the proportions of forest land, grassland, and water bodies over the 20-year period. The proportion of forest land decreased from 17.17% to 3.97%, while grassland decreased from 24.47% to 5.80%. The most significant changes occurred between 2012 and 2022, during which forest land declined from 13.65% to 3.97%, and grassland

declined from 24.50% to 5.80%. In contrast, the proportion of water bodies increased from 13.97% to 36.08%, with the most pronounced change also occurring between 2012 and 2022, rising from 13.65% to 36.08%.

3) The area of zone III (Low ESV - Low Ecological Risk) accounted for the largest proportion of the study area and showed an increasing trend, with areas of 6,617.70 km², 6,702.84 km², and 6,862.77 km² in the three periods respectively. The ESV per unit area was 3.57×10^3 yuan/km², 1.44×10^3 yuan/km², and 1.57×10^5 yuan/km², while the ERI values were 0.0315, 0.0307, and 0.0294. This ecological zone was predominantly composed of cropland, accounting for approximately 53.63%, followed by construction land at about 23.88%.

4) The area of zone IV (High ESV - Low Ecological Risk) accounted for the smallest proportion of the study area and exhibited a declining trend. Its area represented 1.92%, 1.06%, and 0.63% of the total study area in the three periods, respectively. The ESV per unit area was 7.16×10^5 yuan/km², 5.88×10^5 yuan/km², and 6.17×10^3 yuan/km², while the ERI values were 0.0366, 0.0351, and 0.0324. Initially, this zone was primarily composed of cropland and water bodies, accounting for 41.63% and 41.68% respectively. However, by the final period, these proportions had decreased to 30.39% and 32.64%. Concurrently, the proportion of construction land increased from 12.92% to 29.80%, indicating that some cropland and water bodies were converted to construction land.

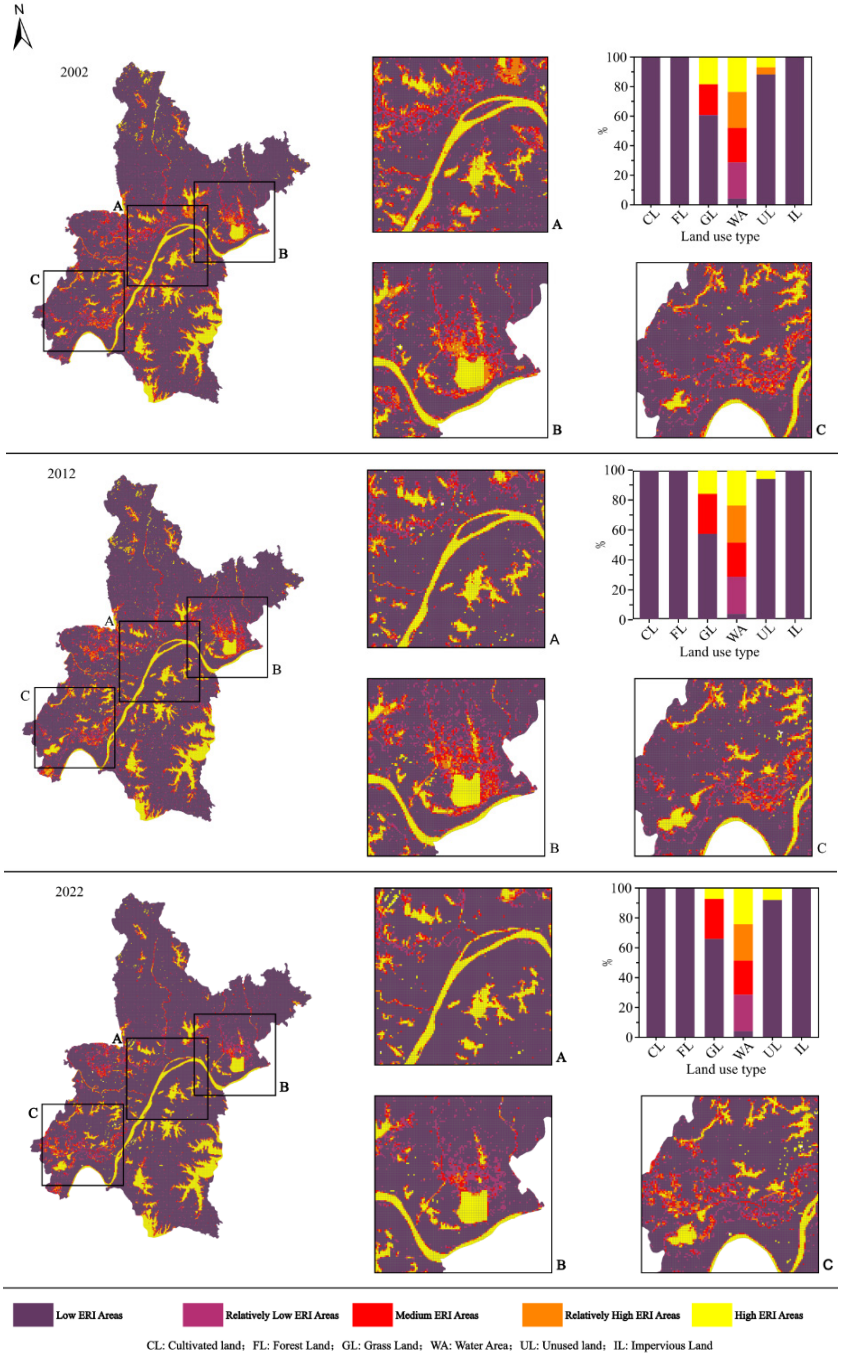

Figure 3 Spatial distribution of landscape ecological risk levels in Wuhan from 2002 to 2022.

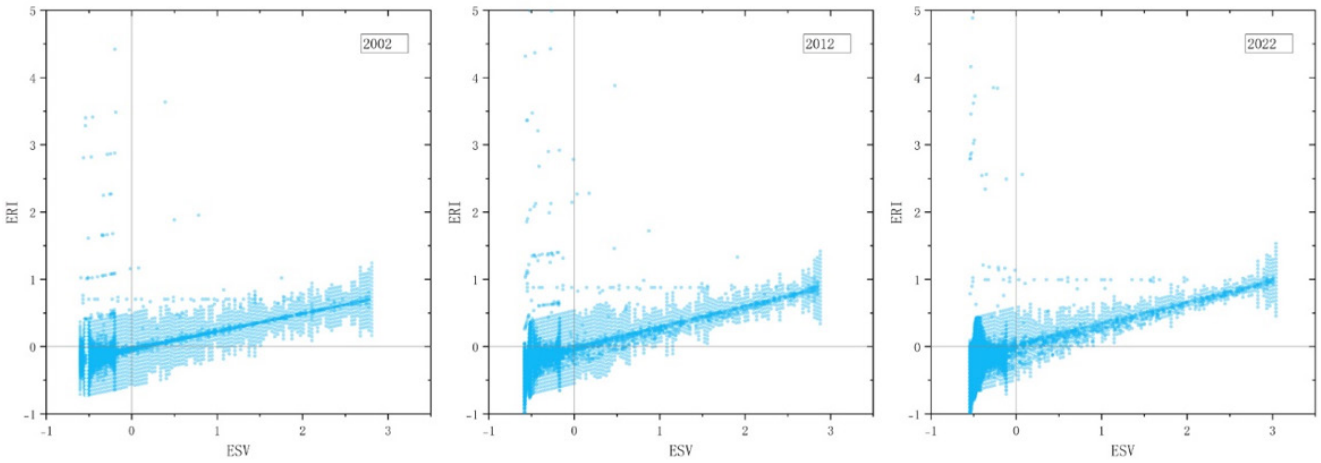

Figure 4 Value-Risk Quadrant Distribution of Ecological Zoning in Wuhan from 2002 to 2022.

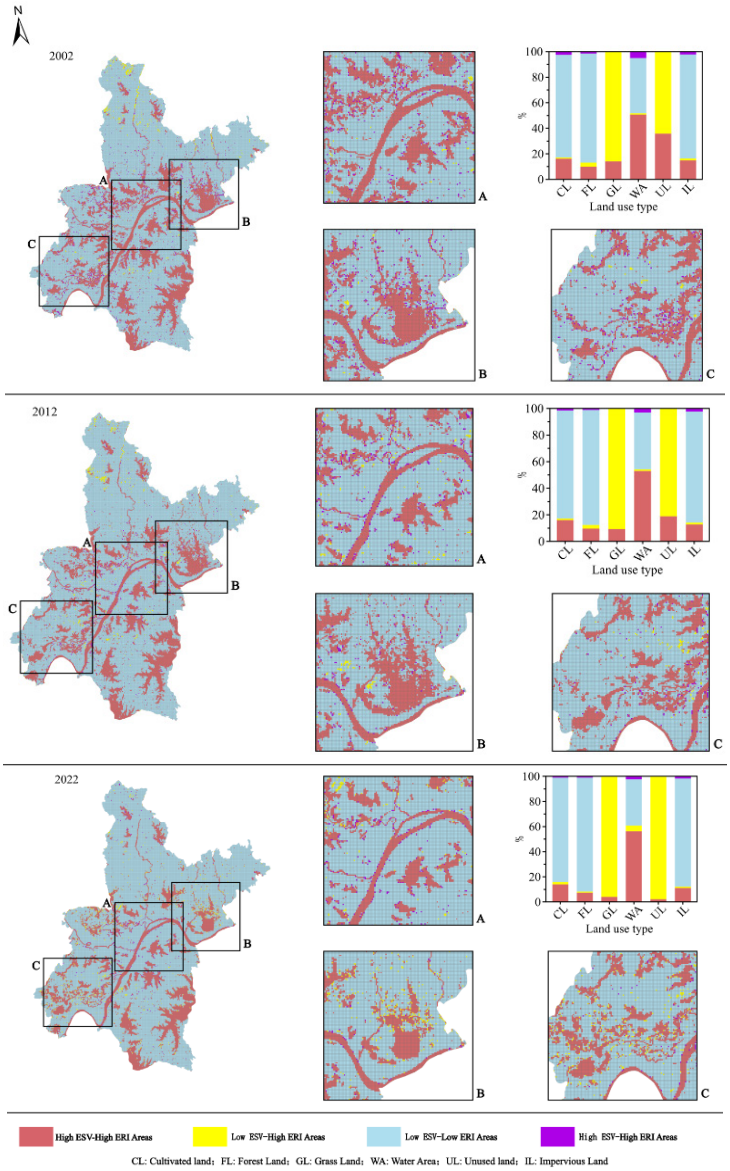

Figure 5 Spatiotemporal Evolution and Zoning Management of Ecological Zones in Wuhan from 2002 to 2022.

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The assessment units were classified into ecological zones based on standardized ecosystem service value (ESV) and landscape ecological risk index (ERI), dividing the study area into four functional categories: ecological restoration zone, ecological reconstruction zone, ecological development zone, and ecological conservation zone. The specific classifications are as follows:

Ecological restoration zone (I): Assessment units within this zone fall into Quadrant I, characterized by high levels of both ecosystem service value and ecological risk. The area is predominantly composed of water bodies and cropland. While it contains high-value aquatic ecosystems, these are susceptible to conversion into cropland, construction land, or other land use types due to significant anthropogenic disturbance. Therefore, priority should be given to the protection and enforcement of regulations for water bodies, preventing ecological security degradation caused by excessive shoreline development. Concurrently, guidance and planning should be enhanced to restore shorelines and protect critical natural resources. For cropland, attention must be paid to environmental deterioration resulting from agricultural pollution and soil degradation. Prompt interception, purification, and remediation measures are necessary for already polluted or degraded water bodies and cropland. Additionally, the protection and restoration of forest land and grassland within the zone should be strengthened.

Ecological reconstruction zone (II): Assessment units in this zone are located in Quadrant II, characterized by low ecosystem service value and high ecological risk. Initially, this zone contained a relatively balanced mix of land types, but a significant portion has since been converted to cropland and water bodies, leading to severe landscape homogenization and habitat destruction. Therefore, it is imperative to strictly define cropland boundaries, implement programs for converting cropland back to forests and grasslands in severely affected areas, and enhance the protection of forest and grassland areas. A robust ecological security monitoring system must be established to restore biological communities and rehabilitate native species habitats, thereby maximizing the conservation of biodiversity.

Ecological development zone (III): Assessment units in this zone are located in Quadrant III, characterized by low levels of both ecosystem service value and ecological risk. Covering the largest extent in the study area, it consists primarily of cropland and construction land. Over the 20-year period, a notable decrease in water bodies within this zone was observed, with conversion mainly to cropland and construction land, while changes in forest land remained relatively stable. This indicates that anthropogenic activities have led to shoreline hardening and homogenization of plant communities, yet a relatively stable ecological structure has subsequently formed under the influence of policy interventions. Management efforts in this zone should focus on the protection and restoration of natural resources. Utilizing native species for greening initiatives can enhance plant diversity and vegetation coverage. Furthermore, hardened shorelines should be modified and restored to rehabilitate the self-purification capacity of water bodies. Creating constructed wetlands utilizing sections of rivers and lakes can be implemented to further enhance this self-purification capacity and generate higher ecosystem service value.

Ecological Conservation Zone (IV): Assessment units within this zone are situated in Quadrant IV, characterized by high ecosystem service value and low ecological risk level. The primary land use types are cropland and water bodies. The abundant water resources contribute to a stable ecological structure and establish a beneficial positive feedback loop, thereby fostering an increase in ecosystem service value. The ecosystem in this zone remains relatively stable. Consequently, management strategies should prioritize the maintenance and protection of the current ecological environment while further minimizing disturbances from anthropogenic activities.

Discussion

Driving mechanisms of the spatiotemporal evolution of ESV and ERI

The continuous decline in the ecosystem service value (ESV) of Wuhan Municipality is closely linked to the reduction in the area of water bodies and cropland. The expansion of construction land has directly encroached upon natural ecological spaces, leading to habitat fragmentation and decreased landscape connectivity.[21] Water bodies contributed a substantial 85.00% to the total ESV of Wuhan, highlighting their critical role in maintaining ecosystem balance. This finding aligns with the research of Zhang Jiarui, confirming that as a primary provider of ecosystem services, fluctuations in the value of water bodies significantly impact the total ESV.[22] During urbanization, water bodies are increasingly encroached upon by construction land. The reduction in water area may diminish their functions in hydrological regulation and biodiversity maintenance, thereby exacerbating regional ecological vulnerability. Research by Li Na et al.[23] in the Loess Hilly Region also demonstrates that protecting water area and improving hydrological environments contribute to enhanced hydrological regulation value.[22] The decline in cropland ESV, accounting for approximately 8.72% to 9.26% of the total ESV reduction, is likely closely associated with agricultural pollution, soil degradation, and monoculture practices. Meanwhile, the expansion of construction land has led to the conversion of forest land and grassland to artificial surfaces, causing the ESV in these areas to approach zero. Although water bodies possess the highest ESV per unit area, their reduction has significantly impacted the total ESV. Low-ESV land types such as grassland and unused land are unable to compensate for this deficit, further exacerbating the imbalance in ecosystem service supply.

The ecological risk index (ERI) of Wuhan ranged between 0.0025 and 0.0029, with low and relatively low ecological risk levels being predominant. This indicates a generally stable overall ecological security situation. However, due to the long-term impact of intensive agricultural activities, the ERI for cropland consistently exceeded 0.020. Although water bodies and forest land experience relatively minor natural disturbances and maintain lower risk levels, their high ecological vulnerability makes them susceptible to factors such as declining ecological stability and anthropogenic interference, which can lead to increased risk levels. The continuous expansion of construction land has exacerbated landscape fragmentation, particularly causing a decline in the landscape connectivity of grassland and water bodies. The observed decrease in the overall ERI reflects the expansion of low-risk areas. Nevertheless, the localized concentration of high-risk zones demands heightened vigilance, as it may be accompanied by localized ecosystem degradation. Future research should focus on the compound effect of "localized high-risk within an overall low-risk context".

Ecological zoning strategies based on ESV and ERI

This study, employing a coupling model of ecosystem service value (ESV) and the ecological risk index (ERI), provides an in-depth revelation of the dynamic interplay between ecosystem services and ecological risks. Based on this analysis, an ecological zoning framework was established, leading to the proposal of corresponding management strategies. Specifically, Ecological Restoration Zone (I), dominated by water bodies and cropland, exhibits an inherent

contradiction between its high ESV and high ERI, highlighting significant anthropogenic pressure on these critical natural resources. The unique river network structure of Wuhan possesses exceptionally high ecological value, necessitating the implementation of stricter shoreline protection measures. Furthermore, Ecological Reconstruction Zone (II), primarily consisting of cropland, faces potential aggravation of ecological risks due to agricultural intensification. Strategies such as returning farmland to water bodies or establishing ecological compensation mechanisms are essential to achieve a coordinated development of agricultural production and ecological conservation.[24] The Ecological Development Zone (III) is extensively distributed, accounting for 78.92% of the total area. This predominance reflects Wuhan's urban expansion model characterized by construction land dominance. There is an urgent need to enhance the ecological resilience of these low-value areas through the addition of green infrastructure. In contrast, the Ecological Conservation Zone (IV), primarily composed of water bodies and cropland, exhibits the most stable ecological security pattern and holds significant scientific value.[25] However, the proportional area of this zone has shown a consistent declining trend over the 20-year period (decreasing from 1.92% to 0.63%). A synergistic pathway integrating "rigid control and flexible restoration" is required to stabilize, restore, and reinforce the conservation zone. This strategy provides a scientific basis for Wuhan's "ecological priority and green development" strategy. For its practical implementation, administrative divisions and community participation should be incorporated to further enhance the strategy's operational feasibility and effectiveness.

Furthermore, the Z-score standardization method effectively overcomes the limitations of traditional studies relying on administrative unit averages, enabling precise identification of key ecological risk areas and addressing previous shortcomings in spatial heterogeneity analysis. However, compared with relevant studies of the Yangtze River Delta urban agglomeration,[26] the proportional area of Wuhan's ecological conservation zones is significantly smaller. This finding highlights the need to pay heightened attention to the issue of "conservation gaps," particularly regarding the prioritized protection of critical water body nodes.

Limitations and future research directions

This study has several limitations. (1) The 30-meter spatial resolution of the data may lead to an underestimation of the role of small-scale ecological patches. (2) The calculation of ecosystem service value (ESV) did not encompass the non-market value of cultural services, such as spiritual experiences. (3) The ecological risk index (ERI) model did not fully account for the dynamic impact of climate change on landscape vulnerability. To address these limitations, future research could further elucidate ecological mechanisms by applying high-resolution remote sensing data, conducting social perception surveys, and performing multi-scenario simulations. Furthermore, integrating the ecological zoning framework with the "Three Zones and Three Lines" policy within territorial spatial planning could help identify synergistic mechanisms between ecological compensation and land transfer policies, thereby promoting the synergistic development of ecological conservation and economic growth.

Conclusion

I. From 2002 to 2022, the total ecosystem service value (ESV) in the study area was 5.021 billion yuan, 4.772 billion yuan, and 4.296 billion yuan, respectively. Water bodies contributed the most to the total ESV, with values of 4.380 billion yuan, 4.151 billion yuan, and 3.644 billion yuan in 2002, 2012, and 2022, accounting for 87.24%, 86.99%, and 84.84% of the annual total ESV in their respective years.

II. Over the 20-year period, the ERI values were 0.0029, 0.0027, and 0.0025 respectively, indicating a generally favorable ecological security status. The study area was predominantly characterized by low-risk areas, accounting for 73.22%, 74.02%, and 77.92% of the total area in the respective years. Relatively low-risk areas were sporadically distributed, while medium-risk areas exhibited extensive contiguous distribution patterns. Relatively high-risk areas were interspersed among low- and medium-risk zones, and high-risk areas demonstrated clustered distribution characteristics.

III. The study area was predominantly characterized by Zone III (Low ESV - Low Ecological Risk), which was widely distributed. Zone I (High ESV - High Ecological Risk) primarily exhibited "corridor-shaped" and "cluster-shaped" distribution patterns, showing significant spatial overlap with water bodies. The area of Zone II (Low ESV - High Ecological Risk) demonstrated an increasing trend and was mainly composed of cropland. Zone IV (High ESV - Low Ecological Risk) accounted for the smallest areal proportion; it was initially dominated by cropland and water bodies but gradually transitioned to construction land over time.

IV. This study provides Wuhan City with precise ecological diagnostic capabilities and differentiated spatial governance tools. For the first time, from the dual perspective of "Ecosystem Service Value-Landscape Ecological Risk," it has accurately identified the spatial distribution and evolutionary patterns of four ecological functional zones in Wuhan, with particular clarity regarding the high-value-high-risk zones centered on water bodies. This creates a "one-map" scientific baseline for urban planning and ecological protection.The research findings can be directly translated into actionable management strategies. For example, they can guide the government to: strictly protect shorelines in ecological restoration zones, implement farmland-to-wetland conversion in ecological reconstruction zones, and increase green infrastructure in ecological development zones. This enables efficient allocation and targeted investment of limited ecological resources.These measures will not only help curb the continuous decline in ecosystem service value and prevent localized high risks, but also represent a crucial step in advancing Wuhan's transition from extensive development to refined governance under the principle of "ecological priority and green development." The study provides essential decision-making support for building a more resilient urban ecological security pattern and achieving sustainable development.

Acknowledgments

None

Conflicts of Interest

The authors have no conflicts of interest to declare.

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