Supplementary Material

1.Methods

(1) Ecosystem services

Table S1. The mean runoff coefficient value of LULC (Ouyang et al., 2016; Xia et al., 2023; Zhou et al., 2024).

LULC	Mean runoff coefficient value
Cropland	19.2
Forest	2.67
Shrub	2.67
Grassland	9.37
Water	0
Wetland	0
Barren	100
Impervious	100

Table S2. The sensitivity of habitat types to each threat factor (Fan et al., 2022; Xia et al., 2023).

Threat factors	Maximum distance of influence	Weights	Decay thpes
Cropland	6	0.5	linear
Road	3	0.5	linear
Construction land	10	1	exponential

Table S3. Habitat suitability and sensitivity of habitat types to each threat factor (Chen et al., 2024; Xia et al., 2023).

Habitat type	Habitat suitability score	Sensitivity to threats			
		Cropland	Urban construction land	Rural construction land	Road
Cropland	0.5	0.3	0.5	0.5	0.2
Forest	1	0.3	0.7	0.7	0.6
Shrub	1	0.3	0.7	0.7	0.6
Grassland	0.7	0.3	0.7	0.7	0.4
Water	0.9	0.6	0.9	0.9	0.6
Wetland	0.8	0.5	0.8	0.8	0.6

Barren	0.2	0	0.3	0.3	0
Impervious	0	0	0	0	0

(2) Ecological process

The formulas for calculating the vigor index components, NDVI and MNDWI, are as follows:

$$NDVI = \frac{NIR-R}{NIR+R}, MNDWI = \frac{p(\ green\ )-p(MIR)}{p(\ green\ )+p(MIR)} \quad (1)$$

Where NIR represents the reflectance in the near-infrared band, and R denotes the reflectance in the red band; p(green) and p(MIR) represent the normalized reflectance values of the green and mid-infrared bands, respectively.

The formulas for calculating resistance (O):

$$O = ESV = \sum A_n \times F_n E_a \quad (2)$$

where O reflects the ecosystem's capacity to resist external disturbances, often represented by ecosystem service value (ESV); A_n is the area (in hm^2) of land use type n; F_n is the contribution coefficient of land use type n to ecosystem services; and E_a represents the per-unit area economic value of ecosystem services (CNY/hm^2).

The formulas for calculating adaptability (A):

$$A = 0.5CONNECT + 0.25SHDI + 0.25CONTAG \quad (3)$$

where adaptability (A) measures the ecosystem's capacity to adjust to environmental changes. CONNECT indicates landscape connectivity, SHDI (Shannon diversity index) quantifies landscape or land use diversity, and CONTAG (contagion index) evaluates spatial distribution and aggregation of land use types.

The formulas for calculating recovery (R):

$$R = \sum S_n \times P_n \quad (4)$$

where recovery (R) reflects the self-regeneration capacity of the ecosystem. S_n is the ecological restoration coefficient for land use type n, indicating its inherent regenerative capacity, and P_n is the area or proportion of land use type n.

The ecological sensitivity index is based on the revised universal soil loss equation (RUSLE), which provides a reliable estimate of soil erosion modulus at the regional scale. The formula is given as:

$$A = R \times K \times LS \times C \times P \quad (5)$$

Where a is the average annual soil loss per unit area (t/ha·yr); R is the rainfall erosivity factor, reflecting the impact of precipitation on erosion; K is the soil erodibility factor, indicating soil susceptibility to erosion; LS is the slope length and steepness factor, capturing topographic effects; C is the cover-management factor, assessing vegetation's protective role against erosion; P is the support practice factor, representing the effectiveness of anthropogenic soil conservation measures.

(3) Landscape connectivity analysis

The Conefor2.6 software calculates the overall connectivity (PC) and element importance (dPC) of ecological patches. The calculation formula is as follows:

$$PC = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\frac{a_i a_j p_{ij}^*}{1+nl_{ij}}}{A_l^2} \quad (6)$$

$$dPC = \frac{PC - PC_{remove}}{PC} \times 100\% \quad (7)$$

In equation (6), n is the number of patches, a_i and a_j are patch areas, A_l is the total landscape area, and p_{ij} is the maximum probability of species dispersal in patches i and j. The range of PC values is [0,1], and the larger the PC value, the stronger the connectivity of the landscape.

In equation (7), the dPC value represents the importance of the deleted component, the PC value is the connectivity probability, and PC_{remove} is the connectivity probability after deleting the corresponding component. The larger the dPC value, the greater the importance of the component.

(4) Ecological sensitivity analysis

Table S4. Classification criterion of influence factors and sensibility in WMA (Cui et al., 2022; Gao et al., 2022; Xiang et al., 2023).

Factors	Sensitivity level					Weight
	High (9)	Relatively high (7)	Moderate (5)	Relatively low (3)	Low (1)	
Vegetation cover	<0.2	0.2-0.4	0.4-0.6	0.6-0.8	>0.8	0.143

Slope (°)	>25	15-25	6-15	2-6	<2	0.238
DEM (m)	>1000	750-1000	500-750	250-500	<250	0.190
Land use	Forest; Shrub; Water	Wetland; Grassland	Cropland	Barren	Impervious	0.285
Soil erosion	Extremely	High	Moderate	Mild	Micro	0.144

(5) Ecological resistance surfaces

Table S5. Resistance factor

Factor	Resistance 1	3	5	7	9	Weight
Land cover	Forest, Shrub	Grass, Cropland	Barren	Water	Impervious	0.22
DEM	<50	50-150	150-250	250-350	>350	0.14
Slope	<3	3-8	8-15	15-25	>25	0.17
NDVI	<0.2	0.2-0.4	0.4-0.6	0.6-0.8	>0.8	0.18
Distance from the road	>3500	2500-3500	1500-2500	500-1500	<500	0.29

(6) Network topological pattern

Degree centrality is calculated as follows:

$$C_D(i) = \frac{k_i}{n-1} \quad (8)$$

where $C_D(i)$ is the degree centrality of node i, k_i is the number of edges connected to node i, and N is the total number of nodes in the network.

Betweenness centrality is defined as:

$$C_B(i) = \sum_{j \neq k \neq i} \frac{\sigma_{jk}(i)}{\sigma_{jk}} \quad (9)$$

where $C_B(i)$ is the betweenness centrality of node i, σ_{jk} is the total number of shortest paths between nodes j and k, and $\sigma_{jk}(i)$ is the number of those paths that pass through node i.

Closeness centrality is defined as:

$$C_C(i) = \frac{n-1}{\sum_{j \neq i} d_{ij}} \quad (10)$$

where $C_C(i)$ denotes the closeness centrality of node i, and d_{ij} is the shortest path distance between nodes i and j.

For a given node i, the clustering coefficient is calculated as:

$$C(i) = \frac{2e_i}{k_i(k_i-1)} \quad (11)$$

where C(i) is the clustering coefficient of node i, e_i is the actual number of edges among the neighbors of i, and K_i is the number of neighbors of node i.

(7) Quantitative regression analysis of network robustness

In order to describe quantitatively the degradation trend of network connectivity with node loss, a linear regression model is introduced to fit the robustness process, and a functional relationship between disturbance intensity and network response is established.

The model form is:

$$y=mx+b \quad (12)$$

Where: y represents the robustness of network connectivity, specifically measured by the ratio of the maximum connected subgraph size (LCC) to the total number of nodes (i.e. GC/N), and the value ranges from 0 to 1. The higher the value, the stronger the structural integrity of the network remains; x represents the proportion of removed nodes; m is slope, representing the rate of decline of robustness with disturbance intensity. The larger the absolute value of slope, the more fragile the network is; b is intercept, representing the initial robustness of the network before disturbance (x=0), which should be close to 1 in theory; R^2 is the coefficient of determination, which measures the fitting accuracy of the model. The closer to 1, the more reliable the regression result is.
By comparing the change of slope m under different attack modes, the sensitivity of network structure to disturbance can be judged. For example, if the slope under target attack is significantly greater than random attack, it indicates that the network has a high degree of dependence on high connectivity or key nodes, and there is a risk of "single point failure" in the structure. On the contrary, if the decreasing trend of robustness under two attacks is similar, it means that the network connection presents distributed characteristics, with strong redundancy and structural elasticity.

2.Results

(1) Spatiotemporal patterns of ecological indicators

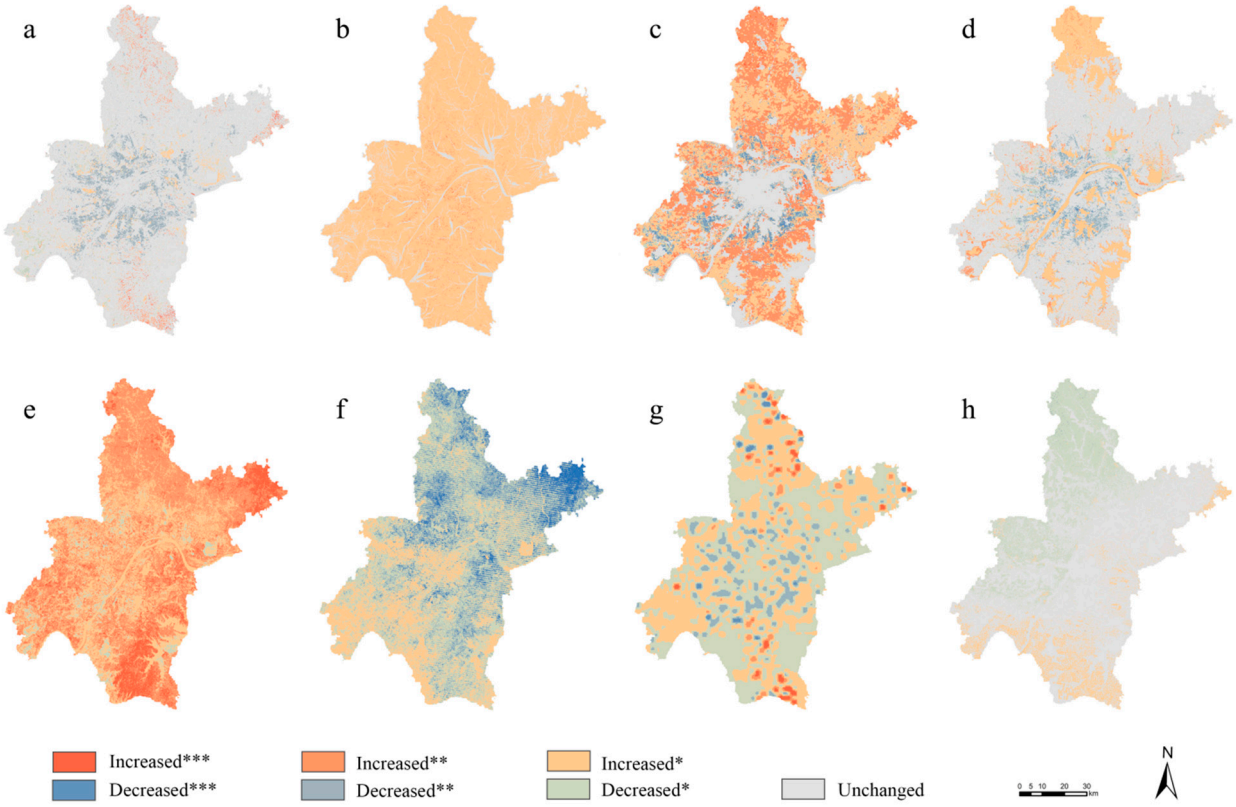

Figure S1. Trends in ecological indicators in Wuhan. The results are based on a comparative analysis between the most recent time slice and the year 2000. a–d represent four ecosystem services: habitat quality, soil retention, carbon sequestration, and water conservation; e–h correspond to four ecological process indicators: NDVI, MNDWI, ecoelasticity, and soil erosion.

(2) EN optimization and effectiveness evaluation

Table S6. Comparative analysis of network optimization under the PFO scenario

Scenario	Attack Type	Regression Slope (m)	R^2	Robustness Trend Description
Original EN	Random attack	-1.11	0.96	Gradual decline; exhibits some redundancy
Original EN	Targeted attack	-0.90	0.81	Rapid decline; structurally vulnerable
Optimized EN	Random attack	-1.07	0.92	Reduced sensitivity; structurally more complex
Optimized EN	Targeted attack	-0.68	0.61	Slowest decline; redundancy improved

Table S7. Comparative analysis of network optimization under the PPO scenario

Scenario	Attack Type	Regression Slope (m)	R^2	Robustness Trend Description
Original EN	Random attack	-1.11	0.96	Gradual decline; exhibits some redundancy
Original EN	Targeted attack	-0.90	0.81	Rapid decline; structurally vulnerable
Optimized EN	Random attack	-1.09	0.92	Initial robustness improved, but decline remains steep; dependence unresolved
Optimized EN	Targeted attack	-0.71	0.60	Enhanced resilience; increased nonlinearity

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