Heliyon 10 (2024) e37870

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Construction of urban-rural ecological networks with multi-scale nesting and composite functions based on the “red-green-blue” spatial perspective: A case study of Dali City, China

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ARTICLE INFO

Keywords:
Urban-rural ecological networks
Multi-scale nesting
Red-green-blue spatial
Dali city

ABSTRACT

Urbanization has facilitated economic development while simultaneously resulting in various ecological issues. Constructing a multi-scale nested and composite functional urban-rural ecological network is crucial for improving ecological security. This study utilizes Dali City as a case study and employs methods including MSPA, circuit theory, and landscape connectivity index to develop the urban-rural habitat network, water green network, and recreation network, focusing on the " red-green-blue " spatial framework. An analysis of the spatial characteristics of source areas, corridors, ecological strategic points, and other spatial elements is conducted to establish a multi-level, multi-objective, and multifunctional composite urban-rural ecological network. The results show that: (1) 13 ecological source areas were identified in both the municipal and main urban areas, along with 22 ecological corridors in the municipal and 20 main urban areas. The distribution of ecological corridors was uniform across the study area. (2) The optimal width for the municipal biological corridor is 150 m, the main urban area should have a width of 90 m. The optimal width for rainwater corridors in municipal and main urban areas is 60 m. (3) The multi-scale nested ecological network identified 4 common ecological sources, 11 ecological corridors, 3 rainwater corridors, 6 wetland nodes, and 7 amusement nodes. Overall, the number of ecological nodes is limited, indicating a need for enhanced node construction. The research findings offer insights for developing ecological networks that integrate urban and rural functions, serving as a reference for ecological protection and restoration in pertinent regions.

1. Introduction

Urbanization’s explosive growth has given rise to a number of issues, including the devastation of human settlements, the decline in biodiversity, the conflict between land and people, and the loss of landscape functions [1–4]. These issues have a major impact on society’s ability to develop sustainably. The issue of how to balance urban growth with ecological preservation has gained international attention and has to be addressed immediately [5]. The term “urban-rural ecological integration and development” has been introduced in this context. It describes the establishment of a mutually beneficial integration and development situation between

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https://doi.org/10.1016/j.heliyon.2024.e37870
Received 6 June 2024; Received in revised form 10 September 2024; Accepted 11 September 2024
Available online 13 September 2024

urban and rural areas, subject to the full development of social productive forces. This condition is brought about by institutional change, technological advancement, and growth in demand [6,7]. This concept is primarily used to investigate the distribution of urban and rural resource elements and the use of urban and rural land space. Regarding the integration and development of urban and rural areas, some academics primarily concentrate on the building of low-carbon, anti-urbanization, and smart cities that integrate urban and rural components as the foundation of urban sustainable development [8]. Building a composite ecological network is a crucial step toward achieving urban-rural integrated development [9]. By identifying important landscape components and elements and creating corresponding spatial association patterns, the ecological network can improve landscape connectivity and safeguard ecology [10].

Numerous scholars who have conducted multifaceted research on the ecological network from the perspectives of method Numerous scholars ology, spatial scale, and ecological security since the network was first proposed in the 1990s of the 20th centuries have formed a basic model of "identifying ecological sources-constructing resistance surface-generating ecological network" [11,12]. Ecological sources are primarily identified in relation to MSPA, landscape connectivity, and habitat quality assessment [13,14]. Important ecological sources for regional ecological security are chosen. The comprehensive resistance surface primarily builds upon topography, data on nighttime light, and the type of land use [15]. Circuit theory, the MSPA approach, the gravity model, and the minimum cumulative drag model are the key tools utilized in the creation of ecological corridors [16–18]. The building of composite ecological networks has made use of the width of ecological corridors and the extraction of ecological nodes as research has progressed [19], and functional research has increasingly expanded in scope. However, existing research, especially on ecological restoration and protection in county areas, overlooks the distinct needs of urban environments and fails to thoroughly explore the interconnected relationships of ecological networks across different scales. Furthermore, few scholars begin their construction of ecological networks from the perspective of "habitat-water-green-recreation" space, failing to take socioeconomic factors and corridor width into account. This is despite some scholars constructing ecological networks based on aspects of society, recreation services, and a comprehensive ecological environment [20]. This study combines the multi-level, multi-objective, and multi-functional spatial linkages within the framework of urban-rural integration. Systematic research on this issue is required to realize ecological conservation and restoration, as well as coordinated development of urban and rural areas.

The "red-green-blue" space refers to a scientific concept that elucidates the integration of several functional zones within the urban ecology. "Red Space" is a designated tourist destination located centrally within the city. The aforementioned regions provide a

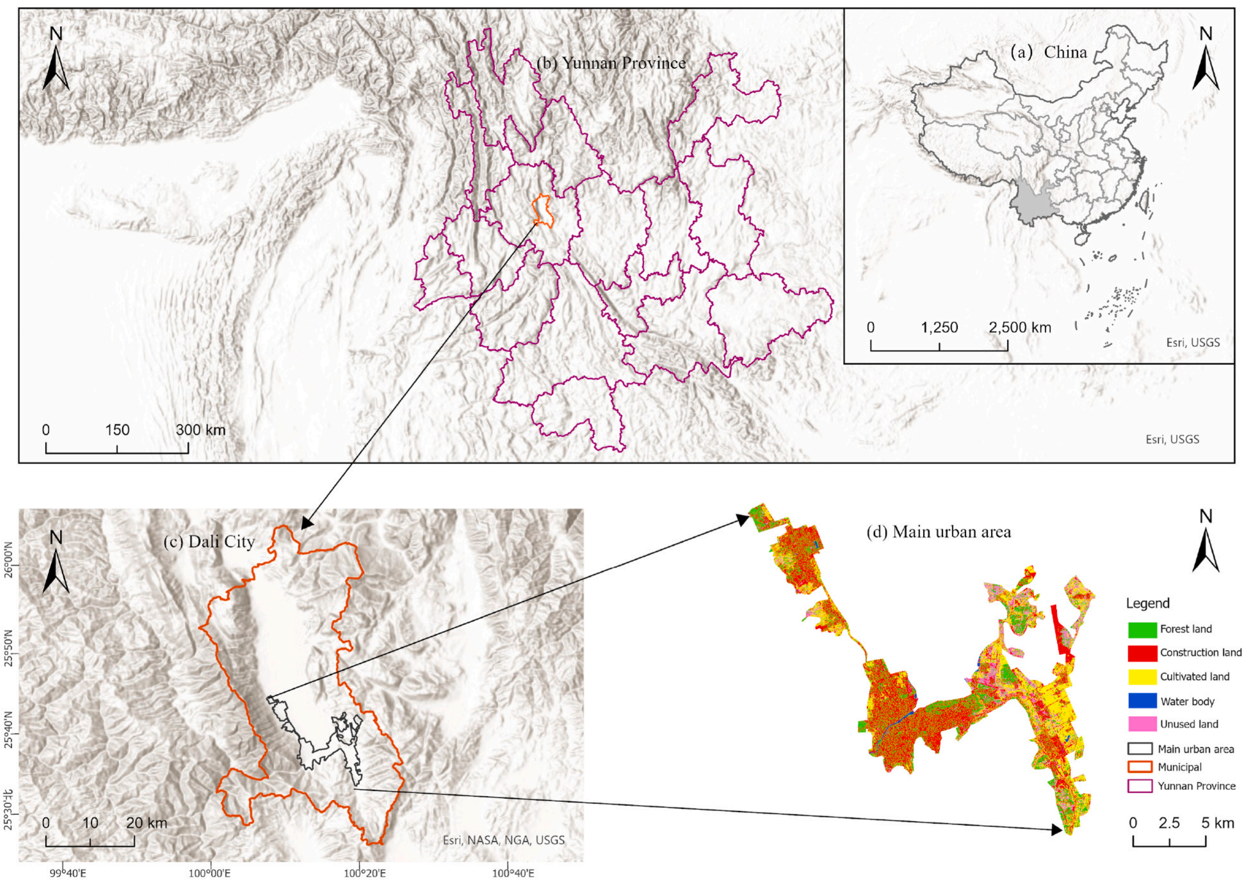

Fig. 1. Overview of the study area.

multitude of entertainment and recreational opportunities for individuals. It possesses both geographical importance and its own distinct culture and history, representing a convergence of natural and human beauty [21]. “Green space” encompasses many natural water bodies, including rivers, lakes, tidal flats, and wetlands, as well as man-made reservoirs and ditches. These elements together comprise a significant “water system network” that plays crucial roles in climate regulation and biodiversity conservation [22]. “Blue space” encompasses parks, green spaces, and other artificial, semi-artificial, or natural ecological areas that play a crucial role in enhancing urban ecology and mitigating the urban heat island phenomenon within cities [23]. The strategic design and arrangement of the “red-green-blue” area are critical in enhancing urban ecological security, improving the quality of the living environment, and establishing a comprehensive ecological network [24]. With its status as a prominent tourist destination in China, Dali has global recognition. Nevertheless, the process of urbanization has resulted in significant environmental issues, including water contamination and the fragmentation of landscapes. The present work focuses on Dali City as a case study and extensively employs MSPA, landscape connectivity index, circuit theory, and other methodologies. Based on the spatial perspective of “red-green-blue,” a multi-scale ecological network including habitat, water, green spaces, and recreation in the city and main urban area was established. The objective was to address the challenge of constructing an urban-rural composite ecological network at various scales within the framework of urban-rural integration. This network should consider biodiversity conservation, climate regulation, and enhancement of recreation functions at different scales. This study presents targeted strategies for optimizing ecological networks with the goal of enhancing the ecological security of both urban and rural areas. These strategies also serve as a reference for the ecological restoration of land space.

2. Materials and methods

2.1. Study area

Dali City is situated in the western region of Yunnan Province and serves as the administrative center of Dali Bai Autonomous Prefecture. It is positioned between the longitudes 99°58′ and 100°27′ east and the latitudes 25°25′ and 25°58′ north (Fig. 1). The city exercises authority over a total of nine municipalities, one township, and three specific streets, as well as the Dali Economic Development Zone and Haidong Development Committee. The overall land area measures 1738.6052 square kilometers, with mountains comprising 71.37 % of the total area. The water area of Erhai Lake contributes 252.8127 km^2, representing 14.54 % of the total area. The region is classified under the monsoon climate of the northern subtropical plateau, characterized by an average yearly temperature of 15.2 °C and an annual precipitation of 1051.1 mm. It boasts a rich history of the humanities and abundant tourism resources, making it a renowned global tourist destination with various nature reserves, ethnic traditions, picturesque locations, and historical landmarks. It has received numerous prestigious accolades, such as "China’s Excellent Tourism City” and “Best China’s Charming City.” Dali’s Gross Domestic Product (GDP) amounted to 47.28379 billion yuan at the end of 2020; its population stood at 648,341; its urbanization rate was 71.22 %; and the proportion of green space in developed regions was 35.35 %.

2.2. Data sources

This study utilizes land use data, natural environment data, and socio-economic data. To enable spatial data analysis, all data are consistently converted to the WGS_1984_UTM_Zone_47N coordinate system. The urban land use data is obtained from Esri Land Cover (https://www.arcgis.com/, accessed on August 22, 2024), featuring a spatial resolution of 10 m. The urban land use data was acquired through the interpretation of high-resolution images utilizing eCognition Developer 64, with images obtained from Google Earth at level 19, which has a spatial resolution of 0.54 m.

Natural environment data: The terrain data is sourced from the geospatial data cloud platform (https://www.gscloud.cn/, accessed on August 22, 2024), featuring a spatial resolution of 30 m. The slope was determined through the calculation of the Digital Elevation Model (DEM) utilizing ArcGIS software. Vegetation cover (NDVI) was derived from Landsat 8 remote sensing imagery obtained from the Geospatial Data Cloud (https://www.gscloud.cn/, accessed on August 22, 2024), dated August 27, 2020, utilizing band number 131/42 and a spatial resolution of 30 m.

Socioeconomic data: The road data is obtained from the Digital Earth Open Platform (https://open.geovisearth.com, accessed August 22, 2024). The nighttime lighting data and point of interest (POI) data are sourced from BIGEMAP (http://www.higemap.com/, accessed on August 22, 2024). The research area boundaries are based on the “General Land Spatial Planning of Dali City (2021–2035)" (https://www.yn.gov.cn/, accessed August 22, 2024).

2.3. Research methodology

2.3.1. Habitat network construction

(1) Identification of ecological sources

Ecological sources serve as the foundation for developing ecological networks [17]. Based on prior research and the current conditions of the study area [25], the MSPA method was employed to identify the ecological source. In accordance with the ecological status of the study area, ArcGIS was employed to designate forest land as the foreground with an assignment value of 2, while other land use types were classified as the background with an assignment value of 1. Using Guido’s software, an eight-neighborhood analysis was established with an urban edge width of 5 and an urban area of 3. Seven landscape types were identified: core, islet, bridge, edge, branch, perforation, and loop [26]. The core area represents a habitat patch characterized by high quality, substantial size, and robust resistance to disturbances. This area is crucial for species migration and dispersal and serves as an important ecological source. Nonetheless, the fragmentation of the core area is significant. For the first time, the core area exceeding 1 km^2 and the main urban area surpassing 0.1 km^2 were designated as the ecological source, based on existing studies [27]. The Conefor software was utilized to compute the overall connectivity index (IIC) and the probable connectivity index (PC) for the city and the primary urban area, respectively, in the context of connectivity analysis. The patch importance index (dPC) was employed to identify the ecological source. The formula is presented as follows [28].

$$\mathrm{IIC} = \frac{\sum_{i-1}^{n} \sum_{j=1}^{n} \frac{a_i a_j}{1+nl_{ij}}}{A_L^2} \tag{1}$$

$$\mathrm{PC} = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} 1 \neq j P^{*}_{IJa_i a_j}}{A_L^2} \tag{2}$$

$$\mathrm{dPC} = \frac{PC - PC_{remove}}{PC} \times 100\% \tag{3}$$

where, n is the total number of patches; a_i and a_j represent the areas of patch i and j; nl_{ij} is the number of connections between patch i and patch j; A_L^2 is the area of the landscape type; the parameter P^{*}_{IJ} is the highest potential migration index between patches i and j; PC_{remove} is the overall landscape connectivity after the patch is removed; IIC reflects the magnitude of connectivity between the overall patches; PC is a measure of the potential connection index of a patch; and dPC is the important degree of the ecological patch.

(2) Construction of ecological resistance surface

Species migration and energy flow between ecological sources are influenced by various factors, necessitating a comprehensive approach in constructing ecological resistance surfaces that account for the hindrance effects of these factors on species exchange between ecological sources [16]. Increased suitability of the ecological source correlates with reduced resistance to biological migration and dispersal. Considering the natural geographical characteristics of the study area and the dual interference of human activities and the natural environment, this study identified land use type, elevation, slope, vegetation index (NDVI), distance from road, distance from river, distance from residential area, and night light index as the resistance factors for analysis. In accordance with the criteria established in prior research [29], the analytic hierarchy process (AHP) was employed to ascertain the weights of each resistance factor (Table 1).

(3) Extraction and width optimization of ecological corridors

Biodiversity protection and species migration are greatly facilitated by ecological corridors, which consist of vegetation, water bodies, and man-made green ecological spaces and serve as the connection connecting species migration between source areas [30]. In order to address the limitations of the least resistance approach in identifying critical nodes and corridor ranges, the circuit theory is founded on the biological random walk feature. In prior research [31], ecological corridors at the municipal and urban scales were identified using the Linkage Mapper Tool. The inherent diversity of the landscape matrix necessitates variations in the width of the ecological corridor. Drawing upon prior research [32], this study established the suitable width of corridors based on the land use type. It also defined buffer zone widths of 30, 60, 90, 150, 300, and 600 m for various corridor types to identify the most effective corridor width.

Table 1
Ecological resistance factor assignment.

Scale	Evaluation factor	Resistance value					Weight
		1	2	3	4	5	
Municipal	Land use type	Forest	Grassland	Cultivated land	Unutilized land	Building land	0.28
	DEM/m	<1500	1500–2000	2000–2500	2500–3000	> 3000	0.19
	Slope/°	0–6.20	6.20–14.63	14.63–23.20	23.20–33.33	>33.33	0.14
	NDVI	−0.21	0.02–0.16	0.16–0.25	0.25–0.34	>0.34	0.06
Main urban	Land use type	Forest	Water	Cultivated land	Unutilized land	Building land	0.24
	DEM/m	<2000	2000–2100	2100–2200	2200–2300	> 2300	0.15
	Slope/°	0–6.05	6.05–18.45	18.45–31.69	31.69–45.87	>45.87	0.15
	NDVI	−0.14	0.01–0.11	0.11–0.20	0.20–0.29	>0.29	0.06
	River/m	<500	500–1000	1000–1500	1500–2000	> 2000	0.07
	Road/m	<500	500–1000	1000–1500	1500–2000	> 2000	0.07
	Residential/m	<1000	1000–2000	2000–3000	3000–4000	> 4000	0.12
	Night Light index	<5	10	15	20	> 20	0.14

(4) Construction of ecological networks

Based on the above analysis, ecological corridors and ecological sources together constitute an ecological network. Ecological pinch points are the only way for species migration and dispersal, and they are the areas with high current values in ecological corridors [22]. On the basis of ecological corridor extraction, the Pinchpoint Mapper module under Linkage Mapper 3.0 was selected, and Circuitscape 4.0 was called to calculate the cumulative value of current density. According to the existing studies [15], the All-to-one mode was selected, the weighted cost distance of 1000 m was set as the corridor width, and the high-value area of cumulative current density was set as the ecological pinch point.

The natural breakpoint approach was employed to categorize it into five groups, and the highest value was overlaid with the primary ecological corridors to get the primary ecological pinch points and the overall ecological pinch points. The ecological barrier points indicate the capacity of regional species to migrate between different sources. The present work utilized the Barrier Mapper analysis module within the Linkage Mapper 3.0 software to compute the cumulative current recovery value through the elimination of barrier locations. The search radius for the city and the main urban region were set at 300 m and 100 m, respectively. Accurately identifying pinch points and barrier spots is crucial for maximizing the connectivity of ecological networks [13]. Notably, the gravity model has the capability to detect significant prospective ecological corridors and establish an ecological security network. The gravity model calculation formula is as reported in Ref. [33]:

$$Gab = \frac{N_a N_b}{D^2 \text{ab}} = \frac{L_{max}^2 \ln(S_a S_b)}{L_{\text{ab}}^2 P_a P_b} \tag{4}$$

where, the interaction force between core plaques a and b is denoted as G_{ab}; L_{max} is the maximum of the minimum cumulative resistance in the region; N_a and N_b are the weight values of plaques a and b; S_a and S_b denote patches a and b's regions area; and the average resistance values of patches a and b are P_a、 P_b, respectively.

2.3.2. Construction of water and green network

An integrated water-green network consists of the water ecological network and the green space ecological network, with the rainwater corridor serving as the foundation for its establishment. Drawing upon prior research [34], the hydrology tool of ArcGIS was utilized to extract the water ecological network. The critical values of 1000 and 3000 were chosen for the confluence of the city and the main urban area. Subsequently, the Strahler classification method was employed to categorize the regional river network and determine the rainwater corridor. Moreover, catchment nodes possess detailed topographical features and hydrological data that have immense importance for the hydrological cycle [35]. Simultaneously, the catchment node provides flood control and storage capabilities, improving the regional ecological environment, providing biological habitats, and ultimately increasing water quality. Given the current conditions in the research area, patches with urban forest area over 2 km^2, lake area over 0.1 km^2, primary urban forest area over 0.002 km^2, and lake area over 0.01 km^2 were selected as suppliers for the water and green network. Based on this premise, the stormwater corridor is linked to the catchment nodes and green patches to establish a water-green biological connectivity [36].

2.3.3. Recreation network construction

The recreational network primarily consists of recreation nodes and recreation corridors, designed to fulfill the recreational requirements of residents [37]. Building upon prior research [38], this work develops a recreation network utilizing circuit theory. Initially, the recreation source and road resistance surface are chosen to establish the network. Subsequently, the Linkage Mapper tool is employed to compute the recreation corridor, as demonstrated in Section 2.3.3. Ultimately, the algorithmic hierarchy process (AHP) was employed to ascertain the weights and assess the appropriateness of the recreation network. The assessment criteria are categorized into four separate groups: ecological local, natural resources, human resources, and transportation resources. The natural recreational resources encompass river systems, urban parks and squares, and other natural landscape resources inside the city. The

Table 2
Appropriateness evaluation for recreational network.

Type		Secondary element		Evaluation methodology
Element	Weight	Element	Weight	
Ecological background	0.16	Slope	0.1	Slope classification 4, 3, 2, 1, 0
		NDVI	0.06	Vegetation cover class 4, 3, 2, 1, 0
Natural resources	0.4	River	0.12	Distance from the river 4, 3, 2, 1, 0
		City parks and squares	0.18	Distance from city parks and squares 4, 3, 2, 1, 0
		Forest parks, scenic areas	0.1	Grade and area of forest parks and scenic areas 4, 3, 2, 1, 0
Human resources	0.24	Unit of cultural relic protection	0.08	Distance from the heritage conservation unit 4, 3, 2, 1, 0
		Characteristic Historical Neighborhoods	0.08	Distance from the Distinctive Historic District 4, 3, 2, 1, 0
		Museums	0.08	Distance from the museum 4, 3, 2, 1, 0
Transportation facilities	0.2	Road traffic network	0.06	Distance from road traffic network 4, 3, 2,1, 0
		Major transportation terminal	0.04	Distance from important transportation terminals 4, 3, 2, 1, 0
		Slow-moving road network	0.1	Distance from the slow-moving road network 4, 3, 2, 1, 0

cultural recreation resources mostly consist of units dedicated to the preservation of cultural treasures, urban historic districts, museums, and memorial halls (Table 2).

2.3.4. Landscape network construction

An objective of constructing a landscape network is to strengthen the linkage between human landscape nodes and natural landscape nodes [39]. The present study developed a suitability assessment system for Dali City based on the real conditions of the study region. The system considers three levels: accessibility, landscape, and service, and used the analytic hierarchy approach. Using water systems, ribbon green areas, historical and cultural blocks, and characteristic roads as the primary lines and traffic arteries as the connecting links, each landscape node is linked in a sequential manner to create a three-dimensional landscape network (Table 3).

2.3.5. Evaluation of ecological network structure

The Network Structure Index evaluates the degree of circulation in an ecological network by quantifying correlations within its structure. In this paper, network closure index (α), line point rate (β), network connectivity (γ), and cost rate (c) are selected to evaluate the red, green, and blue spatial ecological networks in the study area. See references for specific analyses [40].2.3.6 Construction and optimization of multi-scale nesting and composite ecological networks Scale nesting denotes the comprehensive inclusion relationship among various scales, thereby establishing a structural system that encompasses both low-level and high-level scales [41]. This study superimposed overlapping ecological corridors, ecological pinch points, and obstacle points at the primary urban and municipal scales to illustrate the nesting relationship within the ecological network scales. Simultaneously, a habitat network aimed at biodiversity conservation, a water-green network focused on ecological environment enhancement, and a recreation network designed for leisure and recreation were established, considering biological, hydrological, and human processes [42].

3. Results

3.1. Results of the construction of the municipal ecological network

3.1.1. Habitat network results and analysis

Fig. 2 shows that the ecological patches in the city cover a total area of 992.63 km^2, with 807.6 km^2 located in the core, which represents 46.44 % of the whole research area extent. Primarily situated in the vicinity of Erhai Lake, it has a circular distribution, mostly within Cangshan Nature Reserve. The smallest area is islet, with 5,74 km^2, representing 0.58 % of the landscape area and 0.33 % of the total area. This observation shows that there exists a considerable level of connectedness within the urban region; nevertheless, the edge type constitutes a rather significant percentage of 9.54 %. These findings show the presence of fragmentation inside the core region. Furthermore, the ratio of perforation, loop, and bridge regions is reduced, resulting in a limited number of connection mechanisms for the plaque to interact with the external environment. In conclusion, Dali City possesses a favorable ecological environment and extensive forest coverage. However, it faces challenges such as hindrance of material and energy flow and endangerment of species.

The threshold of $dPC>0.5$ was chosen to maintain the integrity of the ecological source and prevent its fragmentation. Ultimately, a total of 13 ecological sources were confirmed, including a combined area of 759.78 km^2, which represents 53 % of the entire research area. The predominant landscape type of ecological source is woodland, with grassland area constituting a very minor portion. An analysis of the research region revealed the presence of 22 natural corridors, which collectively span a total area of 349.20 km^2. The spatial distribution analysis reveals that the western and southwestern regions of the research area exhibit significant forest cover, a robust ecological backdrop, concentrated and continuous source areas, and the longest length of ecological corridors. Numerous significant pathways and general corridors exist in the eastern section of the research region. However, the impact of geological and human activity can account for the presence of rocky deserts and poor ecological stability. Simultaneously, a substantial area of rocky desertification exists in the northern section of the research area, which is accompanied by a widely fragmented river valley landscape. This region's biological environment is delicate, resulting in a significant number of general ecological corridors. In general, the ecological corridor is strategically deployed along the periphery of the research area to establish an ecological network, enhancing the interconnection of ecological resources inside the study region.

The interaction degree between ecological sources is computed using the gravity model, and the results are presented in Table 5. These results indicate that the interaction degree between sources 5 and 6 is the highest. The two sources are situated at the

Table 3
Landscape network construction suitability evaluation.

element	Evaluation factor	Grading indicators	Weight
Accessibility	Resource accessibility	Distance from landscape nodes 4, 3, 2, 1, 0	0.18
	transportation facilities	Distance from transportation terminals 4, 3, 2, 1, 0	0.29
	landscape resources	Distance from landscape resources 4, 3, 2, 1, 0	0.12
Scenic	Characteristic of the place	Historic and Cultural District 4, 3, 2, 1, 0	0.12
	River	Distance from river 4, 3, 2, 1, 0	0.08
	NDVI	Vegetation cover level 4, 3, 2, 1, 0	0.05
Serviceability	Visitor services	Space heat level respectively 4, 3, 2, 1, 0	0.08
	Civic service facilities	Space heat level respectively 4, 3, 2, 1, 0	0.08

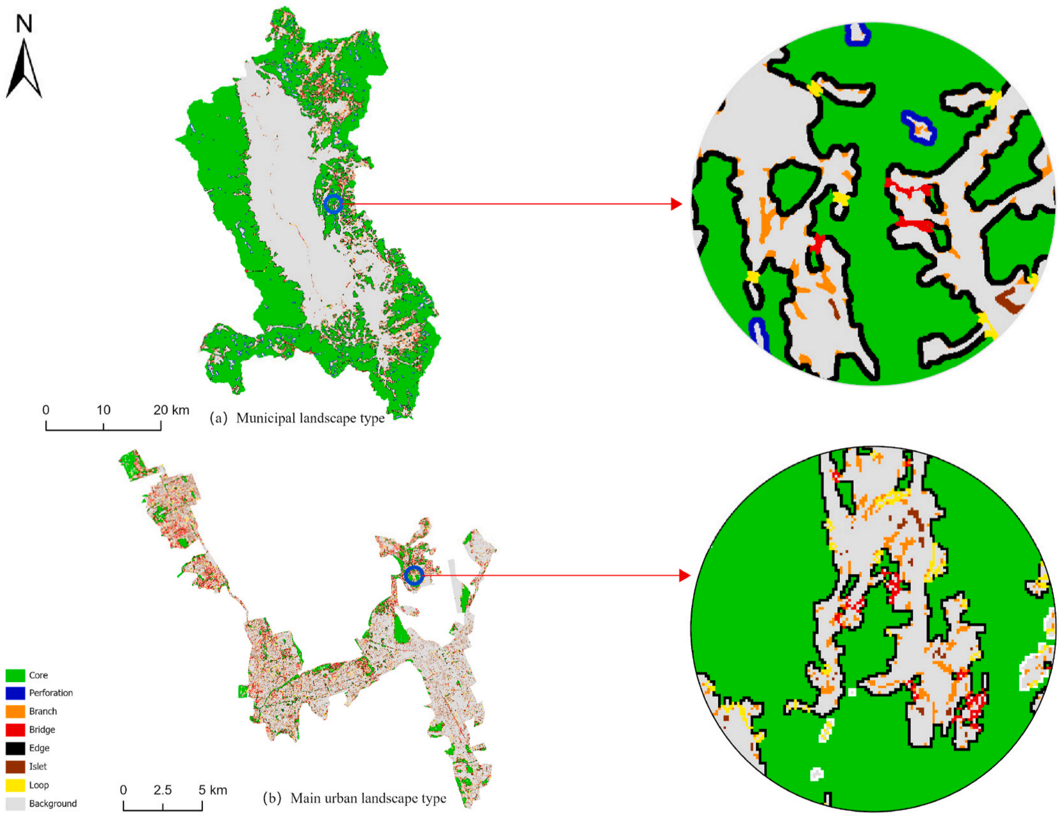

Fig. 2. Spatial distribution of MSPA landscape type.

intersection of Haidong Town and Wase Town, and the predominant land use structure is forested area with abundant vegetation. The habitat quality is excellent, and the resistance between ecological corridors is minimal, facilitating efficient energy exchange and material transfer. Ensuring the protection of this crucial corridor is imperative. The sources 8 and 10 exhibit the least level of interaction, situated in Haidong Town and Xiaguan Town, respectively. These sources are distant from each other, and the middle area is an urban region. The resistance value is high, which hinders the transfer of energy. Hence, when constructing an ecological environment, it is important to focus on optimizing general corridors to enhance their suitability for habitats.

Ecological pinchpoints, characterized by a high cumulative current area, serve as the priority area for ecological restoration. This study identified a total of 22 pinch points, which were distributed in narrow bands. Among them, there are 9 general ecological pinch points and 13 key ecological pinch points (Fig. 3). Haidong Town is the most widely distributed, primarily located in the east and south of the study area. Human activities have strongly disrupted the overall landscape connectivity in these areas due to the extensive distribution of settlements and road networks, underscoring the need for protection and restoration.

The total of 22 ecological barriers were identified in this study, including 13 key ecological barriers and 9 general ecological barriers, most of which were located in general ecological corridors (Fig. 4). The western part of the study area is mainly Cangshan Nature Reserve, with high forest coverage and few obstacle points. Overlay the remote sensing images and land use types, it was found

Table 4
MSPA landscape type statistics.

Element	Municipal			Main urban		
Landscape type	Area (km^2)	Proportion of total landscape (%)	Proportion of study area (%)	Area (km^2)	Proportion of total landscape (%)	Proportion of study area (%)
Core	807.6	81.35	46.44	16.90	46.75	15.69
Edge	94.69	9.54	5.44	7.79	21.55	7.23
Perforation	26.57	2.68	1.53	0.30	0.83	0.28
Branch	25.81	2.60	1.48	4.34	12.01	4.03
Bridge	22.53	2.27	1.30	2.72	7.52	2.52
Loop	9.69	0.98	0.56	0.87	2.41	0.81
Islet	5.74	0.58	0.33	3.23	8.93	3.00
Total	992.63	100	57.08	36.15	100	33.56

Table 5
Intensity of source-to-source interactions based on gravity model.

Municipal		Main urban	
Number	Force	Number	Force
1–2	579.12	1–8	71.40
1–3	571.42	1–9	41.83
1–11	117.71	2–3	5173932.7
2–3	179.59	2–5	7329.59
2–4	166.81	3–4	5498345.64
3–4	373.75	4–5	93261.86
4–5	1239.35	4–7	1676.14
4–6	416.68	4–8	413.82
5–6	3029.13	5–7	1544.72
5–7	393.15	6–7	489.18
6–7	394.96	6–10	199.67
6–9	149.37	7–8	1994.25
7–9	414.27	7–10	463.11
7–13	453.29	8–9	1091.72
8–9	115.94	8–10	311.50
8–10	124.51	10–11	1780.26
8–11	59.99	10–13	1160.15
8–12	341.48	11–12	133073.29
9–10	487.11	11–13	29585.45
9–13	456.38	12–13	6369439.78
10–12	88.98		
10–13	165.95		

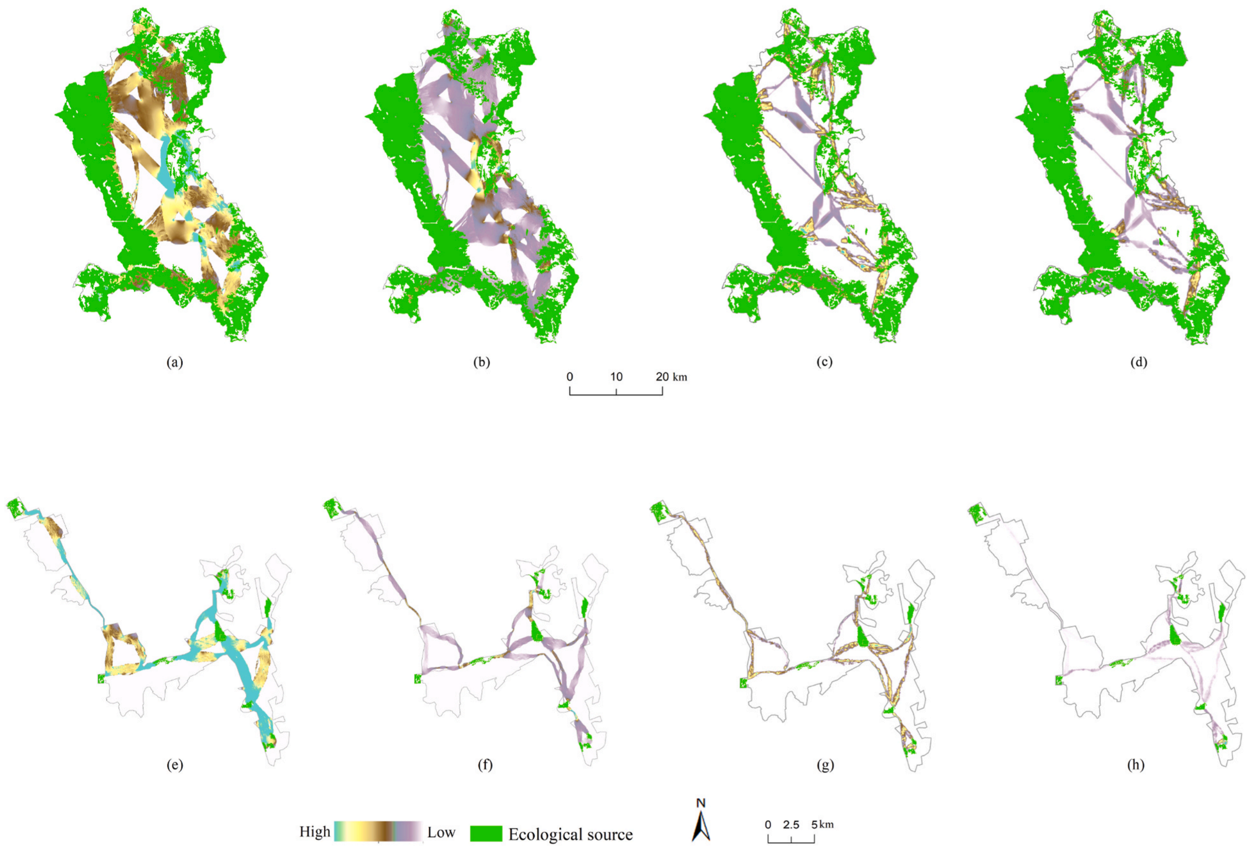

Fig. 3. Pinchpoints and barrier points. (a) Municipal pairwise model; (b) Municipal all to one model; (c) Percentage of municipalities not improving; (d) Percentage of municipal improvements; (e) Main urban pairwise model; (f) Main urban all to one model. (g) Percentage of main urban not improving; (h) Percentage improvement in main urban.

that the ecological obstacles were mostly distributed in high-resistance areas such as cultivated land and construction land, mainly in the eastern part of the study area. To a certain extent, it hinders the migration and spread of species, and lacks connectivity.

3.1.2. Water and green network results and analysis

The circuit theory simulation was conducted on a total of 504 stormwater corridors, which were categorized into three levels: 40 first-level, 18 s-level, and 386 third-level. Geospatial distribution is mostly observed in Cangshan Nature Reserve, characterized by abundant flora and high elevation that facilitates rainfall gathering. Overall, the rainfall corridor exhibits clustering in the eastern region and sparse distribution in the northeastern region. Wetland nodes are established at the river confluence node and the water outlet node based on the features of the rainwater drainage corridor. A total of 112 wetland nodes, covering a combined area of 1016.14 km^2, were identified, with 29 of them predominantly consisting of green patches. Within this group, there were a total of 15 vegetated areas and 14 bodies of water (Fig. 5). The enhancement of connectivity within the water-green network can lead to the formation of a multi-functional water-green network system.

3.1.3. Landscape network results and analysis

Fig. 6 depicts the landscape network, with a high-value core at the center of the research region. This core exhibits a declining spatial distribution as one moves away from the center towards the surrounding areas. Considering the topography of the research area, the central region is characterized by a low elevation, predominantly urban built-up areas and water bodies, and possesses significant landscape value. A significant portion of the study's peripheral regions are mountainous, characterized by high elevation and limited human activity, resulting in a low landscape value. An analysis of the study region revealed the presence of 502 river landscape corridors, mostly located around Erhai Lake and Cangshan Nature Reserve. Additionally, a leisurely road was established around the lake. The transportation networks surrounding Erhai Lake are well developed, with the majority being urban built-up zones. Residents benefit from various amenities, including parks, squares, historical districts, and educational institutions, which offer entertainment and recreation opportunities. The Cangshan Nature Reserve possesses ample water supplies and extensive natural resources, making it well-suited for the development of a landscape network. The development of a landscape network in the northeastern region of the research area is hindered by the extensive rocky deserts, delicate ecological environment, and scarcity of natural resources and cultural attractions.

3.2. The results of the construction of the ecological network in the main urban area

3.2.1. Habitat network results and analysis

As shown in Fig. 2 and Table 4, the core region measures 16.90 square kilometers, or 15.69 % of the overall area. The main urban region consists mostly of building land, leading to a limited landscape area and a concentrated number of core zones. However, it exhibits fragmentation and lacks effective connectivity. A mere 0.28 % of the overall biological environment is characterized by porosity, suggesting that the primary urban region has limited capacity to withstand external disruptions. Located at the intersection of

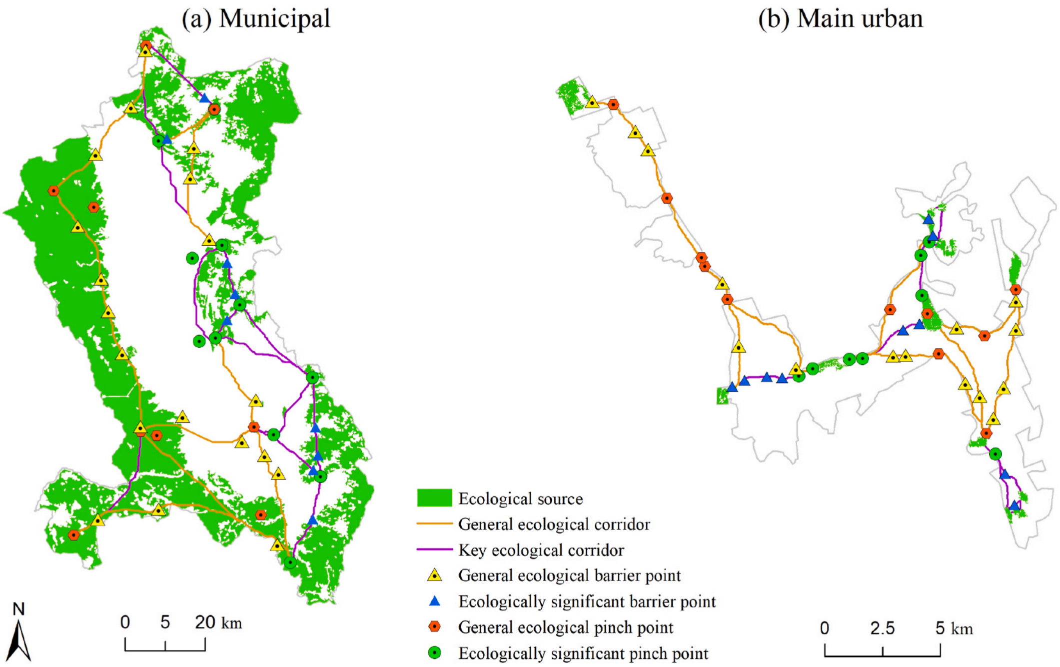

Fig. 4. Spatial distribution of ecological corridors and nodes.

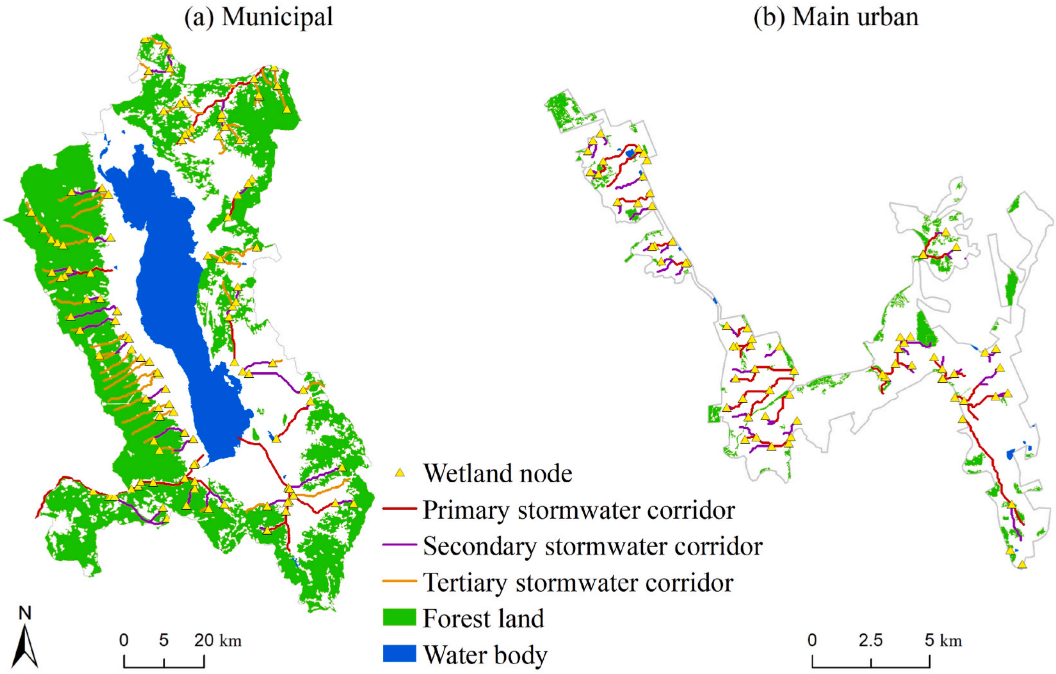

Fig. 5. Spatial distribution of water green network. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

several core, the bridge area constitutes 2.52 % of the overall ecological landscape area, suggesting a lack of coherence within the landscape. Spur lines make up 43 % of the overall ecological landscape area, suggesting an average level of connectivity. Loop lines account for 0.81 % of the total ecological landscape area, while Islet lines encompass 8.93 % of the total ecological landscape area, resulting in fragmentation and dispersion. Collectively, the central region of the primary urban area constitutes a significant portion. However, the fragmentation of the landscape is severe, and the ecological capacity to withstand disturbances is limited. As a result, it is critical to improve the landscape's connectivity in order to facilitate biodiversity movement and dispersal.

In all, 13dpc>1 was chosen as ecological sources, covering a combined area of 5.31 km^2. The biological elements that exhibit strong interconnectedness are mostly located in Cangshan National Geopark to the west, Longquan Park to the south, and Hongshan Village to the east. Due to the presence of building sites, the connectivity of green patches in the center region is limited, resulting in a scarcity of crucial biological resources. A comprehensive set of 20 natural corridors, spanning a total length of 99.23 km, were identified. Within this group, there are a total of 7 main ecological corridors and 13 specific ecological corridors. Fengyi Town in the southern region features an extensive forested area characterized by narrow thoroughfares and concentrated distribution. Impacted by urbanization, it is mostly dispersed along the major transportation routes, with the exception of the southern section of Xiaguan Town, where it is found in all directions. Due to the predominant usage of the region for development, the distance cost of biological migration is not only increased but also the communication between the different sources is impeded. To safeguard species variety, it is necessary to include ecological nodes in the source area, implement ecological restoration operations, enhance ecological source connection, and build habitat networks.

This information shown in Table 5 clearly demonstrates a substantial level of interaction among ecological sources. Notably, the interaction between source 1 and source 9 exhibited the least strength, measuring at a mere 41.83. This suggests that the ecological sources had a significant level of landscape resistance. The highest recorded value was 6,369,439.78, suggesting that the connection between ecological source 12 and source 13 was the most robust. This implies that the habitat conditions were of good quality, and the rates of species migration and energy exchange were minimally impeded. Given the significant role that ecological corridors play in biological migration and material transit, it is imperative to enhance the preservation of these corridors throughout the development of ecological security.

The comprehensive set of 19 ecological pinch points was identified within the research area, comprising 8 significant ecological pinch points and 11 more general ecological pinch points. There exists a total of 25 ecological obstacle locations, comprising 10 essential points and 15 general ecological obstacle points (Fig. 3). From a spatial distribution standpoint, the obstacle spots in the southeast and north are mostly concentrated in the general ecological corridors. These locations serve as both natural sources and primary traffic routes. The southwest region is characterized by a significant urbanization rate and a widespread allocation of building land, impeding the movement of ecological components. Consequently, there is a lack of ecological nodes and obstacles in this area. The ecological restoration of these regions has the potential to enhance the landscape connectivity of ecological networks.

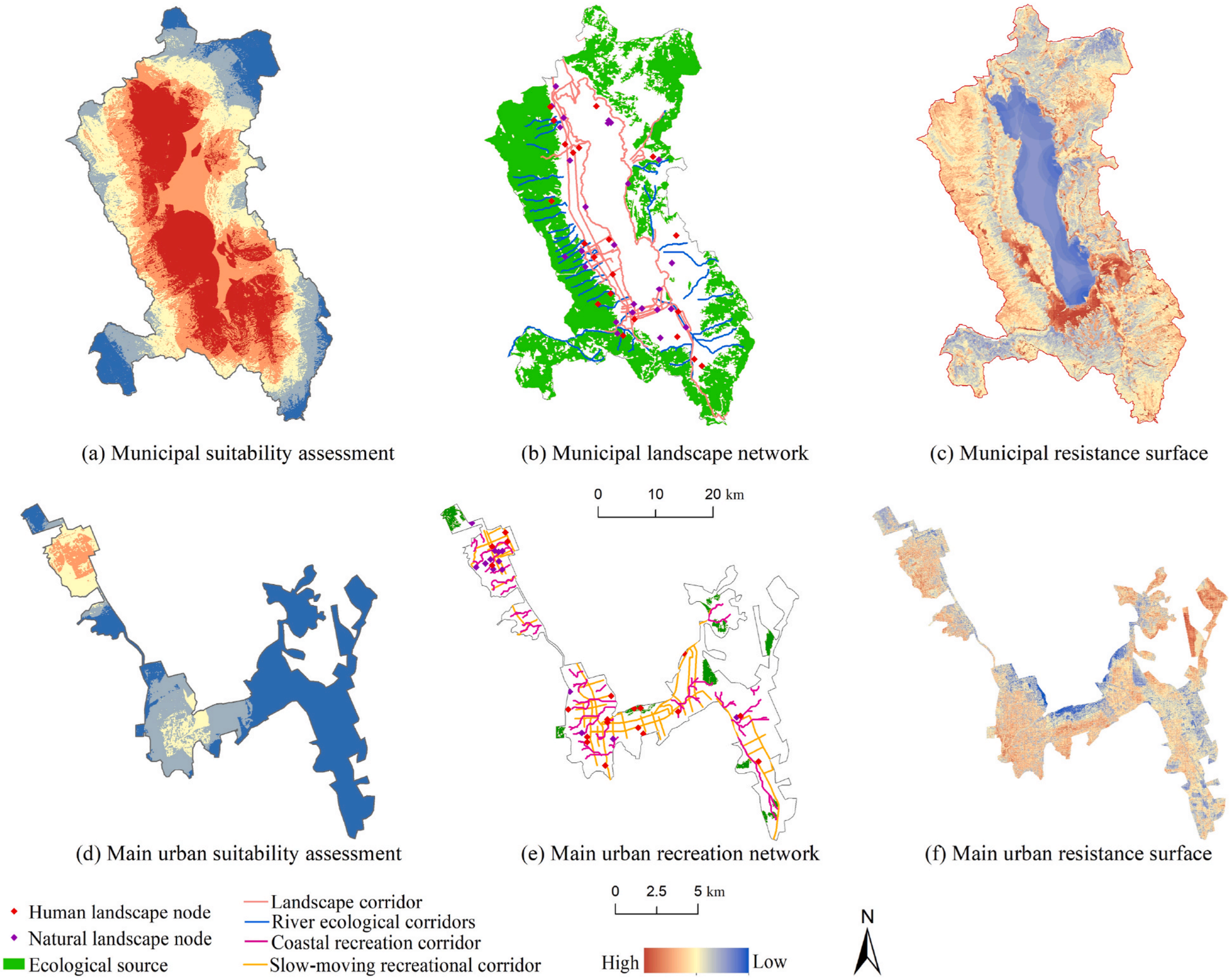

Fig. 6. Spatial distribution of landscape recreation networks and resistance surface.

3.2.2. *Water green network results and analysis*

The rainwater corridors in the main urban area were modeled using circuit theory. A total of 31 first-class corridors and 40 s-class corridors were identified, accounting for a total area of 72.61 km^2 (Fig. 5). This diagram illustrates the spatial patterns of agglomeration in the western region and sparse distribution in the eastern and northern regions. The western region is in close proximity to the Cangshan Nature Reserve, which serves as the primary water source. The eastern and northern regions are primarily characterized by industrial parks, fertile and untapped land, and are situated at high elevations with limited water resources. A study of catchment nodes was conducted based on the features of the stormwater corridor. A total of 80 wetland nodes were successfully identified, mostly situated near the intersection of the rainwater corridor and the green patch. This phenomenon can facilitate the transfer and interchange of urban energy, therefore exemplifying the “compensation-transmission” role of the corridor.

3.2.3. *Recreation network results and analysis*

The identification of 7 riverbank corridors, 31 slow traffic corridors, 19 natural recreation nodes, and 15 cultural recreation nodes was based on circuit theory and analytic hierarchy process (Fig. 6). The corridor mostly extends along the established transportation route, with Xiaguan Town and Dali Town being the most extensively dispersed areas. This region is characterized by high levels of human activity, abundant natural attractions, and abundant cultural resources. These factors make it exceptionally well-suited for the development of recreational corridors to cater to the recreational requirements of its inhabitants. In the present stage of development, the northeastern region lacks any established corridors. Within Dali Town, the node distribution is both the most extensive and dense. By including recreational resources in various regions, the structural interconnection of the recreational network can be enhanced.

3.3. Results and analysis of composite ecological networks

3.3.1. Corridor width characteristics of different land types

Fig. 7 shows that forest land predominates along the 30–90 m range of the municipal biological corridor, with a significant reduction in size at an inflection point at 150 m. Nevertheless, there was a notable expansion in the extent of unutilized land and water bodies, with the aquatic area representing the highest percentage at 150 m. At 600 m, the forested area has once again expanded. The extent of the wetland area exhibited a progressive expansion within the dimensions of the chosen corridors. The available building space diminishes by 30–60 m and expands by 60–600 m. The water body experiences progressive growth throughout the region of 30–150 m and subsequently decreases. Maximum unused land extends up to 300 m. Reduced variability in other ranges. The rainwater corridor in the city had a consistent pattern overall, primarily characterized by building land and forest land. The proportion of water bodies was the least significant, and the change in wetland area was least pronounced. The change inflection point occurred at 60 m and thereafter remained relatively constant. The ecological pathways in the primary urban region have undergone significant

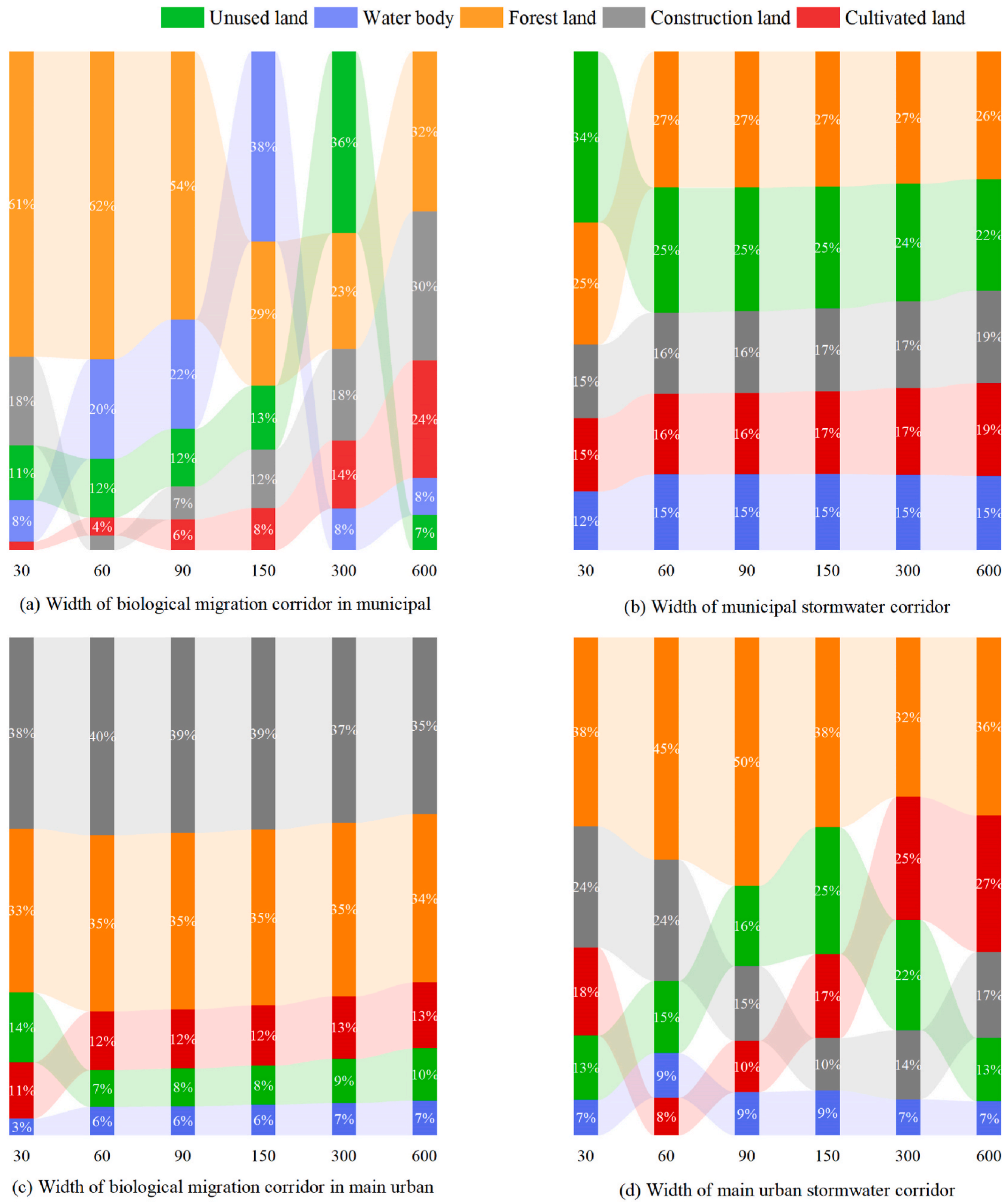

Fig. 7. Percentage of area in land use types with different corridor widths.

transformations, aligning closely with the overall metropolitan landscape and predominantly characterized by forested areas. Notably, the area of water bodies had the least amount of change, whereas the area of wetlands displayed a pattern of initial decline followed by subsequent growth. The alteration of the stormwater corridor is incremental, with a shift inflection point occurring at 60 m, followed by a subsequent slow decline. Based on the current conditions of the research region, the ideal width for the urban biological corridor is 150 m, while the dominant urban area is 90 m. The optimal width for the rainwater corridor in the city and the main urban region is 60 m.

3.3.2. Multi-scale nested network results

The urban ecological network of Dali City was merged with the main urban area's ecological network, and the ecological sources, corridors, and nodes were overlaid and examined to create the hierarchical ecological network of Dali City (Fig. 8). The study identified the 4 common ecological sources covering a total area of 3.65 km^2, 11 ecological corridors measuring 12.93 km^2, 3 rainwater corridors measuring 2.73 km^2, 17 recreational corridors measuring 38.39 km^2, 2 ecological pinch points, 3 obstacle points, 6 wetland nodes, and 7 recreation nodes. The municipality is mostly situated in Dali Town, Xiaguan Town, and Fengyi Town. Although the number of overlapping ecological nodes is limited, the resistance in metropolitan areas is substantial, therefore impacting the exchange of materials and flow of energy. It is necessary to prioritize the optimization of ecological sources and corridors during the creation of an ecological network. Additionally, the connection across different scales should be enhanced by establishing critical ecological nodes. The limited availability of biological resources in the eastern region of the research area has resulted in a compact recreation network, mostly linked by a few ecological patches in the south and north. Consequently, the network structure is somewhat delicate. To maintain the stability of the ecological network through scale nesting, it is necessary to safeguard the overlapping resources within the scale nesting of the ecological network. This will enhance the connectivity between ecological patches and promote a more effective external supporting role for the ecology of Dali City.

3.3.3. Results of multi-functional ecological networks

Different ecological networks have distinct functions. The habitat network mostly focuses on biodiversity protection, the water and green network mainly seeks to enhance the ecological environment, and the recreation network primarily serves leisure and recreation. The 3 components collectively constitute a "red-green-blue" spatial ecological network system, which provides external environmental assistance to both urban and rural development. Analysis of the composite function network reveals that the distribution of each functional corridor is rather consistent, with the Erhai Lake serving as the focal point and extending to the surrounding regions. The abundance of green patches in Fengyi Town contributes to the considerable number of ecological corridors, therefore enhancing the interconnectedness of ecological sources. The recreational corridor and aquatic green corridor are mostly located in Xiaguan Town. Due to the irregular topography and rocky deserts in the northeastern part of the research region, the distribution of ecological corridors is limited. The distribution of ecological nodes is mostly concentrated in the eastern and southern regions, influenced by the natural geography. The primary site of the wetland node is situated within Cangshan Nature Reserve, which offers an ample water supply and excellent circumstances for its establishment. In regard to spatial distribution, the landscape nodes are very uniformly spread, mostly situated in close proximity to forest parks, commercial districts, historic structures, and wetlands. It provides residents with leisure opportunities and improves connectivity across landscape networks.

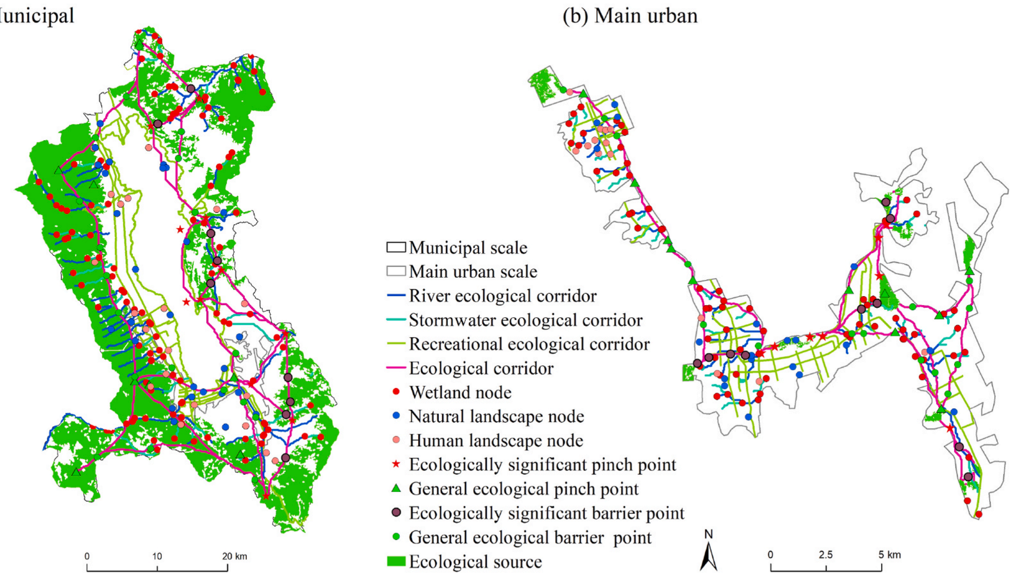

Fig. 8. Composite ecological network.

3.3.4. Ecological network evaluation

The network analysis method evaluated the structure of ecological corridors, landscape corridors, stormwater corridors, and recreational corridors in the study area (Table 6). which showed that the α-values of the corridors in the municipal area were 0.03, 1.79, and 0.94, and the α-values of the main urban area were 0.05, 0.05, and 2.38, indicating that the optimal structural connectivity for stormwater corridors in the municipal area was the best and that the main urban area's open space corridor has a high degree of connectivity between nodes. The municipal corridors had β-values of 1.00, 4.48, and 2.77, while the main urban area had β-values of 1.05, 1.01, and 3.56. Additionally, the municipal stormwater corridor, the landscape corridor, and the triple corridor in the main urban area had index values greater than 1, indicating that they were all intricate ecological network structures with a high level of ecological connectivity. The municipal area's γ values were 0.34, 1.50, and 0.94, while the main urban area's values were 0.36, 0.34, and 1.21. The municipal stormwater corridor and the main urban recreation corridor both had bigger γ values, suggesting that their nodes were more interconnected. Ecological corridor construction was more expensive at both scales, as indicated by the values of c, which were 0.94, 0.61, and 0.68 for the municipal area and 0.80, 0.02, and 0.29 for the main urban area. The research area's agricultural, building, and urban sectors may have interfered with natural processes, and Dali's dispersed nature reserves and complicated geomorphology may have contributed to the complexity of the ecological corridors.

3.3.5. Ecological network optimization strategy

The circular distribution of the composite ecological network is observed in the periphery of the research region, with Erhai Lake serving as its center of gravity. The main urban area is mostly characterized by recreational ecological corridors, complemented by biological ecological corridors and rainwater corridors. These corridors are interspersed with diverse layout features, intricate network structure, and improved spatial connection and anti-interference capabilities. The main concern in ecological restoration of land space should be safeguarding the core ecological source with intricate functions. The restoration of the ecological source area can be achieved by human intervention and the creation of a buffer zone, therefore optimizing the advantages of ecological land. In order to enhance landscape connectedness and avoid fragmentation, it is necessary to implement ecological management and control measures for broad ecological sources. When designing ecological corridors, it is important to thoroughly evaluate the local land use types and ecological environment. The extent of the corridors should be established based on the specific local conditions. Furthermore, the process of ecological protection and restoration should be conducted in a scientific and rational manner. Essential protection measures should be applied to ecological nodes, with a focus on establishing the function of "stepping stones" among ecological sources and prioritizing the preservation of cultural artifacts and historic locations. To optimize ecological corridors in different regions, it is imperative to fully utilize the organizational function of the government, establish regional connections, and aggressively synchronize the diverse interests of businesses, people, and the government. To fully exploit the ecological advantages and facilitate the integrated development of urban and rural areas, it is necessary to acknowledge the external ecological support role supplied by the scale-nested ecological network.

4. Discussion

The founding and enhancement of ecological networks are essential prerequisites for the sustainable development of urban and rural ecology. Therefore, the construction approach holds great significance. This work is grounded on the conventional paradigm of "ecological source identification through resistance surface analysis of ecological networks" [43,44]. The composite ecological network was formed by constructing and analyzing the multi-functional ecological networks of Dali City and the main urban area overlaid correspondingly. The findings of this study align with other research, with the exception that the MCR model is commonly employed for the purposes of constructing ecological corridors [45]. While it can provide an explanation for the fundamental characteristics of ecological corridors [46], it is unable to pinpoint the crucial nodes within these corridors. Hence, this work employed circuit theory and gravity models to establish ecological corridors [47]. The circuit theory was utilized to identify the ecological corridors within the city and the primary metropolitan region, while the gravity model was employed to identify the most significant ecological corridors. Dali City primary ecological sources are Cangshan Nature Reserve, Fengyi Town, and Haidong Town. These areas are characterized by abundant flora and serve as natural ecological sources. This finding is in line with other research publications [48]. Nevertheless, as a result of human activities and the geographical features, the ecological reservoir is fractured, and it is crucial to prioritize the restoration of forests.

This study expanded upon the conventional paradigm of ecological networks by incorporating the concept of ecological corridor width. It demonstrates that the width of corridors plays a vital role in facilitating landscape connectivity. Narrow corridors hinder the growth of biodiversity and limit the mobility of animals. Conversely, an increase in corridor width promotes improved landscape connectivity. The analysis of corridor width revealed that the forest area had the highest percentage of biological corridors within the range of 30–90 m, and thereafter the proportion declined. In general, the rainwater corridor remains mostly unchanged, with the construction land area being the predominant component in the urban area, while the woodland area in the main metropolitan region has the biggest share. This finding is in line with prior research [36]. Hence, it is crucial to choose suitable corridor widths in order to safeguard biodiversity. Furthermore, the majority of prior research on ecological networks has concentrated on a singular size [49], with little consideration given to alternative scales. Furthermore, the majority of the ecological networks were formed within the study area, with a primary focus on natural habitats for ecological source identification [50]. Nevertheless, within the framework of climate change, ecosystems possess distinct requirements for ecosystem services [36]. The present study adopts a "red-green-blue" spatial framework to examine the integrated development of urban and rural areas. It introduces the concept of scale nesting to enhance the construction of ecological networks, thus establishing a multi-objective and multi-functional composite ecological network in Dali City

Table 6
Evaluation results of ecological network.

Level	Indicator	L	V	CL/km	α	β	γ	c
Municipal	EC	22	22	349.20	0.03	1.00	0.34	0.94
	SC	502	112	1298.41	1.79	4.48	1.50	0.61
	LC	130	47	406.88	0.94	2.77	0.94	0.68
Main urban	EC	20	19	99.23	0.05	1.05	0.36	0.80
	SC	71	70	72.61	0.05	1.01	0.34	0.02
	RC	121	34	171.38	2.38	3.56	1.21	0.29

EC: Ecological corridor; SC: Stormwater corridor; LC: Landscape corridor; RC: Recreation corridor; L: Corridor number; V: Node number; CL: Corridor length; α: Network closure Index; β: Line point rate; γ: Network connectivity; c: Cost ratio.

and the main urban area. The primary objective is to enhance the environment and recreation services by prioritizing ecosystem services [51]. Additionally, it aims to offer solutions for regional ecological restoration and urban ecological value, which holds significant reference value for improving the efficiency of regional ecological protection and urban and rural ecological development.

Utilizing circuit theory and multi-scale nesting, this work establishes a composite ecological network in both the main urban area and the city area of Dali City. The findings have significant implications for biodiversity conservation, climate improvement, and the optimization and coordinated development of land spatial patterns in Dali City. Additionally, the study offers ideas for constructing a multi-scale urban-rural composite ecological network. However, there are still certain limitations. Primarily, this work establishes an ecological network at the small and medium scale utilizing the "red-green-blue" spatial perspective. The concentration is on the primary urban center, but the precision of the internal corridors in smaller villages inside Dali City requires enhancement. Furthermore, the landscape and recreation network presented in this paper is a virtual network that possesses socio-economic characteristics. However, this network's specific application necessitates a more thorough examination and investigation. This includes developing a multi-factor evaluation system to assess the influence of possible ecological risks on the stability of the ecological network from various viewpoints. In this study, determine the ecological corridor width by analyzing land use types without considering the adaptability of various species to the corridor width. Therefore, future research should focus on increasing the analysis of corridor width by different species and considering the construction cost of new ecological corridors to enhance the method of constructing ecological networks.

5. Conclusions

Utilizing the spatial perspective of "red-green-blue" in Dali City, this study focused on biodiversity conservation, environmental improvement, and recreation services. By analyzing spatial components such as ecological sources, corridors, and nodes, the width of the ecological corridor was determined. This analysis led to the construction of a multi-scale, multi-objective, and multi-functional urban-rural composite ecological network. This research explores the implementation of the composite ecological network to enhance the integration of urban and rural development. It also presents a theoretical framework for the efficient distribution of multi-functional composite space and the construction of urban and rural ecological systems. The finding may be summarized as follows:

(1) The study documented 13 ecological sources within the city, encompassing a combined area of 759.78 km^2, as well as 13 ecological sources within the major urban area, covering a total area of 5.31 km^2. The city and main urban areas have a total of 22 and 25 ecological obstacle locations, respectively. The primary challenge areas are situated within the ecological corridors, necessitating greater focus on safeguarding ecological resources and enhancing the interconnectivity of these corridors.
(2) The scale nesting analysis of the two networks revealed the identification of 4 shared ecological sources spanning a total area of 3.65 km^2, as well as 11 ecological corridors spanning a length of 12.93 km^2. The system consists of 3 rainwater corridors comprising 2.73 km^2, 17 leisure corridors totaling 38.39 km^2, 2 ecological pinch points, 3 barrier locations, 6 wetland nodes, and 7 recreation nodes. Through the implementation of scale nesting, Dali City has successfully enhanced the provision of regional ecosystem services by linking the ecological network between the city and the primary urban area while keeping the total ecological land use constant.
(3) Through the interconnection of the ecological source and each node, the multi-functional ecological network optimizes the functions of the ecological network, enhances its capacity to handle natural disasters, and simultaneously fulfills the ecological requirements of inhabitants, ensuring ecological security. Within territorial spatial planning, research can be conducted on the development of ecological strategic points, integration of functional spaces, and establishment of a multi-scale, multi-objective, and multi-functional ecological network for promoting ecological security.

Funding

This research received no external funding.

Institutional review board statement

Not applicable.

Informed consent statement

Not applicable.

Data availability statement

The data associated with this study has not been uploaded into a publicly available repository. However, data will be made available upon a reasonable request.

CRediT authorship contribution statement

Shunmin Zhang: Writing – original draft, Software, Investigation, Data curation. **Xiang Li:** Writing – original draft, Resources, Investigation, Data curation. **Rong Chen:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Xiaoyuan Huang:** Project administration, Conceptualization. **Jiansong Peng:** Project administration, Conceptualization.

Declaration of competing interest

There is no declaration of interest.

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