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Original Research

Simulation of the Potential Impact of Land Use Change on Ecological Networks in the Context of Rapid Urbanization

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Abstract

Ecological networks (ENs) are considered an effective means of biodiversity and ecosystem protection. However, the potential impact of land use change on ENs in rapid urbanization remains poorly understood. This study combines patch generation land use simulation model (PLUS), circuit theory and complex network theory to simulate the evolution of ENs in Jingmen City from 2020 to 2050, and constructs a comprehensive evaluation framework for evaluation from two perspectives of function and structure. The results show that ecological sources are decreasing in three scenarios in 2050. In particular, the natural development and urban development scenarios lose 122.14 km^2 and 155.55 km2, and lose 2 key corridors, respectively. Urban expansion is essential reason for the loss in ecological network. Additionally, the conflict between ENs and land development lead to functional degradation, manifested as an increase in connectivity defects and a decrease in local centrality. Land expansion will weaken the structural robustness of ENs, increase areas with weak ecological connections, and thin the backbone structure. The potential negative impact of different expansion patterns on ENs varies, with restricted development scenario being the smallest. The result reminds us that may be promoting urbanization at the expense of sacrificing areas with significant ecological value.

Keywords: ecological networks, land expansion scenario, PLUS model, complex network theory, rapid urbanization

Introduction

As the unceasing advancement of urbanization, the rapid expansion of built-up areas contributes to large-scale loss, degradation, and fragmentation of natural habitats, which poses a grave menace to biodiversity and ecosystem services [1, 2]. Increasingly, ecological networks (ENs) have been supposed to form an ideal landscape method to curb these adverse aftereffects [3, 4]. ENs are constructed to organize isolated and fragmented natural habitats into network forms, thus forming a network system that maintains ecosystem connectivity and integrity [5]. However, the enormous efforts to implement ENs construction have not achieved the expected results, and biodiversity is still dropping globally [6, 7]. Several studies indicate that the function

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and structure of ENs have not been adequately maintained due to invasion during land development, particularly in the context of fast urbanization [8, 9], leading to such low efficiency in nature conservation practices. Therefore, constructing ENs followed by maintaining their good connectivity becomes the key to effectively conserve biodiversity and ecosystems, and identifying the potential impacts of land use change on ENs is crucial for the conservation and restoration of ENs.

Since the 20th century, ENs have been the hotspot of ecological protection research, and the basic research paradigm of "identifying ecological sources and extracting ecological corridors" has been formulated in the long-term development [10]. Based on the above basic paradigm, critical natural areas and ecological corridors with essential connectivity have been identified in a wide range of areas globally, and regional ENs have been established at different scales and in a vast number of regions, including cities, regions, even the whole country [11-15]. However, previous studies have primarily specialized in ENs construction, and studies exploring the influences of land use change on ENs are currently extremely limited. A couple of studies analyzing the evolution of ENs during historical land-use change have found that there has been a continuous degradation and loss of ENs function and structure [16, 17]. This is because land development activities have become more intense than ever in recent decades, resulting in the ongoing erosion of ecological sources and corridors by land expansion. Therefore, to explore the potential negative impacts of future land use changes on ENs is crucial to maintain the functional continuity and structural stability of ENs. However, existing studies commonly consider ENs only as restricted areas for land development, and predict future land use distribution patterns by setting up scenarios of restricted development or ecological protection [18, 19]. These studies still concern the dynamic change of land use, however, ignoring the potential impacts of future land use change on ENs. Therefore, there is a need to strengthen the simulation of the evolution of ENs in the process of future land use change, as well as the research on the evaluation of the impact of land use change on ENs.

With the maturation of the theory of ENs, research on the assessments of ENs has progressively gained attention, and is now primarily concerned with functional and structural aspects. The core function of ENs is to connect fragmented habitats to restore ecosystem connectivity, therefore connectivity has emerged as a key indicator for evaluating ENs' functional effectiveness [20]. Some scholars used connectivity indices for instance circularity (α), node corridor ratio (β), and connectivity (γ) to reveal the effect of historical land use change on the connectivity function of ENs [10]. These indices, however, are global indicators and are unable to rate the partial connectivity of ENs. The application of circuit theory enables the detection of connectivity defects in ENs like obstacles and pinch points that restrict the flow of ecological elements [21]. The centrality index measures the transmission function and relative accessibility of network nodes, allowing for an accurate evaluation of the relative significance of each component of EN to the overall connectivity [22]. On the other hand, the structural evaluation of ENs has also received significant attention. Structural evaluation is essentially still aimed at maintaining and improving connectivity, so some researchers optimize ENs by adding sources and corridors while continuing to use α, β, and γ indices to assess the difference in network structure between before and after optimization [23]. And other studies examine the coverage blind zones of ENs and suggest the Blind-zone centroid-based scheme (BCBS) model finds and improves the sparsely distributed blind areas of the network as a technique to assess the structural enhancement of ENs [24]. Still, the majority of these assessment techniques ignore the topological structural characteristics, which are crucial for maintaining ENs' stability. The introduction of complex network theory offers a fresh perspective for structural assessment studies of ENs, since on the basis of the theory of landscape ecology, ENs are a unique complex network consisting of two landscape pattern elements: ecological sources and ecological corridors [25]. To better understand the structural properties of ENs and the structural stability characteristics in the presence of disturbances, complex network analysis techniques including community detection algorithm [26], Minimum Spanning Tree (MST) [27], and robustness analysis [28] can be applied.

In summary, research on ENs has yielded rich outcomes, but remains characterized by the following shortcomings. First, rarely have studies investigated and evaluated the potential impacts of future changes in land use dynamics on ENs, instead focusing mostly on the construction of ENs and the evolution of ENs in the course of historical land expansion. Second, current methods of functional assessment rely heavily on global indicators and are unable to effectively assess the connectivity deficiencies and local importance of ENs, while methods of structural assessment tend to ignore the topological features of ENs. Finally, the evaluation of ENs relies on single perspectives and indicators and lacks a comprehensive evaluation framework, thus making it difficult to comprehensively detect the impacts of land expansion on ENs.

China's urbanization has been progressing at a rapid pace since the 1990s [29]. Prevention of damage to ENs from these substantial increases in built-up land is a huge challenge because land use changes brought on by urbanization are almost irreversible throughout human life spans [2, 30, 31]. Given the speed at which China is urbanizing, it is critical to strengthen the reporting of potential negative impacts of future land use changes on regional ENs to create a proactive conservation strategy. However, relatively little has been reported in this area, so this study presents comprehensive research with Jingmen City, Hubei, China as the study target. The innovation of this study is based on the perspective of scenario simulation, integrating functional and structural evaluation methods to reveal the possible effects on ENs during future land use change. Therefore, we identified the following research objectives: (1) based on dynamic analysis, we combined the PLUS model, MSPA, and circuit theory to simulate the evolution of ENs under different land expansion scenarios; (2) we constructed an integrated evaluation framework for ENs by combining both functional and structural perspectives to probe the latent effects of future land use changes on ENs. The research aims to provide forward-looking suggestions for the protection and restoration of ENs.

Methods

Taking Jingmen City as the study object, this study has formulated a comprehensive research framework for detecting the potential impacts of future land use changes on ENs, which can also be applied to other rapidly urbanizing regions. This will help to reveal the hidden threats of land expansion to ENs and contribute to the development of prescient measures for the protection and restoration of ENs.

The research framework is divided into two steps (Fig. 1.). In the first step, we combined the PLUS model, MSPA and circuit theory to simulate the evolution of ENs under three land expansion scenarios of natural development, restricted development and urban development in Jingmen City from 2020 to 2050, in order to exploit the changes and spatial-temporal differences in ENs. In the second step, we combined circuit theory, centrality evaluation index and complex network theory to establish a comprehensive evaluation system from both functional and structural perspectives, and applied it to complete the exploration of the potential impacts of land use change on ENs.

Study Area

Jingmen City is in central Hubei Prefecture, China, and includes five subordinate districts: Duodao District, Zhongxiang City, Shayang County, Jingshan District, and Dongbao District (Fig. 2.). The city has a high topography and is encircled by mountain ranges to the east, west, and north. The Han River, an important tributary of the Yangtze River, runs through the city, and the central and southern sections are plain lakes washed by the Han River with low topography. Jingmen is abundant in natural resources and has a sound ecological foundation, with over 170 species of major terrestrial wildlife, including more than 20 species of national key protected wildlife. Woodland is the predominant land use type in this city, and over half of its territory covered by forests. These wild species have access to large-scale, high-quality habitats due to the massive primary forests in the eastern Dahongshan Mountains and the western Jingshan Mountains. Jingmen City, however, has gone through an era of rapid expansion in the past decades, with an urbanization rate of 58.74% and more than 80% in the Duodao District in 2020. Land use has changed substantially due to continuous urbanization, and built-up area continues to erode on natural areas, resulting in a significant decline in ecological quality and biodiversity. Also, Jingmen City will continue to see rapid urbanization for an extended period. Therefore, modeling the functional and structural evolution of Jingmen's ENs is required to highlight the potential threats caused by future land expansion, for managing the city to safeguard biodiversity and ecological integrity in a preventative perspective.

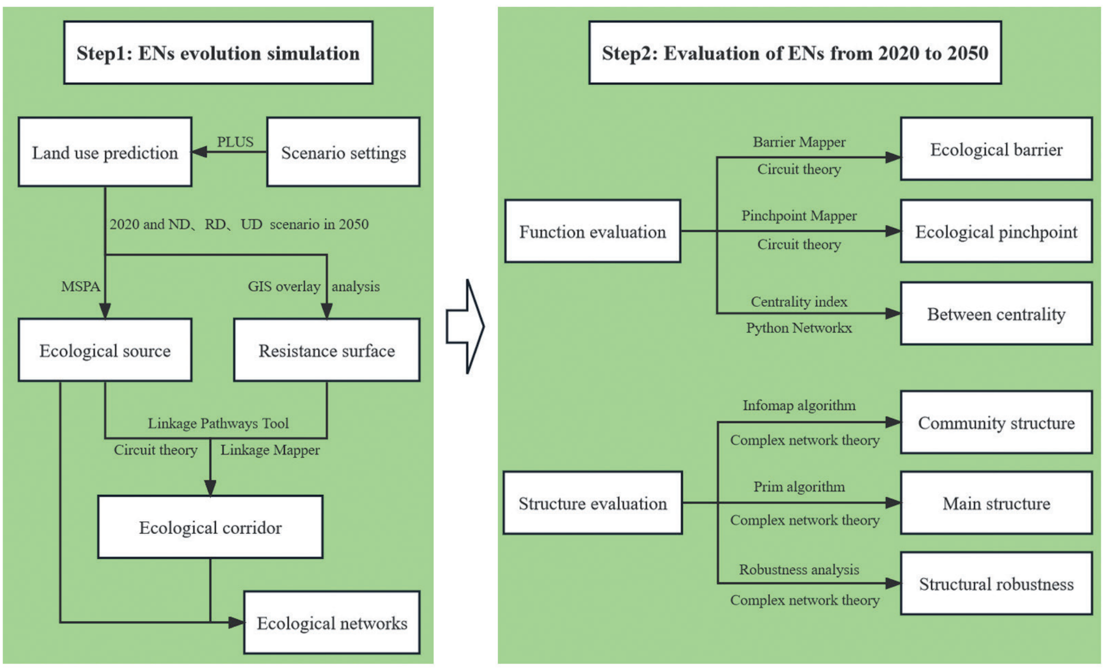


Fig. 1. Research framework.

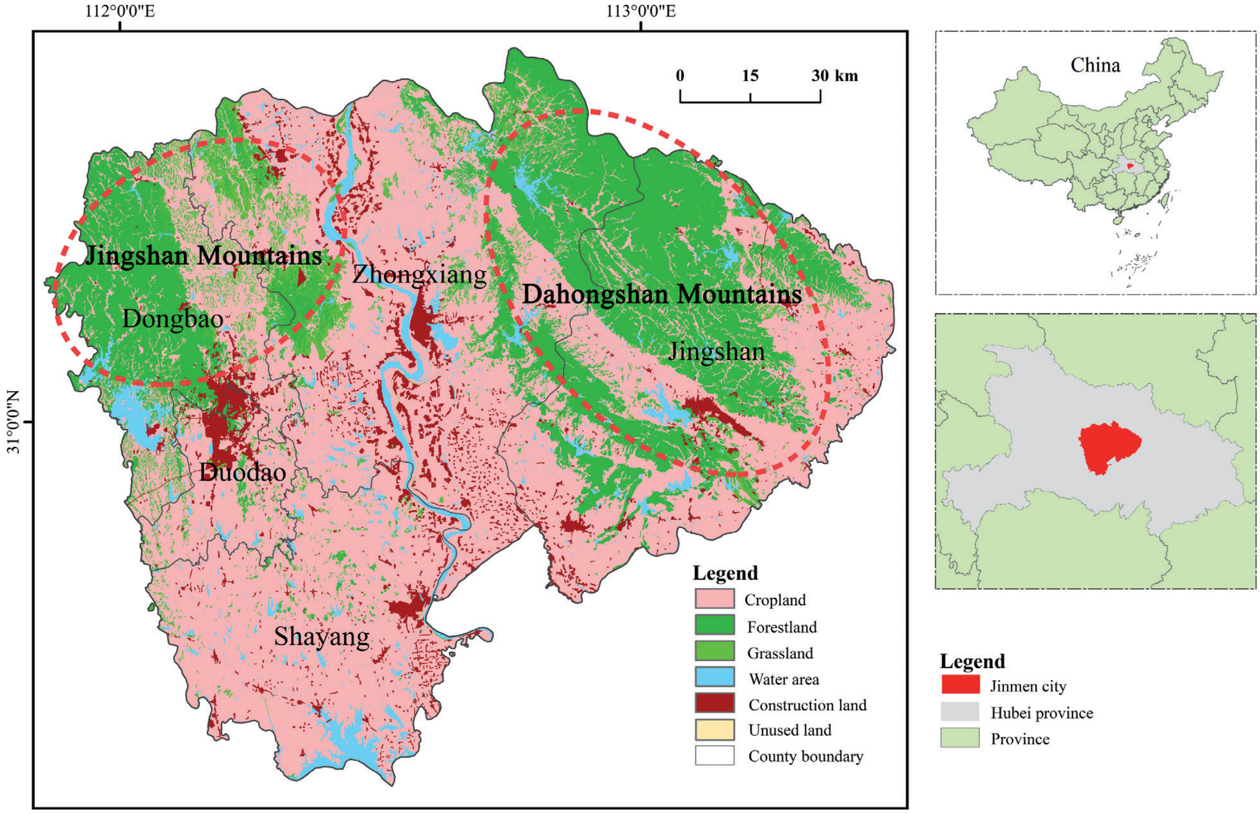


Fig. 2. The spatial distribution of location and land use types in Jingmen City.

Data Sources

The data utilized in this research primarily consists of (1) 30m resolution land use data from GlobeLand30 (https://www.globallandcover.com/), including three periods in 2000, 2010, and 2020, which we reclassify into six major categories, cropland, forest land, grassland, water area, construction land, and unused land. (2) Digital elevation model (DEM) from NASA (https://www.nasa.gov/) at 30m resolution, which we use to generate elevation, slope, and terrain undulation data. (3) Population density data from WorldPop (https://www.worldpop.org/geodata) at 1km resolution. (4) Nighttime light data from the National Tibetan Plateau Science Data Center (http://data.tpdc.ac.cn/zh-hans/) at 1km resolution. (5) NDVI data from Resource and Environmental Sciences and Data Center, Chinese Academy of Sciences (http://www.resdc.cn). (6) 1:1 million national basic geographic information data from the National Basic Geographic Information Center (https://www.Webmap.cn/). (7) Annual precipitation and temperature data from WorldClim (https://worldclim.Org/data/monthlywth.html).

Ecological Networks Evolutionary Simulation

Land Use Prediction

Patch-generating land use simulation (PLUS) model is a Cellular Automata (CA) model for patch-scale land use/land cover (LULC) change simulation based on raster data [32]. It integrates a rule mining framework based on the land expansion analysis strategy and CA based on a multi-type stochastic patch seeding mechanism, and can be utilized to mine the drivers of land expansion and predict the dynamic changes of land use more accurately [32]. For land expansion rule mining, the model entails extracting the expansion component of land use types from two or three stages with land use data. The CA model is then utilized to predict the spatial distribution of each type of land use [32]. On the premise of the land use data from 2000 to 2020, this model was employed to simulate the temporal and spatial changes in land use in Jingmen City in 2050.

To explore the evolution of ENs during future land use changes, we set up and simulate three land expansion scenarios to construct the ENs in 2050 and 2020 for comparative analysis, taking into account all scenarios as much as possible.

(1) Natural Development Scenario (ND) follows the historical expansion pattern of LULC from 2010 to 2020 and uses a Markov chain-based transfer probability matrix to control for land use change in 2050 (Table.S1) [19].
(2) Restricted Development Scenario (RD) is set up to safeguard essential habitats, so the core areas of woodlands and grasslands are identified using the MSPA method and included in the restricted areas of land use conversion [7].
(3) Urban Development Scenario (UD) highlights the priority for meeting urban development needs. The

probability of construction land expansion in this scenario is 10% higher than in the ND scenario, and the amount needs to be modified since a portion of other land types will be converted to building land, in addition to the change in demand for building land [8]. The adjustment is done as follows:

$$A_{adjust}^{k} = (A_{UD}^{C} - A_{ND}^{C}) \times H^{k-u}$$

Where A_{adjust}^{k} is the area subtracted from land use type k in the ND scenario. A_{UD}^{C} and A_{ND}^{C} are the areas of construction land in the UD and ND scenarios, respectively, and H^{k-u} is the ratio of area loss due to encroachment of construction land into land use type k from 2010 to 2020 (Table S2).

To validate the exactitude of land use prediction, we use the Kappa coefficient to verify the applicability of the PLUS model. In general, a Kappa coefficient higher than 0.75 means that the simulation results have a high fit with the actual situation. Referring to previous research [8, 18, 19], we take 2000 as the initial year, select 15 driving factors (Fig. S1.), and land use data for the two periods of 2000 and 2010 as predictor variables into the PLUS model, and calculate the growth probabilities of each land use type in Jingmen city. On this basis, the PLUS model is used to output the 2020 land use forecast results and compare them to the actual land use distribution. With a Kappa rating of 0.82 for our projected land use results for 2020, it is clear that utilizing this verified parameter in the simulation of 2050 land use is strongly justified.

Ecological Sources Identification

Ecological sources are large-scale habitats that perform a major role in landscape connectivity, as well as the conservation of biodiversity and ecosystems. MSPA is a binary image structure and connectivity mining method, founded on the mathematical morphological principles of erosion, expansion, opening, and closing [33]. It requires reclassifying land use raster data into foreground and background by describing the properties and connectivity of geometric landscape elements, and identifying and segmenting the images into seven landscape types: core, islet, perforation, edge, bridge, branch, and loop [34]. We extract woodland and grassland as foreground and other land use types as background, then use the Guidos Toolbox to perform MSPA analysis on the raster data. Among them, cores represent relatively large habitat patches for wildlife and are the most advantageous landscape types for species habitat and reproduction, and dispersal, and they are used as alternative patches for ecological sources. To reduce the effect of landscape fragmentation, we exclude sporadic patches with an area of less than 3 km2, and the rest of the patches are used as ecological sources.

Ecological Corridors Extraction

Ecological corridors are ribbon-like elements with connecting functions that provide suitable pathways for species dispersal, energy flow, and material cycling. The Linkage Mapper toolbox of circuit theory is utilized in this study to select ecological corridors in Jingmen City that connect ecological sources. Based on the circuit theory, organisms with random wandering characteristics are comparable to electrons, ecological resistance surfaces and ecological sources are similar to electronic resistance surfaces and circuit nodes [35]. Meanwhile, suitable pathways for species dispersal can be identified by simulating the biological flow process [35]. Ecological sources are the starting point of species dispersal, and to simulate the ecological corridor between biological sources, a resistance surface needs to be constructed. The resistance value represents the energy expended by the species to cross the land surface, and the higher the energy consumption, the more difficult it is to pass, while the resistance surface is generated by a combination of natural and human disturbance factors [19]. We select three types of resistance factors, including land use, topography, and distance from different roads to create a comprehensive resistance surface (Table S3), taking into account the factual state of the study area and relevant studies [36].

Ecological Networks Evaluation

Most of the previous ENs evaluations concentrated on a single perspective, however, developing a comprehensive evaluation is conducive to identifying the latent influences of land use change on ENs in a more thorough way. This study combines both functional and structural perspectives to establish an integrated assessment framework. On the one hand, the core function of ENs is to restore ecological connectivity, and we conduct a functional assessment of ENs through circuit theory and centrality index. The ecological barriers and pinch points identified utilizing circuit theory are considered connectivity defects of ENs, and the centrality index is used to measure the connectivity of each component of ENs. On the other hand, the structural integrity and stability of ENs determine whether their functions can be performed properly, and this study introduces complex network theory for the structural assessment of ENs. The topological characteristics such as community structure and backbone structure of ENs, as well as the structural robustness characteristics of ENs under external attacks, are analyzed using complex network theory.

ENs Functional Evaluation

(1) Ecological Barriers, Pinch Points Identification

Ecological barriers are parts of corridors that impede the flow of species, usually consisting of unnatural landscapes such as construction land and cropland, and are functional defects of connectivity in ENs. The presence of barriers increases the amount of energy required for species migration and reduces species survival [21]. In circuit theory, the restored value of cumulative current represents the benefit after repairing the barrier, and the high-value area is the barrier point [36]. We use the

Barrier Mapper tool in the Linkage Mapper toolbox to recognize ecological barriers.

Ecological pinch points are narrow parts of corridors where currents are dense, and generally consist of natural landscapes such as forests. On the one hand, pinch points are essential and critical areas for species migration and are therefore indispensable parts. On the other hand, pinch points are formed because the corridor is squeezed by anthropogenic landscapes for instance built-up land and cultivated land on both sides, and the corridor range is contracted, causing species to have to converge here to pass, so pinch points are also the connectivity defects of ENs. In circuit theory, the current concentration represents the net mobility of the organism, and the zone with high values of current concentration is the pinch point [37]. We utilized the Pinchpoint Mapper tool in the Linkage Mapper toolbox to recognize ecological pinch points.

(2) Centrality Evaluation

The centrality index is a partial statistic that measures the connectivity of nodes and edges. More elements are connected, and connectivity is stronger when nodes and edges are more central [22]. Applying the centrality index to the functional assessment of ENs can determine the significance of ecological sources and corridors to the integral connectivity of the network [38]. In this study, we use the NetworkX library in Python to calculate the betweenness centrality of ecological sources and corridors in Jingmen. The betweenness centrality can mirror the transmission function of each component of ENs, and if an ecological source or corridor is on multiple shortest paths of other components, then it has a strong transmission function.

$$BC = \sum_{s,t \neq i} \frac{d_{st}(i)}{d_{st}}$$

Where d_{st} describes the quantity of shortest paths from s to t, and $d_{st}(i)$ denotes the quantity of nodes i passing through in the shortest path from s to t.

2.4.2. ENs structural evaluation

ENs are special complex networks constituted of ecological sources and corridors. Ecological sources, which can be abstracted as nodes, are the basic units that constitute ENs, whereas ecological corridors, which can be abstracted as edges, represent the role relationships between the units. Topology is a significant element in the study of complex networks, including several important structures such as community structure, tree structure, and structural robustness, and the application of complex network analysis in the assessment study of ENs helps to explore the structural changes of ENs.

(1) Community Structure

Complex networks typically consist of multiple communities, where nodes of the same community are tightly associated with each other, while nodes of dissimilar communities are weakly connected, and different communities are connected by some edges [39]. Applying community discovery algorithms to detect the hidden community structure of ENs can explore and reveal the aggregation behavior of their constituents, as well as the internal interaction characteristics of ENs [40].

The Infomap community discovery algorithm was utilized to discern the community structure of ENs in our study. Infomap algorithm is a network clustering algorithm that combines random wandering and information compression to identify communities in complex networks [26]. It uses two layers of Huffman Coding to characterize the order of node encoding for information flow in the network. The first layer is the encoding of the community, and the second is the encoding of nodes within the community, and then the nodes are classified into different communities by searching for the path with the least coding length by random wandering. The algorithm has two features, firstly, the codes of nodes within different communities can be reused, which significantly reduces the length of the information description. Secondly, nodes that are visited more frequently are given shorter codes, while the opposite is true for longer codes. This means that the total length of codes for nodes in the same community is comparatively short because the more connected the nodes are, the more frequently they are visited [26]. We use Infomap online (https:/www.mapequation.org/Infomap/) to probe the community structure of eco-nodes in Jingmen.

(2) Backbone Structure

In complex networks, a connected graph without loops is the most concise and dominant structure, called the spanning tree [27]. The tree with the smallest sum of the weights of all edges in the spanning tree is the Minimum Spanning Tree (MST), which has four properties: connectivity of all nodes, no loop structure, minimal connection cost, and the amount of nodes is the amount of edges plus one [27]. As a result,, MST is the backbone in a complex network, and once the nodes and edges in it are lost, the structure of ENs will be severely damaged. Applying MST analysis helps to uncover the critical and superfluous components of ENs.

We use the Prim algorithm to explore the hidden minimum spanning tree of ENs as a way to identify the backbone structure that plays a major connecting role. In the Prim algorithm, edges with smaller connection costs or weights are prioritized for connection until all nodes are connected and satisfy the four principles mentioned above [39]. In this study, the inverse of Between centrality is used as the connection cost, and the lower the value of the inverse, the lower the connection cost of the edge. We perform this work in Python, identifying the MST as the backbone of the ENs and the rest as the residual structure.

(3) Structural Robustness

The loss of constituent elements during continuous land expansion has a dramatic effect on the connectivity of ENs, so the spatial structure of ENs is a guarantee for their proper functioning. Structural robustness analysis can be applied to assess the ability of ENs, a complex network system, to retain its function during disruptions

[28]. When ENs are damaged, the robustness reflects not only the resistance of the network structure to destruction, but the competence of the network to restore the damaged structure as well [41].

To assess the influence of future land use changes on the structural robustness of ENs, we use the NetworkX library in Python to abstract the actual ENs, generate the undirected topology graph, and set up two attacks, random attack, and intentional attack, to simulate the network robustness under different node removal rules. The random attack is grounded on the rule of randomly removing network nodes, while the intentional attack is grounded on the rule of removing network nodes in order of centrality from the largest to the smallest. Connectivity robustness and global efficiency are often used to weigh the structural robustness of complex networks, with connectivity robustness reflecting the ability of the network to sustain steady connectivity after damage, and global efficiency reflecting the efficiency of transmission between network nodes after damage [42]. The formula is as follows:

$$R_c = \frac{C_{max}}{n - n'}$$

Where R_c is the connectivity robustness of ENs, n is the amount of original nodes, n' is the number of removed nodes, and C_{max} is the number of nodes in the maximum connected subgraph in the network after node removal.

$$E = \frac{1}{n(n-1)} \sum_{i \neq j \in G} \frac{1}{d_{ij}}$$

Where E is the global efficiency of ENs, n is the number of nodes, G is the set of network nodes, i and j are any two nodes in the set G of network nodes, and d_{ij} is the shortest path length between nodes i and j.

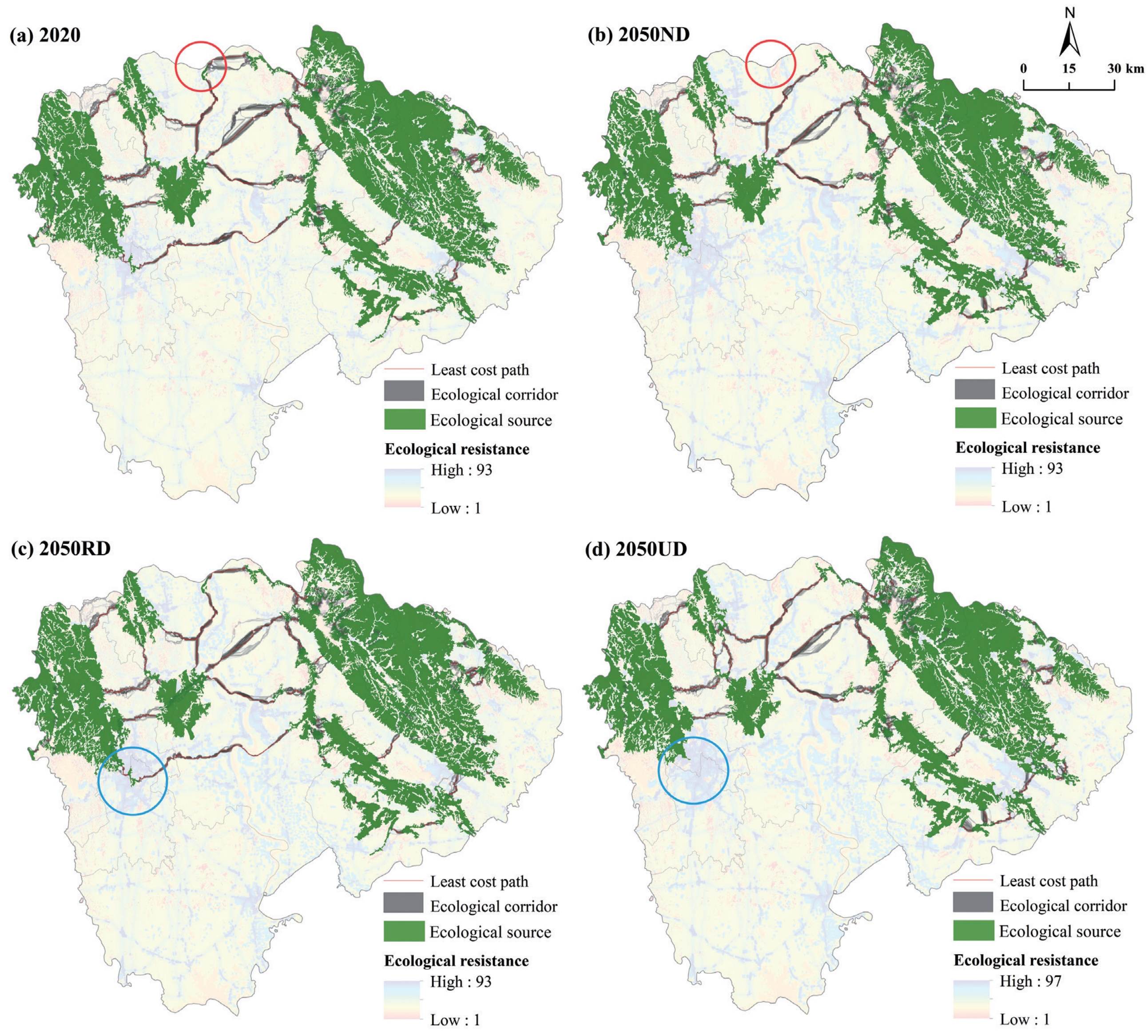


Fig. 3. Spatial distribution of Jingmens ecological network.

Results

Spatiotemporal Evolution of ENs

The ecological sources in Jingmen City are mostly distributed in the Dahongshan Mountains and Jingshan Mountains on the sides, with less distribution in the central and southern plain lake areas (Fig. 3.). Compared with 2020, there is no major change in the spatial distribution of ecological sources in the three scenarios in 2050, but there are significant differences in the ecological sources. The total ecological sources in the ND and UD scenarios decrease from 2815.82 km^2 in 2020 to 2693.68 km^2 and 2660.27 km^2, respectively, while the RD scenario decreases slightly to 2813.81 km^2. In the ND scenario, 13.59% and 25.71% of the ecological sources lost are converted to cropland and construction land, respectively, and 8.63% and 34.84% of the ecological sources lost in the UD scenario are also converted to cropland and construction land. It can be found that urban and farmland expansion is an extremely important cause of natural habitat loss. According to our predictions, the flat topographic plain lake areas in northern, central, and southern Jingmen, which are most suitable for urban and agricultural development, are the main areas of building land growth. Therefore, in the ND and UD scenarios, an important ecological source is lost in the northern part of Zhongxiang City and the Duodao District during future land expansion, respectively (red and blue circles in Fig. 3.). In addition, a large amount of the lost ecological sources remains as woodlands and grasslands, which are transformed into non-source lands due to further fragmentation of local natural habitats to form larger-scale habitats.

The ecological resistance in high-value zones is mostly distributed in the central urban area of each district and county in Jingmen (Fig. 3.), showing a multi-core distribution trend, with the highest ecological resistance in the Duodao District. From the results of the scenario prediction, the scope of high ecological resistance will gradually diffuse from the core to the periphery in the future. The mean value of resistance in 2020 is only 28.94, the mean values of resistance in ND and UD scenarios increase to 31.04 and 31.50, respectively, and the value in the RD scenario increases to 30.49. This indicates that the energy required for the circulation of organisms and ecological elements is increasing under the impact of land development activities.

The spatial extent of ecological corridors between ecological sources is identified from the ecological resistance surface (Fig. 3.). From a distribution perspective, these ecological corridors are extensively distributed in the mountainous zones to the east and west and in the plain lakes in between, and the significant ecological sources in the eastern Dahongshan Mountains and the western Jingshan Mountains are effectively connected through the ecological corridors in between. Ecological corridors often lose their practical significance due to the loss of ecological sources, thus two important corridors are lost in the central and northern Jingmen in the 2050 ND and UD scenarios. This means that alternative pathways for species migration are reduced, ecological connections in the mountains on both sides of the study area will be further weakened, and the risk of biodiversity loss rises. From a scale perspective, the overall area of the ecological corridor is 842.46 km^2 in 2020, and 751.17 km^2, 858.94 km^2, and 780.67 km^2 in 2050 for the ND, RD, and UD scenarios, respectively. From a composition perspective, the number and ratio of construction land in the ecological corridor show an increasing trend from 2020 to 2050 (Table 1), even though the total area of the corridor in the ND and UD scenarios see a significant reduction in the overall corridor area. This phenomenon indicates a significant increase in human-dominated landscapes in ecological corridors as a result of urban expansion. Moreover, urban expansion at the expense of agricultural land loss is also a significant phenomenon, so the amount and percentage of cultivated land within the ecological corridor show a decreasing trend in all predicted scenarios.

Functional Evaluation Results of ENs in Different Scenarios

Results of Ecological Barrier and Pinch Point Identification

The presence of ecological barriers can hinder the effective circulation of ecological elements and is a connectivity defect in ecological corridors. From a

Table 1. Ecological corridor land use type composition.

Land use type		Cropland	Forestland	Grassland	Water area	Construction land	Total
2020	Area(km^2)	303.57	346.6	92.02	89.24	11.00	842.46
	Percentage(%)	36.03	41.14	10.92	10.59	1.32	100.00
2050ND	Area(km^2)	244.77	332.12	80.58	81.65	12.03	751.17
	Percentage(%)	32.59	44.21	10.73	10.87	1.60	100.00
2050RD	Area(km^2)	266.14	377.38	103.11	95.58	16.71	858.94
	Percentage(%)	30.98	43.94	12.01	11.12	1.95	100.00
2050UD	Area(km^2)	254.59	340.70	91.33	79.60	14.44	780.67
	Percentage(%)	32.61	43.64	11.69	10.19	1.85	100.00

Table 2. Composition of land use types at ecological barriers.

Land use type		Cropland	Forestland	Grassland	Water area	Construction land	Total
2020	Area(km^2)	27.49	0.75	0.35	0.38	7.48	36.48
	Percentage(%)	75.38	2.07	0.97	1.06	20.52	100.00
2050ND	Area(km^2)	36.17	1.05	0.69	1.04	10.30	49.27
	Percentage(%)	73.41	2.14	1.41	2.13	20.91	100.00
2050RD	Area(km^2)	28.29	0.64	0.40	0.55	12.54	42.43
	Percentage(%)	66.67	1.52	0.95	1.30	29.56	100.00
2050UD	Area(km^2)	36.91	0.90	0.85	1.09	12.01	51.77
	Percentage(%)	71.29	1.75	1.64	2.11	23.21	100.00

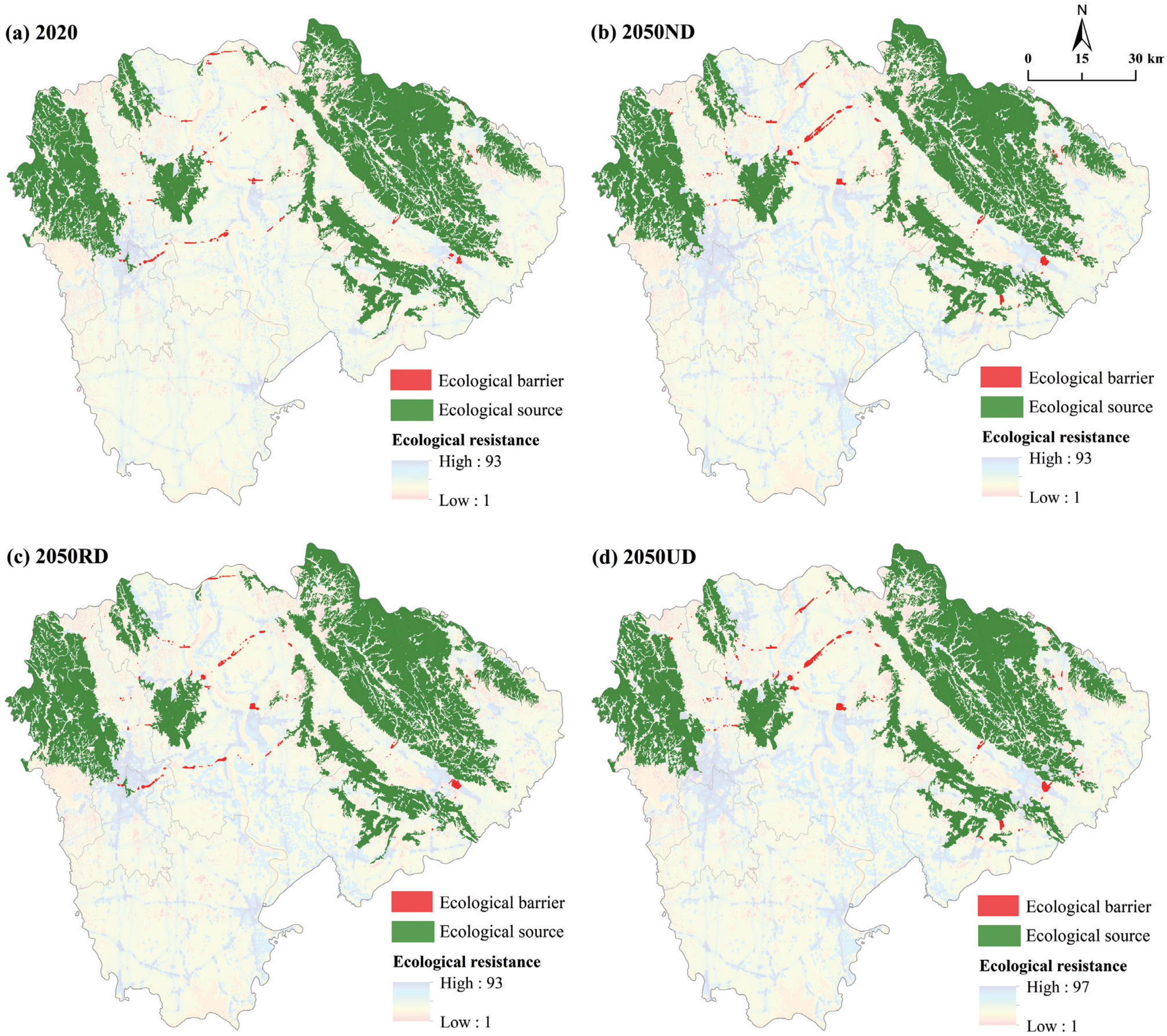


Fig. 4. Spatial distribution of ecological barriers.

scale perspective, the area of ecological barrier points in Jingmen shows an increasing trend (Table 2), which is 36.48 km^2 in 2020, while the scale of ecological barriers increases to 49.27 km^2, 42.43 km^2, and 51.77 km^2 in 2050 in ND, RD and UD scenarios, among which the ecological barriers increase the most in UD scenario. From a composition perspective, the ecological barriers mostly consist of cropland and construction land, and the sum of both accounts for more than 90% of the overall area of the barriers in the three scenarios in 2020 and 2050. However, the proportion of cropland decreases in all three scenarios, from 75.38% in 2020 to 73.41%, 66.67%, and 71.29% in ND, RD, and UD scenarios, respectively. In contrast, the ratio of construction land is increasing in all scenarios, with ND, RD, and UD scenarios increasing from 20.52% to 20.91%, 29.56%, and 23.21% in 2020. From a distribution perspective, the ecological barriers in 2020 are mostly distributed in Zhongxiang District, Duodao District, and the southern part of Jingshan District (Fig. 4.). While the number and area of barriers in the central and northern parts of Zhongxiang City significantly increase in the three scenarios in 2050, especially the ND and UD scenarios will increase more than the RD scenario. The dense distribution of cropland and construction land in these areas, as well as the flat topography that is suitable for urban expansion, pose a major threat to the ecological corridors both now and in the future.

The distribution of ecological pinch points in Jingmen does not change significantly from 2020 to 2050, but the area of ecological pinch points shows a decreasing trend. 15.72 km^2 in 2020, while the area of ecological pinch points decreases to 12.14 km^2, 15.52 km^2, and 10.18 km^2 in 2050 in ND, RD, and UD scenarios, respectively. Fig. 5. shows that the ecological pinch points usually occur in areas with dense built-up land. When the ecological corridor passes through the construction region, the corridor area is often reduced under the pressure of the built-up land, resulting in the formation of pinch points. This will be more serious in the future land expansion process, so the area of ecological pinch points in the ND and UD scenarios is significantly reduced. In particular, the UD scenario decreases by 1.96 km^2 more than the ND scenario, which means that the natural habitats are continuously eroded under the influence of urban expansion, and the ecological corridors are further squeezed at the pinch points, and there is a risk of breakage, posing a serious threat to the circulation of species and ecological elements.

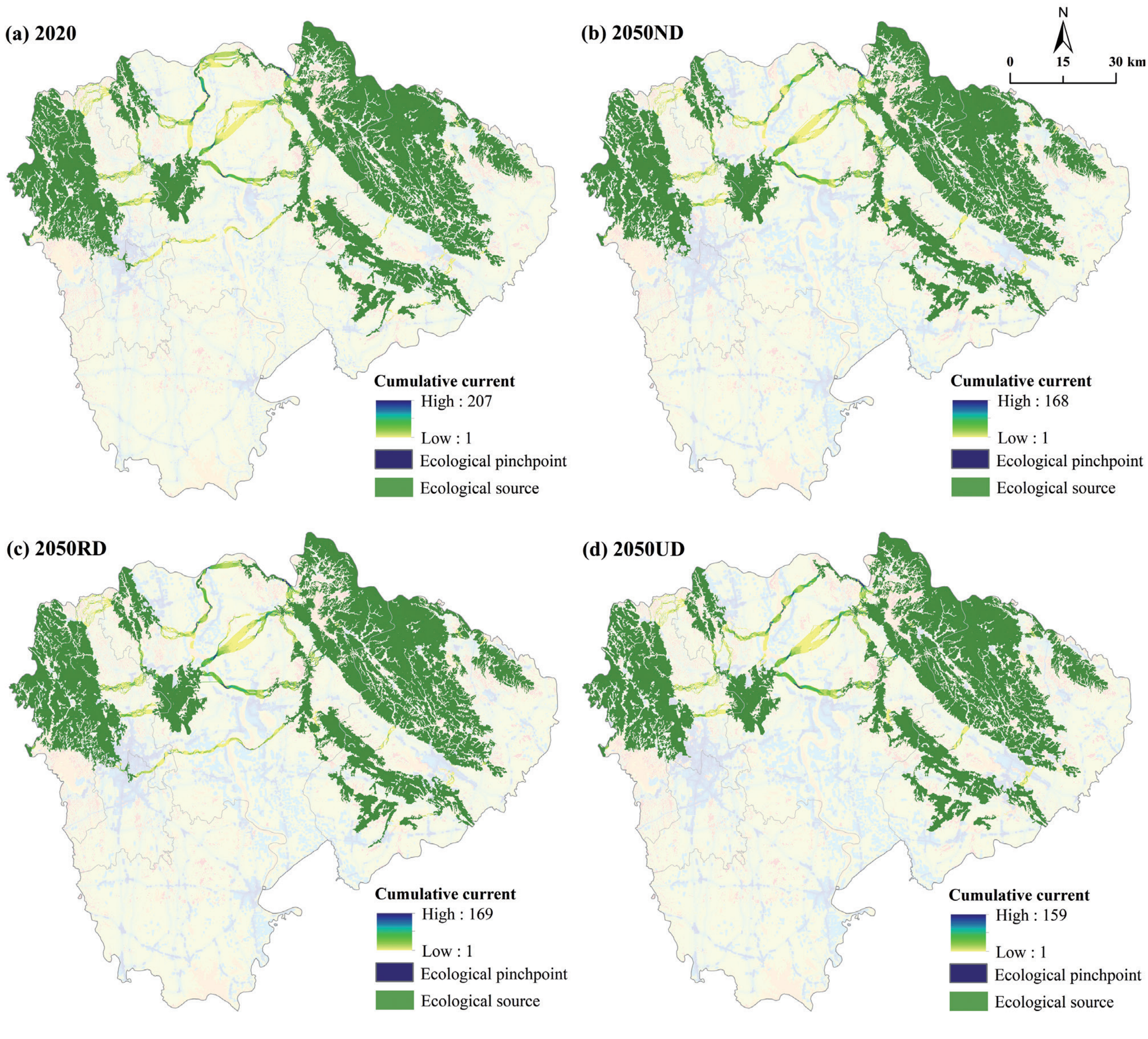


Fig. 5. Spatial distribution of ecological pinch points.

Centrality Evaluation Results

Betweenness centrality can reflect the connectivity of ecological networks by measuring the transmission function of nodes and edges. Overall, the centrality of the ecological network changes by 2050. The mean value of centrality for ecological sources in 2020 is 0.0674 (Table 3), however, it decreases to 0.0657 and 0.0659 in 2050 in the ND and UD scenarios and increases slightly to 0.0675 in the RD scenario. The ecological corridor follows a similar trend to that of nodes. The ND and UD scenarios in 2050 decreased from 0.0545 in 2020 to 0.0514 and 0.0498, and the RD scenario increased to 0.0554. It indicates that the transmission function of the ecological network is affected to some extent in the ND and UD scenarios, inducing a decrease in its connectivity, while the transmission function of the ecological network could be better maintained in the RD scenario.

The centrality values of the components of ENs can reflect the spatial differences in network connectivity.

Table 3. Centrality mean of ecological networks.

Centrality mean	Ecological source	Ecological corridor
2020	0.0674	0.0545
2050ND	0.0657	0.0514
2050RD	0.0675	0.0554
2050UD	0.0659	0.0498

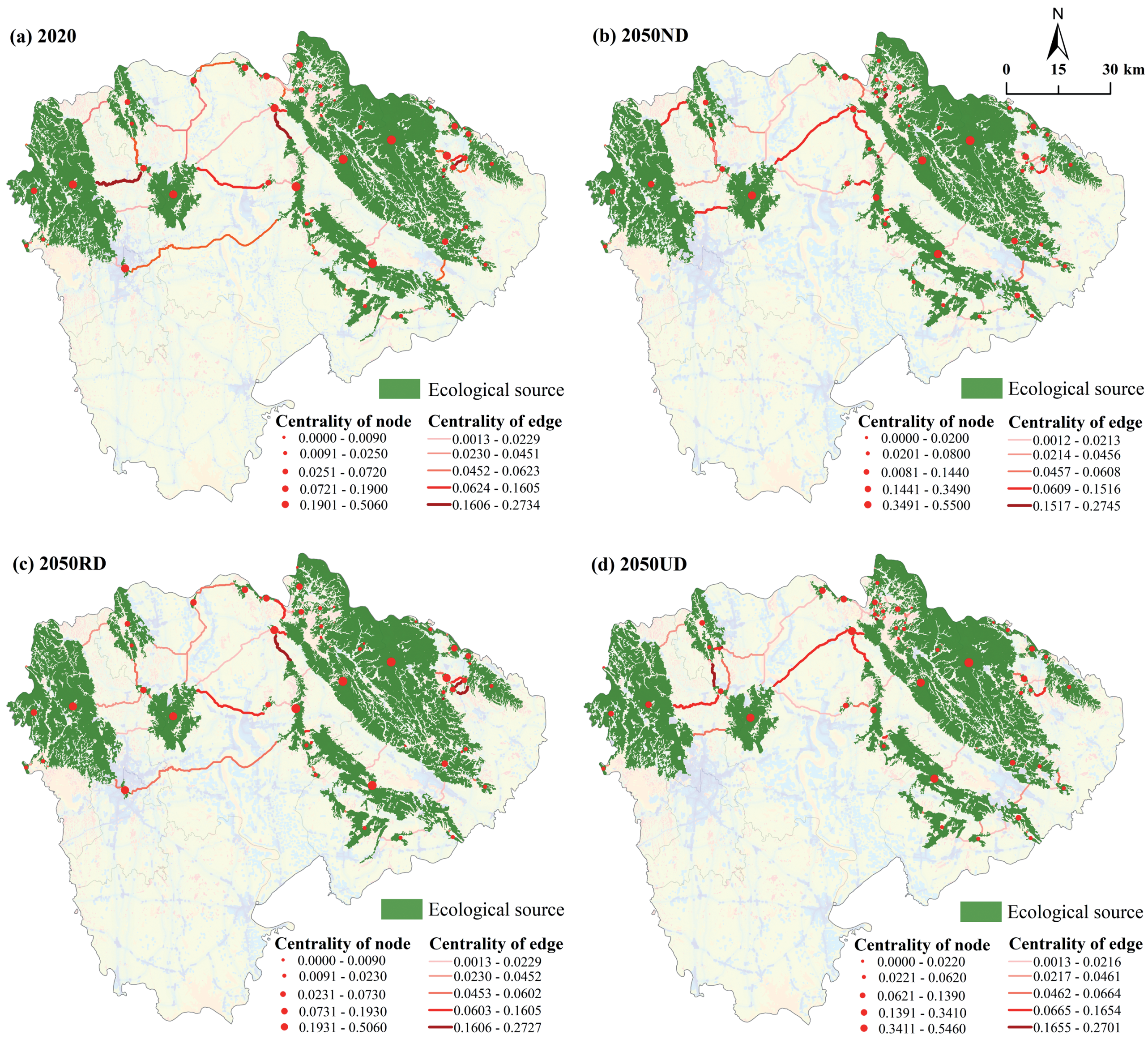


Fig. 6. Spatial distribution of ecological network centrality.

Partially, there is some variation in the centrality of the parts of the ecological network. In 2020, ecological sources distributed within the eastern Dahongshan Mountains and the western Jingshan Mountains have high centrality (Fig. 6.), and the massive primary forests in these zones provide high-quality habitats and migration corridors for species, and are therefore important for biodiversity maintenance. However, we found that ecological source centrality decreases in the southern Dahongshan Mountains and Jingshan Mountains in the 2050 ND and UD scenarios. Similarly, the ecological corridors linking the mountainous zones to the east and west of Jingmen have high centeredness in 2020 (Fig. 6.), while the centrality of ecological corridors in these areas diminishes to different degrees in all development scenarios in 2050. Compared to the RD scenario, the corridor centrality decreases more severely in the ND and UD scenarios, mainly in the central and northern plain lakes. This region is a major area for urban and agricultural development, and the dramatic land expansion unavoidable has a negative effect on the corridors distributed in this region, which will further weaken the ecological connections between the mountainous areas on both sides.

Structural Evaluation Results of ENs in Different Scenarios

Community Structure Analysis

Based on the results of the construction of the 2020 ENs in Jingmen, we use the Infomap algorithm to detect the community composition of the ecological network and identify a grand total of five different ecological communities (Fig. 7.), including Dongbao-Zhongxiang Western Ecological Subregion (D-ZWES), Zhongxiang Northeast Ecological Subregion (ZNES), Jingshan Central-North Ecological Subregion (JC-NES), Jingshan

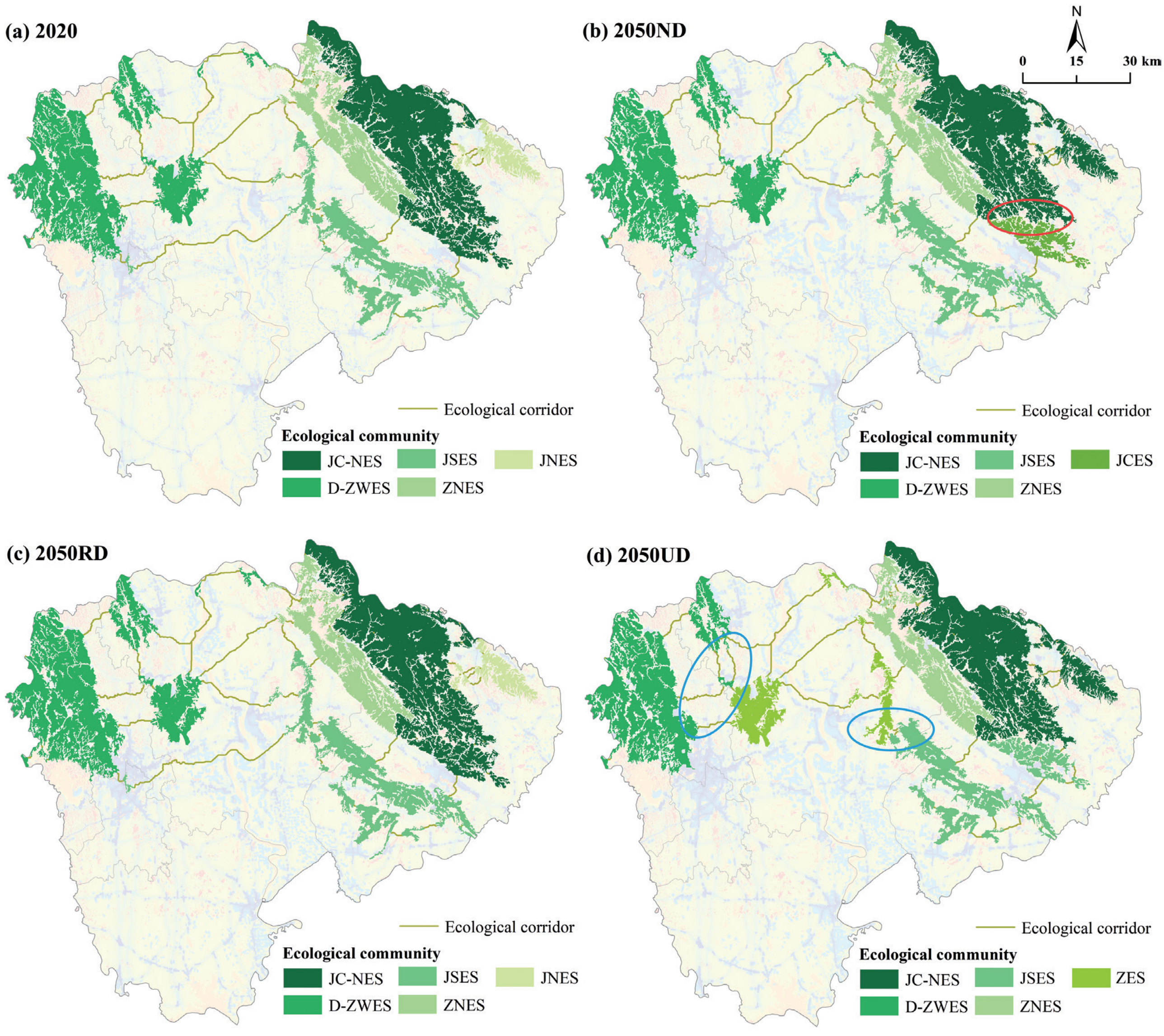


Fig. 7. Spatial distribution of ENs community structure.

Northeast Ecological Subregion(JNES), and Jingshan Southern Ecological Subregion(JSES). D-ZWES is separated from other ecological subregions by dense urban and cropland on both sides of the study area, indicating that the ecological linkages between the two major mountain ranges in eastern and western Jingmen are not particularly strong. The ecological connections between the eastern and western Jingmen Mountains are not particularly close. Moreover, ZNES, JCNES, JNES, and JSES cover parts of the southern foothills of the Dahongshan Mountains separately, which implies that there are zones of weak ecological connectivity within the Dahongshan in eastern Jingmen.

Compared to 2020, the natural habitats in the 2050 RD scenario are relatively well protected and therefore their community structure does not change significantly. In the ND scenario, ZNES becomes more tightly connected to JCNES, but the ecological connection between some ecological sources formerly belonging to the southern part of JCNES is weakening (red circles in Fig. 7.), splitting a new ecological subregion (JCES, Jingshan Central Ecological Subregion). And in the UD scenario, the ecological community structure further changes, and some important ecological sources in D-ZWES and JSES located in Zhongxiang City break away from the original community (blue circles in Fig. 7.) and form a new ecological subregion (ZES, Zhongxiang Ecological Subregion). These phenomena suggest that the community structure of ENs in the ND and UD scenarios would be more affected by land expansion than in the RD scenario.

Backbone Structure Analysis

The Prim algorithm is used to identify the MST of the ENs as a way to mine the critical and redundant parts of the ecological network in Jingmen City. The MST is the most important backbone structure of the ENs, consisting of ecological nodes and edges, and its use

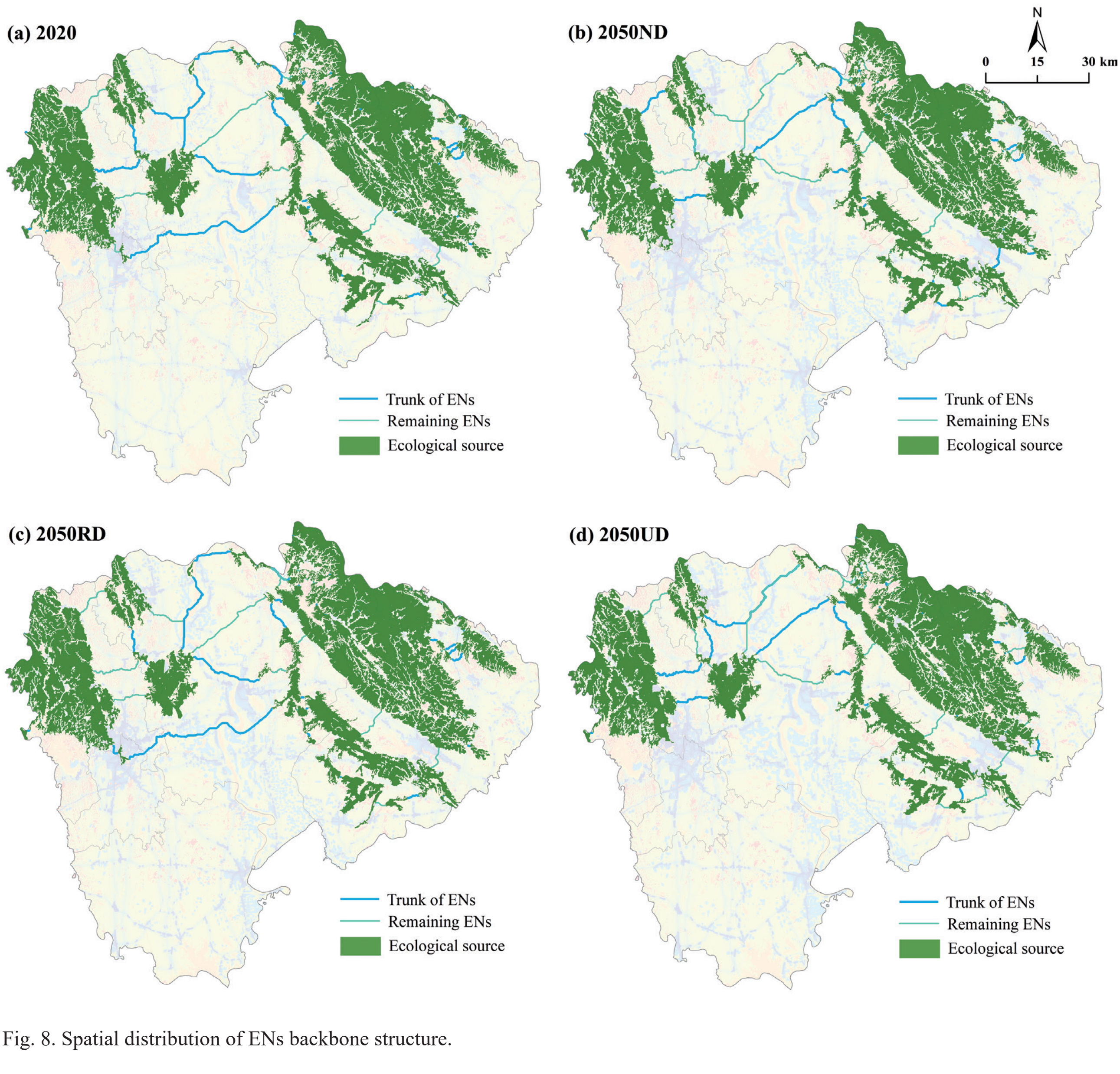
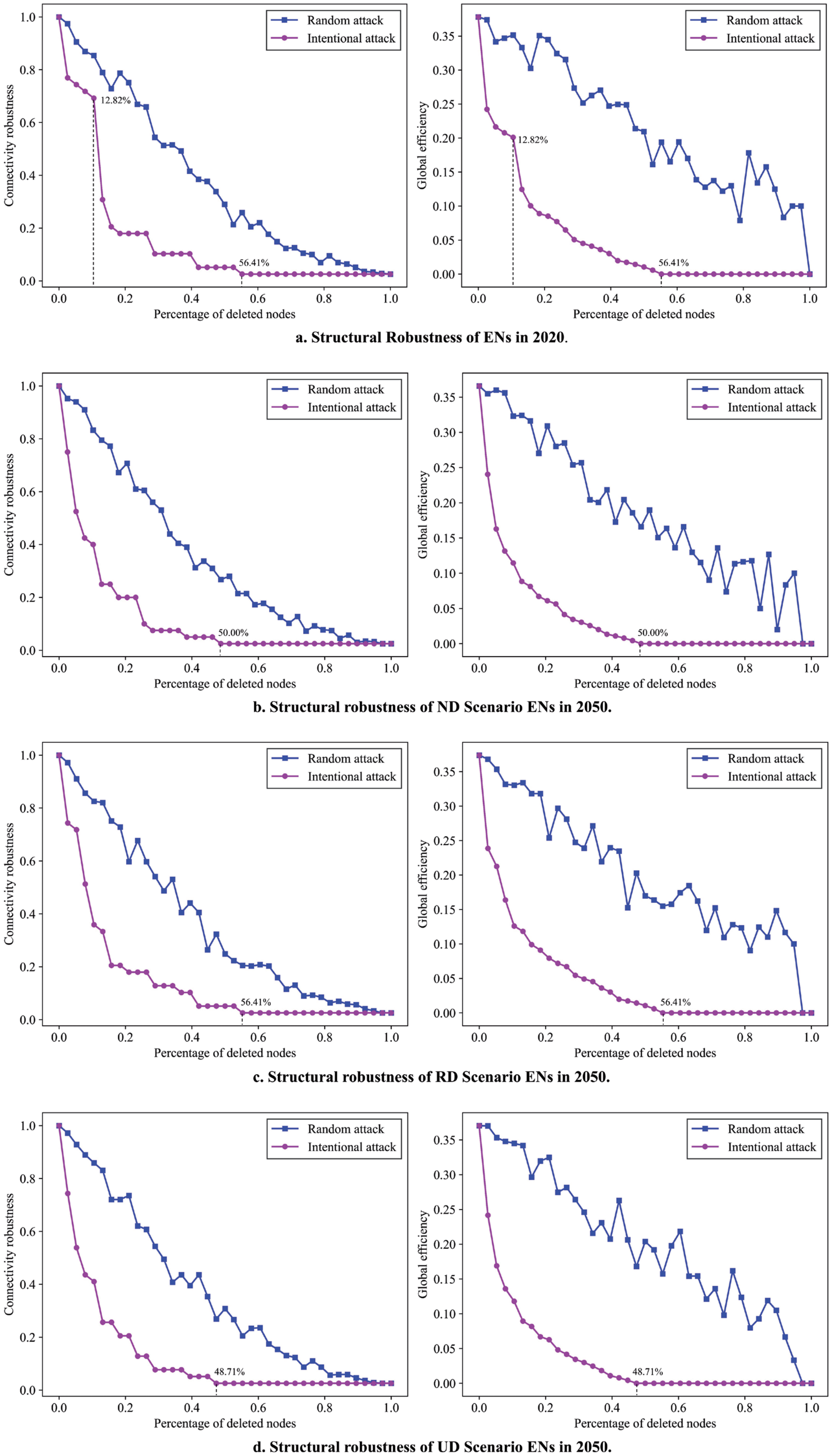


Fig. 8. Spatial distribution of ENs backbone structure.



a. Structural Robustness of ENs in 2020.

b. Structural robustness of ND Scenario ENs in 2050.

c. Structural robustness of RD Scenario ENs in 2050.

d. Structural robustness of UD Scenario ENs in 2050.

Fig. 9. Structural robustness of ENs in 2020 and under different land expansion scenarios in 2050.

of minimum cost connects all the nodes to form a fully connected network. For the ND, RD, and UD scenarios in 2020 and 2050, the number of trunk edges is 38, 39, 38, and 38, respectively, while the rest are non-trunk structures (Fig. 8.). In 2020, the trunk edges are mostly densely distributed in the central and northern regions, which have many alternative paths and high accessibility, and play a significant role in efficacious connecting the habitat patches in the mountainous zones to the east and west, indicating that this region is the most critical part of the ecological network structure. However, in 2050, the distribution of trunk edges in the central and northern regions gradually thins out, especially in the ND and UD scenarios, and several trunk edges evolve into non-trunk edges, indicating that the accessibility of this region decreases significantly, and its role in maintaining the effective connectivity of habitat patches throughout the region is also significantly reduced.

Structural Robustness Analysis

In the "random attack" mode, the change in connectivity robustness and global efficiency in 2020 and the three scenarios in 2050 are similar, showing a slow decline (Fig. 9.). In the "intentional attack" mode, the change in structural robustness in 2020 and the three scenarios in 2050 showed different characteristics (Fig. 9.). When the nodes with the highest intermediary centrality are removed, the connectivity robustness and global efficiency of the ecological network drop sharply in 2020, followed by a short period of stability until the connectivity robustness and global efficiency of the network drop sharply again after 12.82% of the nodes are removed. However, the rate of decline in the connectivity robustness and global efficiency of the network becomes more dramatic in the three 2050 scenarios, indicating that the three networks are more sensitive to external disturbances. Furthermore, by comparing the threshold values for complete network collapse during node removal, we observe that both connectivity robustness and global efficiency drop to zero in 2020 when 56.41% of the nodes are removed, indicating that the 56.41% node removal ratio is the threshold for ecological network collapse. However, the threshold of network collapse in 2050 drops to 50.00%, 56.41%, and 48.71% in ND, RD and UD scenarios, respectively, which implies that the structural robustness of the ecological network will be lower in 2050, and the ability to resist external disturbances becomes weaker, especially in the UD scenario where the ecological network structure is the most fragile.

Discussion

Insights From Simulating Potential Impacts of Future Land Use Change on ENs

With the rapid urbanization, a massive amount of natural habitats have been substituted by built-up land and agricultural land [43], and ENs running through the whole landscape will unavoidably be tremendously affected [44]. Previous studies have begun to pay attention to the evolution of ENs [16, 45, 46], and have discovered that due to drastic changes in land use, the area of ecologically valuable ecological sources has been on a decreasing tendency, and some critical ecological corridors have disappeared, which has had a significant negative impact on the functions and structure of regional ENs. However, these studies normally focus only on the evolution of ENs during historical land use change. In view of the fact that the period of rapid development will continue for a long time to come and the dramatic changes in land cover and landscape will persist, ENs remains at serious risk of degradation [47, 48]. It is essential to simulate the evolution of the ENs during the future land use development process in order to underpin the preservation and restoration of ENs [7]. Additionally, some studies have begun to evaluate ENs to probe the impacts of land use development on ENs, such as assessing the stability [41] and structural resilience of ENs [28, 49], and assessing the changes in the connectivity function of ENs [10]. However, there is still a lack of a comprehensive assessment framework that can enable a comprehensive detection of the impacts of land use change on ENs. This study developed an integrated evaluation framework for ENs based on multi-scenario simulations in order to observe the functional and structural evolution of ENs under the impacts of future land expansion. The framework synthesizes both functional and structural aspects by integrating assessment methods such as circuit theory and complex network theory as a means to provide a comparative assessment of ENs under three scenarios for 2020 and 2050 in Jingmen, in order to better understand the potential impacts of land use change on ENs. The necessity of conducting this research is further emphasized by our results, which bring to light the hidden threats to ENs. The following insights summarized from the results will contribute to broadening the understanding and horizons of researchers and planners.

Spatiotemporal Response of ENs to Land Use Change

The spatial distribution of ENs is often significantly influenced by the distribution of land use [16, 50]. Therefore, the distribution pattern of ENs usually shows heterogeneity, where the phenomenon is also found in previous studies [17]. In our study, the ecological sources in Jingmen are primary spread on the Dahongshan and Jingshan mountain ranges on the east and west sides, which are the most natural zones for wildlife habitats. In contrast, the central and southern plains and lakes are densely populated with construction land and cropland, and the high intensity of urban construction and agricultural production activities result in fewer ecological sources. Jingmen's ecological corridors, on the other hand, are mostly situated in the mountainous zones on the east and west sides and in the plain lakes in the middle, which together constitute a channel for the spread of regional organisms and ecological elements. The intermediate ecological corridors pass through or bypass urban and cropland areas, effectively connecting important ecological sources in the eastern Dahongshan Mountains and the western Jingshan Mountains. The southern part of Jingmen also has no ecological corridor passing through it due to the scarcity of large habitat distribution, thus forming an ecological blind zone with sparse ENs. These results are highly similar to those obtained in previous studies [36].

As well, the spatial and temporal evolution of ENs is significantly influenced by land expansion [30, 47, 51]. The results of the ENs evolution simulation show that the loss of natural habitats due to urban expansion is a major cause of the decline of ecological sources [17, 52]. 122.14 km2 of ecological sources are lost in the ND scenario in 2050, with 25.71% converted to construction areas. This phenomenon is more evident in the UD scenario, where 34.84% of the 155.55 km2 of ecological sources lost are converted to built-up land. The topography usually determines the location of new urban areas [47], and the flat topography of the central plain lake area is most suitable for urban development. Therefore, an important ecological source is lost in the northern part of Zhongxiang City and Duodao District due to intense land development activities in the ND and UD scenarios. Although the mountainous topography would block the expansion of urban areas to a certain degree, the part of ecological sources near the plain lake zone is also severely affected, and habitat fragmentation is further intensified. With the loss of the two ecological sources, one important ecological corridor is lost in the central and northern parts of Jingmen each in the ND and UD scenarios. Not only does the total area of the ecological corridor decrease significantly, but also the number and proportion of built-up land within it show an upward trend. Therefore, we conclude two important causes for the perishing of ecological corridors. First, the loss of ecological corridors as vinculum between ecological sources has caused them to lose their practical significance of existence [17]. Second, land development activities continuously increase the pressure on ecological corridors, causing them to narrow, break, or divert [51].

Land Use Change Drives the Evolution of Ens Function and Structure

First, we realized that the functional degradation of ENs commonly originates from conflicts with land development activities [17, 53]. In our research, Ecological barriers and pinch points are mainly located in northern and central Jingmen, where urbanization and agriculture are relatively developed and erosion of natural habitats is most serious. Compared with 2020, the area of ecological barriers in 2050 increases by 12.79 km2, 5.95 km2, and 15.29 km2 for ND, RD, and UD scenarios. The ratio of construction land in ecological barriers is increasing, from 20.52% to 20.91%, 29.56%, and 23.21% in 2020 for ND, RD, and UD scenarios, expressing that ecological corridors are increasingly threatened by urban sprawl encroachment. The main areas where ecological barriers increase and ecological pinch points decrease remain in northern and central Jingmen, where land use changes are more intense, and as the sparsely distributed natural habitats are further eroded and connectivity defects within become larger, the transmission efficiency of the network part of the region is greatly reduced. Therefore, we also found that the centrality of ecological corridors in northern and central Jingmen continues to decline, which implies that habitat isolation in the mountainous areas to the east and west will become more severe, as evidenced by the declining centrality of some important ecological sources in the eastern Dahongshan Mountains and the western Jingshan Mountains. These phenomena suggest that future land expansion will be destructive to the function of ENs, especially in the UD scenario, where this destructiveness is most severe.

Second, land expansion is an essential driver of the structural evolution of ENs [10, 20, 44]. According to the detection of community structure, there are zones of weak ecological connectivity in important natural habitats in Jingmen, mainly within the Dahongshan, and between the Dahongshan and Jingshan. In the 2050 ND and UD scenarios, the ecological connectivity in these areas is further weakened, so that more ecologically connected gaps appear. Based on the backbone structure identification results, it is found that there is a great utility difference between the backbone and non-backbone of ENs. The ecological corridors connecting the eastern Dahongshan Mountains and the western Jingshan Mountains are densely distributed and mostly on the main trunk side, effectively alleviating the ecological insularity in the mountainous areas on both sides. It indicates that this part has a great contribution to maintaining the stability of the network structure and is an irreplaceable key part of ENs. However, in the three scenarios of 2050, where the land development activities in the region are extremely active, part of the structure of this network suffers a strong impact, resulting in the evolution of several trunk edges into non-trunk, which is the most serious in the UD scenario. The outcome of the analysis of the robustness of the network structure show that ecological nodes with high centrality have a better ability to support the whole network structure. They connect more nodes directly or indirectly, and when these nodes are disrupted, the network connectivity and operational efficiency are greatly reduced, which reflects the sensitivity of ENs when facing disturbances. Compared to 2020, the ND, RD, and UD scenarios all become more sensitive in 2050, especially in the UD scenario, where the network robustness decreases most sharply after the loss of important nodes. In addition, the threshold of complete network collapse reflects the steadiness of the network structure, and the entire network fails completely in 2020 when 56.41% of the nodes are removed. However, in the ND and UD scenarios, this threshold drops by 6.41% and 7.70%, indicating that the network structure is more vulnerable to disruption. These phenomena suggest that there is a very significant spatial and temporal response of the structure of ENs to land expansion.

Differences and Similarities in the Effects of Different Land Use Patterns on ENs

Furthermore, the degree to which different land use patterns impact the structure and function of ENs varies [54]. The ENs are most affected by land expansion in the 2050 UD scenario, followed by the ND scenario. In contrast, ENs are relatively less affected in the RD scenario, which has the least increase in connectivity deficiencies and the least decrease in the centrality of constituent elements. It is better able to retain the community and backbone structure of the ecological network in 2020 and maintain its normal functioning during the disturbance process. Nevertheless, the influences of land expansion on ENs are negative in nature, regardless of the development pattern. The RD scenario, which focuses on protecting the highest quality natural habitats in Jingmen, only reduces the negative influences of land expansion on ENs, but does not eliminate them completely. It is relatively effective in stopping the severe loss of ecological sources, however, the area of barriers in the ecological corridor still shows a significant increase of 5.95 km2 and the mean value of ecological resistance also increase by 1.55 compared to 2020, and the benefits of ENs in terms of material cycling, energy flow, and species migration are significantly reduced. Therefore, we believe that the mere inclusion of ecological sources in restricted land development areas is completely insufficient to achieve the goal of protecting ecosystem connectivity and integrity. In fact, ecological corridors play an important role in realizing the conservation of ecosystems and biodiversity at the landscape level, which needs to be focused and strengthened in the future.

The negative impacts of land expansion within the ecological corridors triggered by urbanization on ENs are similar in the three scenarios. With the total area of the ecological corridor gradually decreasing, there is a tendency for the zone of built-up land within it to increase, accounting for 1.32% in 2020 and increasing to 1.60%, 1.95%, and 1.85% in 2050 for the ND, RD, and UD scenarios, and the ecological corridor is still at great risk of being encroached upon and fragmented by urban expansion. In contrast, we observe that the area of cultivated land in ecological corridors shows a significant decline, with the ratio of the land-use type decreasing from 36.03% in 2020 to 32.59%, 30.98%, and 32.61% in ND, RD, and UD scenarios. In our projections, the expansion of construction land is mostly at the expense of farmland, which accounts for more than 90% of new construction land since 2020. Farmland is usually flat, close to urban areas, and more likely to become newly built-up land [47]. In the case of Jingmen City, this type of land use change may be even worse because most of the forests and grasslands are situated in mountainous zones with rugged terrain. Although farmland ecosystems are not suitable for large-scale species habitat, they still have some function of carrying species migration [55]. Therefore, the negative effect of the replacement of cropland by construction land on ENs is also noteworthy, and the protection of cultivated areas in ecological corridors should be enhanced.

Recommendations for ENs Conservation

Establishing ENs and maintaining their sound connectivity can effectively resolve a series of ecological and environmental problems, such as habitat fragmentation and degradation of ecosystem service functions [34, 52, 56]. In the process of rapid urbanization, human-induced land use changes may destroy ENs, and we need to strictly protect ENs so that it will continue to play an ecological protection role. This study proposes the following recommendations:

First, ENs are required to be integrated into the "one map" of spatial planning. In 2019, China's State Council announced the need to establish an integrated spatial planning system across the country to underpin high-quality urbanization and sustainable development. Different sectoral plans should be harmonized as "one map". The conservation and restoration of ENs should be an essential aspect of this planning system. On the one part, it is necessary to identify the ecological sources scientifically and incorporate them into the restricted development areas for urban development, so as to avoid encroachment by the uncontrolled expansion of built-up land and farmland. On the other part, there is an urgent demand to define the spatial scope and boundaries of ecological corridors and to include them in the restricted development areas. However, this is difficult, and there is yet to be a consensus on the width of the ecological corridors. Referring to the Shanghai Urban Master Plan (2017-2035), we suggest that the width of the ecological corridor in the main urban area must be greater than 100 meters, the proportion of built-up land within the corridor must be controlled at less than 20%, and the forest coverage should be at least greater than 50%. Based on this, in the process of land space planning in Jingmen City, ENs must be emphasized by decision makers, and should be included in the "one map", so that it can be spatially specified. Moreover, it is recommended that decision makers formulate laws and regulations for ENs conservation, which will provide strong policy support and judicial governance for resolving conflicts between land development and ENs, and effectively protect ENs from being encroached upon.

Second, the conservation priority of ENs elements is determined according to the connectivity function. According to our results, ecological sources and corridors with high intermediate and intermediate centrality play a greater role in maintaining the structure and function of the entire ENs, and the loss of these elements could be devastating to the Jingmen ENs. Therefore, we suggest that priority should be given to strictly protecting the ecological patches in the Dahong Mountains in the east and the Jingshan Mountains in the west, which are the most pristine and have good integrity, and play an important role in maintaining the habitat of species and regional ecological services. There is therefore a need to increase the construction of large nature reserves or forest parks to protect these important ecological sources. In addition, we recommend prioritizing the conservation and restoration of ecological corridors in central and northern Jingmen. These corridors run through or around urban and farmland areas, connecting critical ecological patches in the two major mountain ranges in the east and west, linking different ecological communities, and contributing greatly to restoring the city's ecological connectivity. However, they are distributed in the intensive area of land development in Jingmen, so they bear a serious risk of degradation, and need to focus on improving these corridors, clarifying the key protection and restoration areas of the corridors, and repairing damaged ecological pinch points as well as removing ecological obstacle points. In addition, the remaining ecological sources and corridors should all be gradually and orderly incorporated into the protection sequence. Some smaller ecological patches, which can give full play to their roles as urban green spaces, country parks and ecological stepping stones to enhance urban vitality, need to be given appropriate protection. Other ecological corridors can be used as alternative corridors for species migration and spreading of ecological elements, and their connectivity functions such as material circulation and energy flow should be fully protected to alleviate the ecological environment pressure in the city.

Outlook

First, this study utilized 30-meter resolution data to simulate land use change, owing to limitations in equipment and data. This facilitated the modeling process, but may result in uncertainty in land expansion. Scale is a core issue in landscape ecology, and varying scales often cause different outcomes [57]. Therefore, in future researches we will conduct comparative studies with different regions, scales, and data accuracy in order to further validate the reasonableness of the results.

Second, this study did not consider the scenario of cropland protection because the spatial data of basic permanent farmland are confidential and difficult to obtain in a short period of time. Cropland is an essential vehicle for achieving food security, and the results of this study show that cropland is an important landscape type for forming ecological corridors, so urban expansion at the expense of large-scale encroachment on cultivated land will pose a great threat to food security and ecological corridors [55, 58]. To address this issue, in the future, we will continue to collect data and then conduct further comparative studies on the evolution of ENs under cropland protection scenarios versus scenarios without cropland protection to explore the landscape and ecological impacts of cropland protection policies.

Finally, this study may have overlooked some smaller natural areas in the screening of ecological sources, which play a minor role in species habitat but are stepping stones to help species complete their migratory activities during their life cycle and should be included in ENs [6]. This was not considered in this study as it focused on developing an integrated assessment framework for detecting the potential impacts of future land use change on ecological networks and was limited by the length of the article. In future studies, we will separately simulate the potential impacts of land expansion on ecological stepping stone systems to better understand the relationship between land development and ecological conservation.

Conclusions

In this study, the spatial location of ENs in Jingmen City was determined and the evolution of ENs under different scenarios from 2020 to 2050 was simulated by utilizing the PLUS model, circuit theory and complex network theory. Furthermore, the joint functional and structural evaluation analysis proves that land use changes in the future development process will have potential negative effects on ENs.

First, we identify the most natural habitat areas and the most suitable potential ecological corridors for species dispersal in Jingmen City, as well as the potential network components that would be most affected by the future land expansion. There was a total of 2815.82 km^2 of ecological sources in Jingmen City in 2020, primarily distributed in the Dahong Mountain Range in the east and the Jingshan Mountain Range in the west. And a total of 842.46 km^2 of ecological corridors were identified, which were broadly distributed in the mountainous areas on the east and west sides and the plain lakes in the middle, effectively connecting the major ecological sources in the east and west. However, the total amount of ecological sources in 2050 decreases to 2693.68 km^2 and 2660.27 km^2 for the ND and UD scenarios, respectively, and slightly decreases to 2813.81 km^2 for the RD scenario, and the north and center of Jingmen, which are the densely areas of the future urban development, are the most seriously eroded ecological source areas. Moreover, a key corridor was lost in northern and central Jingmen in the ND and UD scenarios, respectively. In addition, the negative impacts of land expansion on ENs are manifested in functional degradation and structural damage. Functional degradation is characterized by an increase in ecological barrier points and a decrease in ecological pinch points, as well as a decrease in local centrality, which is most pronounced in the northern and central parts of Jingmen. Land expansion also affects the structure of the ENs by increasing the number of areas with weak ecological linkages between important habitats, weakening the backbone structure as an important link between east and west mountain areas, and weakening the structural robustness of the ENS. These negative impacts are most pronounced in the UD scenario, followed by the ND scenario, and minimized in the RD scenario.

Therefore, with such rapid urbanization, it is clear that simply constructing regional-scale ENs can only barely satisfy temporary nature conservation and is not sufficient to achieve the requirement of maintaining ecosystem connectivity and integrity on a lasting basis. In fact, defining the spatial extent of ENs and implementing strong conservation is essential to protect biodiversity and ecosystems and enhance human well-being. Our results can provide a visionary support for the conservation and restoration of ENs, thus contributing to the sustainable development of human society.

Funding

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Conflict of Interest

The authors declare no conflict of interest.

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