CONSTRUCTION AND OPTIMIZATION OF ECOLOGICAL NETWORK IN CHENGDU-CHONGQING URBAN AGGLOMERATION, CHINA

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Abstract. Establishing ecological networks is an important strategy for maintaining ecosystem integrity and promoting the resilience of natural systems. In this study, the China's Chengdu-Chongqing urban agglomeration was used as the research region, and The Morphological Spatial Pattern Analysis (MSPA) Model and landscape index method were used to screen out important ecological source for ecological corridor construction. The Minimum Cumulative Resistance (MCR) Model was used to construct an integrated resistance surface, and then the coastal path tool in Arc GIS was used to create ecological corridors. Finally, an optimized ecological network of the China's Chengdu-Chongqing urban agglomeration was formed. The results of the study can provide a reference for developing similar regions. The research findings indicate that, using the MSPA method, 30 patches covering a total area of 75,206.90 km^2. Were identified among the ecological sources, accounting for 37.86% of the total area of the China's Chengdu-Chongqing urban agglomeration. The constructed comprehensive resistance surface exhibits a spatial characteristic with higher values at the periphery and lower values at the core. Finally, 80 ecological corridors, totaling 7547.85 km in length, were identified using the gravity model. The China's Chengdu-Chongqing urban agglomeration urgently needs to increase high-quality forests as the ecological cornerstone in the central area, and form a hot springs-type layout of peripheral ecological barriers around the core area of the urban agglomeration, so as to build an ecological security pattern that can not only guarantee the ecological balance of the urban agglomeration, but also effectively alleviate the pressure of urban development.

Keywords: *landscape ecological pattern, morphological spatial pattern analysis (MSPA), minimum cumulative resistance model (MCR)*

Introduction

In the current rapid scientific and technological development the construction of ecological networks has become a key strategy for coping with the challenges of the ecological environment and promoting the harmonious coexistence of man and nature. It is also the current hot spot in ecological restoration research that has attracted much attention (Pilosof et al., 2017). The construction of scientific and rational ecological networks can effectively alleviate the pressure of urban expansion on the environment, promote biodiversity conservation, and enhance the overall service function of the ecosystem (Shen et al., 2023; Z. Wu et al., 2021).

Since the 1990s, many scholars have integrated the theories and methods of ecology, geography, urban planning, and other disciplines to deeply analyze the multiple dimensions of the construction of ecological networks in urban agglomerations (Huang et al., 2021; Linehan et al., 1995; Vimal et al., 2012). In the construction of the theoretical framework, various models such as the ecological footprint model (Wiedmann & Barrett, 2010; Xun & Hu, 2019), the Morphological Spatial Pattern Analysis (MSPA) (Hu, Wang, Huang, et al., 2022; Y.-Y. Li et al., 2021; Qin et al., 2024), the Minimum Cumulative Resistance (MCR) (Hu, Wang, Wang, et al., 2022; Ye et al., 2020), and the Degree of Interaction (DOI) (Dai et al., 2021) were innovatively proposed, which laid a solid foundation for the scientific construction of the ecological network of urban agglomerations. Many scholars have studied the ecological network in the China’s Chengdu-Chongqing urban agglomeration (Ying et al., 2022; Y. Zhang et al., 2024), Pearl River Delta urban agglomeration (L. Li et al., 2023; Z.-T. Li et al., 2020), Beijing-Tianjin-Hebei urban agglomeration (Ji et al., 2020; Y. Zhang et al., 2017), and various watersheds (Ma et al., 2019; T. Wang et al., 2024; X. Zhang et al., 2021), etc. From the perspectives of ecological risk evaluation (Gao et al., 2022; H. Wang et al., 2021), ecological sensitivity (Bai & Guo, 2021; Cariboni et al., 2007; B. Jiang et al., 2023), dynamic landscapes (Gu et al., 2023), carbon sinks (Z. Tang et al., 2023), and biodiversity conservation (Asaad et al., 2017) and formed the basic process of “identifying ecological sources - constructing ecological corridors - extracting ecological intersections” for the construction of ecological networks (B. Jiang et al., 2023; S. Zhang et al., 2024).In terms of research methodology, the introduction of modern information technology such as remote sensing, GIS, big data, and other modern information technology has realized the accurate monitoring and assessment of ecological resources in urban agglomerations, which provides strong technical support for the optimal layout of ecological networks (Guo et al., 2023). Regarding empirical research, scholars have extensively collected and analyzed several urban agglomerations' ecological network construction cases, summarizing successful experiences and lessons learned from failures (Tan et al., 2018; Zhao et al., 2024).

Through this process, the key elements of ecological network construction and their influencing factors are refined, a significant reference value for constructing ecological networks in the China’s Chengdu-Chongqing urban agglomeration. In the theoretical research on the construction of the environmental network in the research area, the relevant results mainly focus on the spatiotemporal evolution of city cluster resilience (Lu et al., 2022), eco-efficiency and its determinants (He & Hu, 2022), and the characteristics of spatiotemporal distribution of tourist attractions (Weng et al., 2023), etc., but there are fewer kinds of research on the construction of the ecological network. In future research, we can refer to the successful experiences of ecological network construction in urban agglomerations in China and abroad and combine them with the actual situation of the China’s Chengdu-Chongqing urban agglomeration to propose the theoretical framework and strategies of ecological network construction.

The China’s Chengdu-Chongqing urban agglomeration is located in southwestern China and includes the two core cities of Chengdu and Chongqing, as well as several surrounding cities and counties. The region is rich in natural resources and humanistic landscapes and possesses a significant economic, cultural, and transportation hub status. Under the rapid pace of urbanization, the original layout of natural landscapes is undergoing substantial changes, and many ecological areas are unfortunately being encroached upon, thus exacerbating the conflict between urban construction and ecological protection in terms of land resource allocation (Lei et al., 2024). This phenomenon has led to increased fragmentation of ecological habitats, a significant decline in biodiversity, and a weakening of ecosystem services, which poses an obstacle and a challenge for cities in their quest for long-term, sustainable development paths (Wu et al., 2024). Compared to common study areas such as Beijing-Tianjin-Hebei, Pearl River Delta and some watersheds (X. Zhang et al., 2021; L. Li et al., 2023), although the China’s Chengdu-Chongqing urban agglomeration is larger in size and the experimental results may not be as accurate as in smaller areas when used as a study area, because key ecological processes such as species migration and water containment naturally cross administrative boundaries, focusing on the core area alone will sever the ecosystem continuity and ignore the pressures of peripheral support and expansion of the core area, resulting in a network distortion (Mao et al., 2021). As a national strategic region, its sustainable development relies on cross-municipal ecological synergies, and a holistic scale can systematically identify key corridors, nodes, and conflict zones, providing a core basis for unified regional ecological control and restoration and avoiding fragmented approaches. Although the small scale can improve the local accuracy, this study aims to solve the core problem of regional synergy, and the holistic scale ensures the systematicity and completeness of the ecological network as well as the practicality of serving the national strategy, so that the two form a necessary complement (W. Wu et al., 2024b). The research results on the construction of an optimized ecological network system in the China's Chengdu-Chongqing urban agglomeration will provide a scientific basis for the planning of ecological space networks, ecological restoration strategies, and protection measures in the China's Chengdu-Chongqing urban agglomeration and similar regions and provide essential references for promoting the sustainable development of the region and optimizing ecological, environmental governance.

Materials and methods

Study area

The China's Chengdu-Chongqing urban agglomeration of China (27°39'N ~ 33° 101°56E ~ 110°11'E) comprises Chongqing Municipality and the 15 prefecture-level cities of Chengdu, Deyang, Luzhou, Leshan, Meishan, Dazhou, Yibin, Nanchong, Guangan, Zigong, Mianyang, Suining, Yaan, Ziyang and Neijiang in Sichuan Province (*Fig. 1*). The China's Chengdu-Chongqing City Cluster is a pivotal economic engine and ecological barrier in China's western region. The region is distinguished by its diverse landscapes, mountains, and waters, as well as its mild and humid subtropical climate, which is characterized by four distinct seasons, abundant rainfall, and a wide range of vegetation cover. This vegetation cover encompasses a variety of ecological types, ranging from forests to grasslands. The region's distinctive natural environment and robust ecological foundations provide a solid foundation for developing an ecological network. Despite the success of the China's Chengdu-Chongqing urban agglomeration in ecological environment construction, numerous challenges persist. The rapid development of modernized cities has resulted in the proliferation of high-rise buildings, which have encroached upon a substantial portion of valuable ecological land. The original green areas, wetlands, and biodiversity-rich ecosystems face an unprecedented threat in this process. The exacerbation of land use conflicts disrupts the region's ecological balance and poses a significant challenge to the sustainable development of the China's Chengdu-Chongqing urban agglomeration. Consequently, the pressing issues in Chengdu-Chongqing Urban Agglomeration are the scientific and rational construction and optimization of an ecological network, the promotion of economic growth, and the realization of harmonious coexistence between urban and natural environments.

Data source

The data and period of this study are based on 2020, and the data related to the study include surface cover data, DEM data, and other basic geographic data:

(1) The surface cover data used in this study were derived from Globeland 30 (https://www.globeland30), which has an overall accuracy of 85.72% and meets the accuracy requirements of the study through a Kappa coefficient value of 0.82. The dataset covers ten major surface categories: farmland, scrub, forest, grassland, wetland ecosystems, watersheds, tundra, artificial surfaces, bare ground, glaciers, and perennial snow areas. In contrast, for the specific region of this study, the remaining nine surface types, except tundra, were covered.

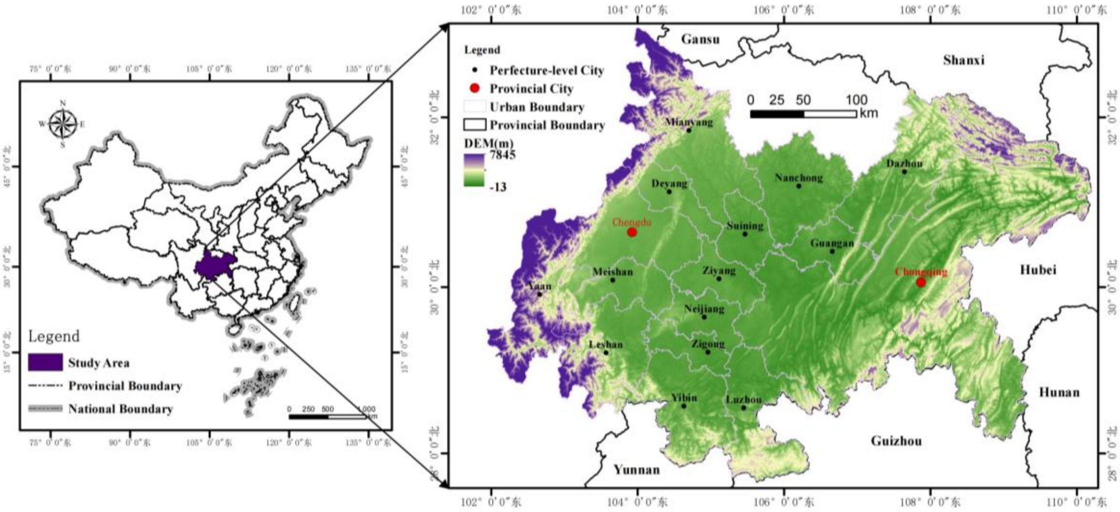

Figure 1. Geographic location of the study area

(2) The digital elevation model (DEM) data were obtained from the Geospatial Data Cloud Platform (https://www.gscloud.cn) of the Computer Network Information Center of the Chinese Academy of Sciences. The GDEMV2 version was utilized, and the spatial resolution was configured to 30 meters to ensure the optimal presentation of topographic information.

(3) The Normalized Vegetation Index (NDVI) data, a crucial indicator of vegetation growth status, can be traced back to the National Ecological Science Data Center (http://www.nesdc.org.cn), which provides essential basic data for ecological environment analysis.

(4) Additional fundamental geospatial data, encompassing, but not limited to, administrative area division data, residential settlement information, water body distribution data, and transportation road networks, is derived from two authoritative platforms: the Global Geographic Information Resource Catalog Service System (https://www.webmap.cn) and the Resource and Environmental Science Data Platform of the Chinese Academy of Sciences (https://www.resdc.cn).

Methods

Identifying ecological sources

The cornerstone of the ecological network is constructing the ecological source area, which is of central significance to promoting a sustainable development strategy. It is an essential source of ecological service value and is responsible for preventing ecosystem degradation and avoiding related adverse impacts. Its contribution is indispensable to the maintenance of ecological balance and the goal of sustainable development. This study used the Morphological spatial pattern analysis method, MSPA to extract the ecological source (Zhao et al., 2022). As shown in *Figure 2,* in the implementation process, woodland, grassland, shrubland, wetland, and water bodies were set as the foreground elements in the MSPA analysis. At the same time, the rest of the landscape types were considered as the background environment. The remaining landscape types are regarded as the background environment. The final MSPA outputs contained seven landscape categories: Core, Islet, Perforation, Edge, Bridge, Loop, and Branch (Qin et al., 2024).

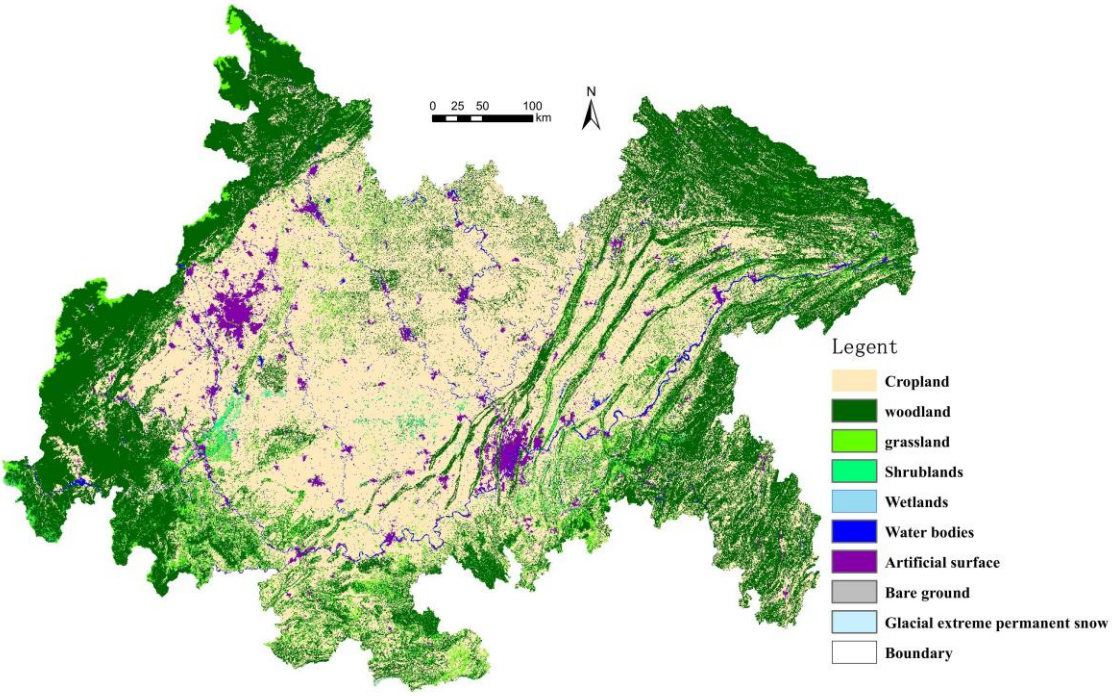

Figure 2. *Spatial distribution of land use types in the study area*

Constructing resistance surfaces

Concerning previous studies and closely integrating the current ecological environment and economic development of the China's Chengdu-Chongqing urban agglomeration, the three core elements of the natural environment, society, and landscape pattern are selected as the analytical framework from a multi-dimensional perspective (Qin et al., 2024; Zhou et al., 2024). Focusing on natural geographic features such as elevation and slope while considering indicators reflecting ecological sensitivity and intensity of human activities such as distance from water bodies, distance from roads and distance from settlements, as well as Shannon's Diversity Index (SHDI), Shannon's Evenness Index (SHEI), Contagion (CONTAG) and Aggregation Index (AI) (Liccari et al., 2022; Shu et al., 2021), surface cover type and vegetation cover, a total of 11 indicator factors are used to construct the ecological resistance surface of the China's Chengdu-Chongqing urban agglomeration (*Table 1*). Resistance levels 1-5 are assigned, and as the resistance level increases, the interference with ecological processes also increases. In the data processing stage, the Sharpness Homogeneity Index, Sharpness Diversity Index, Contagion Index, and Agglomeration Index were visualized by Fragstats 4.2 software; meanwhile, elevation, slope, and vegetation cover were classified by natural break point method in ArcGIS 10.8 software. Finally, the 11 indicator factors were assigned corresponding weights using hierarchical analysis.

Table 1. *Grading criteria for evaluation of ecological resistance factors in the study area*

Indicator type	Evaluation factor	Level					Weight
		1	2	3	4	5	
Natural	DEM (m)	<623	623-1114	1114-1808	1808-2805	2805-7845	0.0622
	Slope (°)	0-8.73	8.73-17.12	17.12-26.55	26.55-38.08	38.08-89.44	0.0987
	Distance from water (km)	28-35	21-28	14-21	7-14	0-7	0.0392
Society	Distance from road (km)	40-50	30-40	20-30	10-20	0-10	0.1000
	Distance from settlements (km)	20-25	15-20	10-15	5-10	0-5	0.1000
Landscape pattern	SHDI	<0.32	0.32-0.64	0.64-0.96	0.96-1.28	1.28-1.6	0.1044
	SHEI	<0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1	0.0817
	CONTAG	4.2-5.0	3.4-4.2	2.6-3.4	1.8-2.6	<1.8	0.0505
	AI	64-80	48-64	32-48	16-32	0-16	0.0505
	Land cover	Woodland, wetlands, water	Grassland, shrubland	Cultivated land	Bare ground, permanent glaciers	Artificial surface, construction land	0.2190
	Vegetation coverage (%)	76-100	67-76	56-67	35-56	≤ 35	0.0940

Establishing ecological corridors

The Minimum Cumulative Resistance (MCR) model mainly describes the geographic phenomenon in space from the starting point to the end point of the cumulative resistance to minimize the path selection problem. The MCR model can more accurately identify the optimal pathway between ecological sources, that is, the area of the path of least resistance, and as a basis for constructing an efficient Ecological corridor (L. Zhang & Wang, 2006). The application of this model not only enhances the identification of ecological network connections but also promotes the science and rationality of ecologic al corridor planning. The formula is as follows:

$$MCR = f_{min} \sum_{i=1}^{m} \sum_{j=1}^{n} \left(D_{ij} R_i \right) \qquad \text{(Eq.1)}$$

where MCR denotes the cumulative value of the minimum resistance between ecological source sites *i* and *j*; D_{ij}denotes the minimum distance between ecological source sites *i* and *j*, and R_i denotes the value of the total resistance encountered by ecological flow in the patch; f_{min} denotes that the minimum value is taken as MCR (Y.-Y. Li et al., 2021; Ye et al., 2020). Based on the above analysis, the MCR model was used to calculate the cumulative distance from each ecological source site to other sites. The cost back link data were obtained using the cost distance tool in ArcGIS 10.8, and then the cost path tool was used to calculate the minimum cost path from the source patch to the target patch.

Selection of priority ecological corridors

Gravity models are used to estimate some kind of interaction or flow between two sites and can effectively express the strength of interactions between ecological source sites (Su et al., 2019). The calculation formula is as follows:

$$G_{ab} = \frac{{L_{max}}^2 \ln S_a \ln S_b}{{L_{ab}}^2 P_a P_b} \quad \text{(Eq.2)}$$

In the formula, Gab denotes the interaction strength between ecological source sites a and b; Lmax is the maximum ecological resistance value between different patches; Sa and Sb denote the area of ecological source sites a and b, respectively; Lab is the cumulative ecological resistance value between ecological source sites a and b; and Lab is the average resistance values of ecological source sites a and b.

Gravity modeling can more accurately identify ecological corridors of higher importance between ecological sources, extract the appropriate number of corridors with higher interaction forces as key environmental corridors, and prevent the construction of high-cost, low-effect corridors.

Identification of ecological nodes

Ecological nodes act as bridges and links in ecosystems, connecting different environmental sources, facilitating the flow of organisms and energy, enhancing landscape wholeness, and maintaining healthy ecological functioning (Fu et al., 2022). The ecological nodes in this paper are the intersections of key ecological corridors with resistance contours.

Results

Foreground landscape typology analysis

Forestland, grassland, shrubland, water, and wetland in the China's Chengdu-Chongqing urban agglomeration were selected as the key elements for prospective analysis. In contrast, cropland, artificially covered surface, bare land, glacier, and permanent snow constituted the background analysis data of MSPA (*Fig. 3*).

The distribution and area share of each type of landscape element were statistically calculated (*Table 2*). The results showed that the most significant area in the prospect value is the core area, which can be used as an ecological source area. Combined with the analysis of land use data, the Core area of the China's Chengdu-Chongqing urban agglomeration mainly consists of forested land, with a total area of 91,240.25 km^2, which accounts for 83.35% of the prospect value and 37.86% of the overall landscape area of the China's Chengdu-Chongqing urban agglomeration. The core is a more critical part of the landscape, with the most significant area and connectivity, and is the center of various ecological projects. the China's Chengdu-Chongqing urban agglomeration should establish more patches that can be used as ecological sources to enhance its ecological intensity.

This is followed by Edge, with an area of 8989.73 km^2, accounting for 8.21% of the outlook, indicating a high degree of fragmentation of landscape patches in the region and weak connectivity between small patches. Edge area as a transition zone between the Core and background area, and the connectivity of its ecological engineering is crucial for the stability of the whole landscape system; in landscape planning and design, more attention should be paid to the connectivity and wholeness of the landscape, to avoid excessive human intervention and landscape fragmentation.

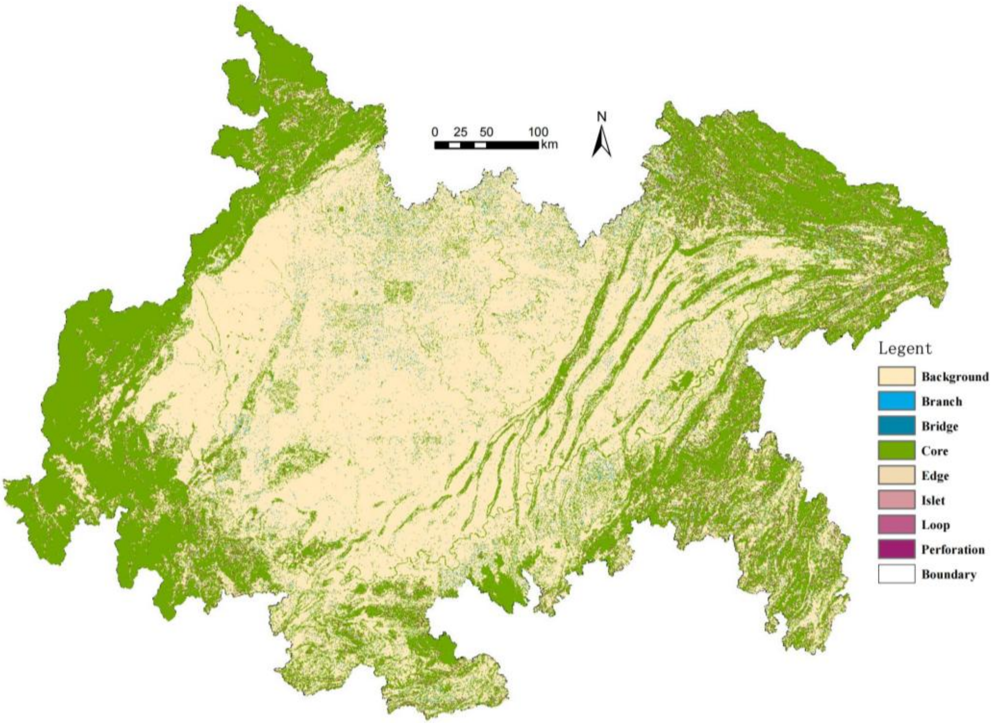

Figure 3. *Spatial distribution of landscape types in the study area (based on MSPA analysis)*

Table 2. *Area statistics for each landscape type in the study area*

Landscape type	Area (km²)	Percentage of prospect value (%)	Proportion of the study area (%)
Core	91240.25	83.35%	37.86
Edge	8989.73	8.21%	3.74
Perforation	4986.64	4.56%	2.08
Branch	2575.73	2.35%	1.07
Bridge	1027.66	0.94%	0.43
Islet	383.87	0.35%	0.16
Loop	266.98	0.24%	0.11
Total	109470.85	100.00%	45.44

The perforation type is third in the area, with 4986.64 km^2 and 4.56% of the prospect. Perforations usually refer to landscape elements that are small in size, irregular in shape, and surrounded by non-ecological spaces such as built-up land. Perforation space can be reasonably utilized in the planning process, such as installing ecological corridors and increasing green space coverage, to enhance the ecological value and connectivity of the landscape.

The fourth-ranked Branch type of patches has a small area share of 2.35%, implying that connectivity between landscape elements is limited, and ecological processes are impeded due to the fragmentation of the landscape caused by human activities, which has fragmented the landscape into multiple isolated parts. In landscape planning and management, attention should also be paid to the construction and maintenance of the Branch, and the connectivity of the landscape should be enhanced through measures such as the restoration of natural channels and the construction of ecological corridors.

The proportion of area occupied by patches connecting Bridge, Islet, and Loop morphologies is minimal, an observation that is a significant indicator of weak connectivity between patches that serve as potential ecological source sites. Therefore, it is imperative to strengthen the ecological links between patches and build efficient ecological corridors to promote the overall connectivity and stability of the ecosystem.

Although the woodland-dominated Ecological Core is large and concentrated, the landscape is highly fragmented. Edge, Perforation, and branch-type patches reflect weak connectivity between small patches and impeded ecological processes. To enhance ecological intensity and connectivity, it is necessary to strengthen the construction of ecological corridors, focus on the wholeness of landscape planning, and avoid fragmentation caused by human intervention to promote the sustainable development of the ecosystem of the China’s Chengdu-Chongqing urban agglomeration.

From the analysis of *Figure 4,* it can be seen that the ecological source area of Ya’an, Mianyang, Leshan, and Dazhou in Sichuan accounts for a large proportion of the area, and its area is more than 5000 km².

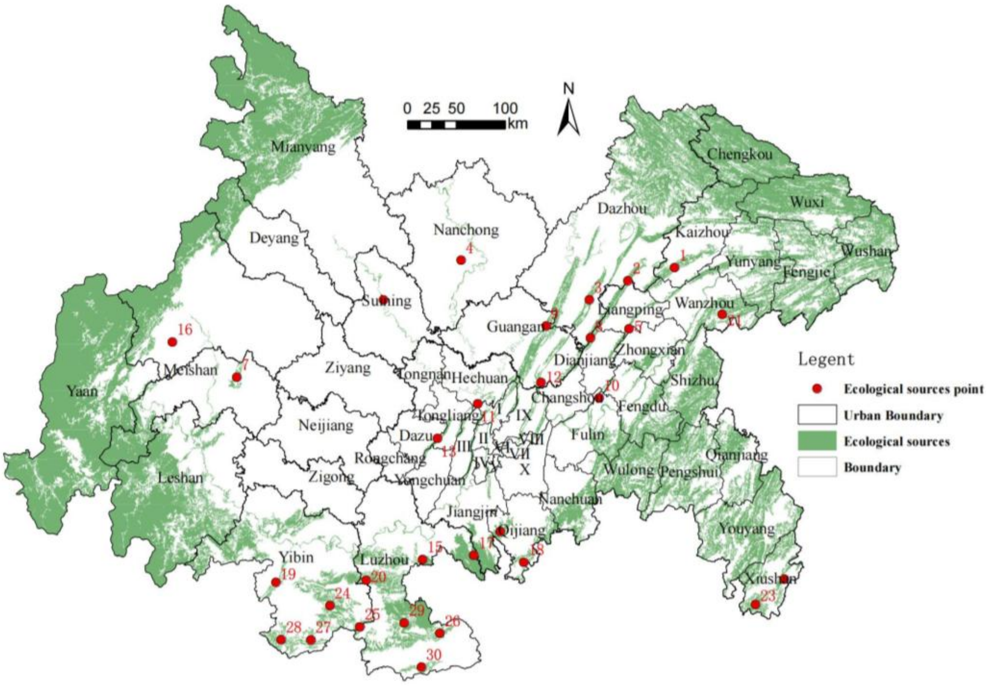

Figure 4. *Spatial distribution of ecological source sites in the study area. (1-30: ecological source numbering, I.: Beibei, II.: Shapingba, III.: Bishan, IV.: Jiulongpo, V.: Dadukou, VI.: Yuzhong, VII.: Nan’an, VIII.: Jiangbei, IX.: Yubei, X.: Banan)*

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This is followed by Luzhou, Yibin, Chengdu, Meishan, and Deyang in Sichuan Province and Wuxi, Chengkou, Youyang Tujia, and Miao Autonomous Counties Fengjie, Fengjie, Wushan, Pengshui Miao and Tujia Autonomous Counties, Wulong, Shizhu Tujia Autonomous Counties, Yunyang County, Kaizhou and Fengdu Counties in Chongqing Municipality, which have an area of more than 1000 km². The remaining districts and counties, such as Guang’an, Nanchong, Neijiang, Suining, and Zigong in Sichuan Province, and Qianjiang, Wanzhou, Xiushan, and Nanchuan in Chongqing Municipality, have a small ecological source distribution area. For Ya’an, Mianyang, Leshan, Dazhou, and other regions with a large share of ecological sources, the focus can be on strengthening these regions’ ecological protection and restoration. At the same time, protection and restoration work should also be strengthened in the remaining districts and counties of Guang’an, Nanchong, Neijiang, Suining, and Zigong in Sichuan, as well as in the areas of Qianjiang, Wanzhou, Xiushan, and Nanchuan Districts in Chongqing, where the distribution of ecological sources is low. Although small patches are small in total area, they are equally crucial to ecosystem health and integrity. Therefore, the protection and management of these small patches should be enhanced to avoid their further destruction or disappearance.

Construction of resistance construct

The resistance surface can assess and distinguish the variation of resistance encountered in species migration among multiple ecological units. Thus, it can reveal the distribution pattern of the degree of resistance of ecological flow in the spatial dimension and further clarify the obstruction characteristics of ecological flow paths. Areas of low resistance usually imply better ecological connectivity, favoring species migration and ecological flow, while areas of high resistance may become bottlenecks or barrier points for ecological flow.

This study constructed an ecological resistance model containing 11 independent factors based on three core dimensions: natural environment, social factors, and landscape pattern. Subsequently, the comprehensive ecological resistance surface map of the China’s Chengdu-Chongqing urban agglomeration was drawn through the implementation of scientific integration and assignment weighting processing of these factors. As shown in *Figure 5,* this comprehensive resistance surface map reveals the overall impediment dynamics facing ecological flows in the region: The ecological resistance surface of the China’s Chengdu-Chongqing urban agglomeration is higher in the west, northwestern, northeastern, and southwestern parts of the city and the distribution characteristics of lower resistance in the middle. From the perspective of the three factors in the natural environment, the China’s Chengdu-Chongqing urban agglomeration has good natural conditions, with low resistance dominating the elevation (*Fig. 6a*), slope (*Fig. 6b*), and distance from water bodies (*Fig. 6c*), with the elevation and slope showing the distribution of high peripheral resistance and low center resistance. From the map of distance from water bodies, we know that the water bodies in the China’s Chengdu-Chongqing urban agglomeration are better connected, which provides a channel for species to migrate and inhabit and is conducive to the spread of species and gene exchange.

Analyzing the ecological resistance of the China’s Chengdu-Chongqing urban agglomeration from the perspective of two factors in the social dimension, the distance from settlements (*Fig. 6d*) and the distance from roads (*Fig. 6e*) are dominated by high resistance due to the impacts and resistance to the process of landscape connectivity generated by anthropogenic disturbances and urbanization development. The ecological resistance of the

China’s Chengdu-Chongqing urban agglomeration was analyzed from the perspective of six factors in the landscape pattern, of which the surface cover type factor (*Fig. 6j*) indicated that the three land types of the China’s Chengdu-Chongqing urban agglomeration, namely artificial surface, bare ground, glacier, and permanent snow, accounted for a low percentage and the overall resistance was low. Vegetation cover (*Fig. 6k*) accounts for a large area of 76% or more, indicating excellent vegetation conditions in the China’s Chengdu-Chongqing urban agglomeration. the China’s Chengdu-Chongqing urban agglomeration exhibits rich landscape diversity, but its spatial aggregation characteristics are poor, and the distribution pattern shows significant non-equilibrium. Analyzed from an overall perspective, the region faces high resistance to ecological flows (*Fig. 6i*), while the quantitative indicators of its spreading trend remain in the medium range, and the connectivity between patches is mediocre (*Fig. 6h*), which needs to be further optimized to promote the coordinated development of the region’s ecology and space.

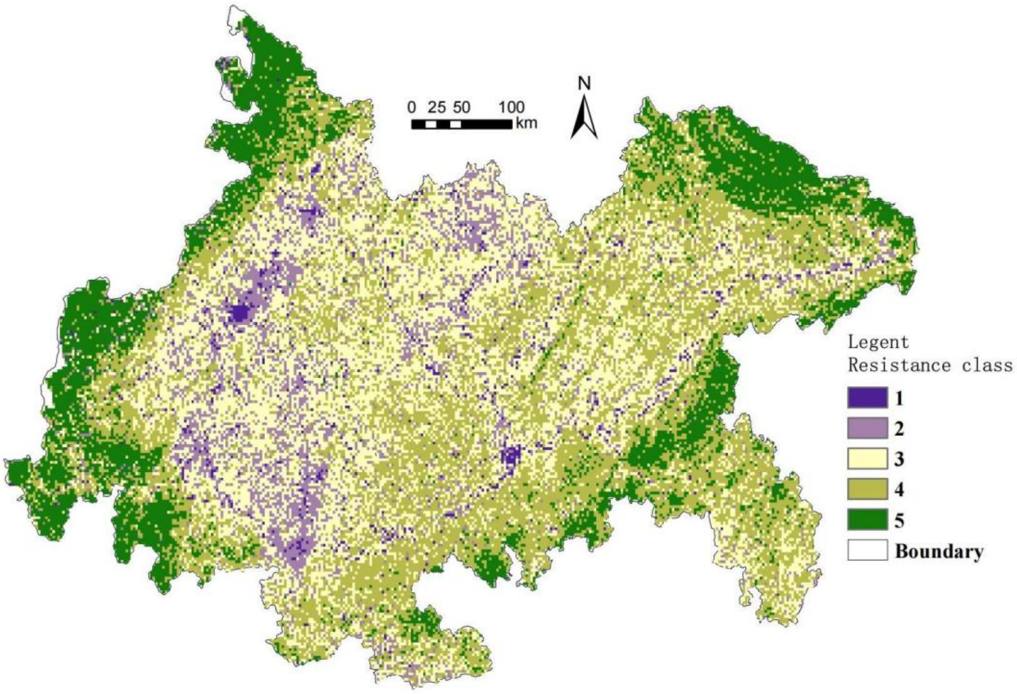
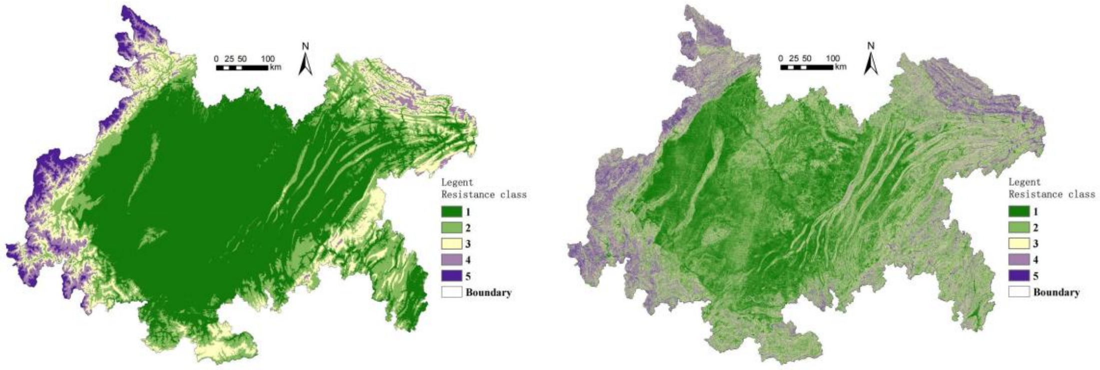
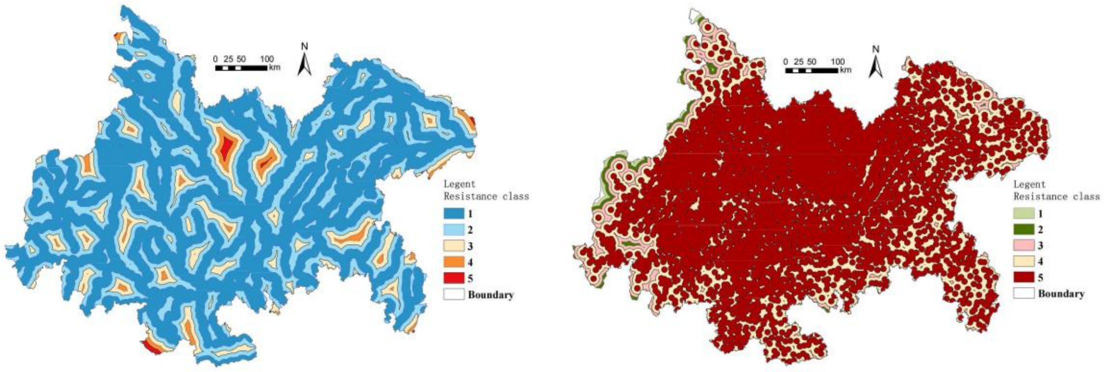


***Figure 5.** Composite resistance surface*



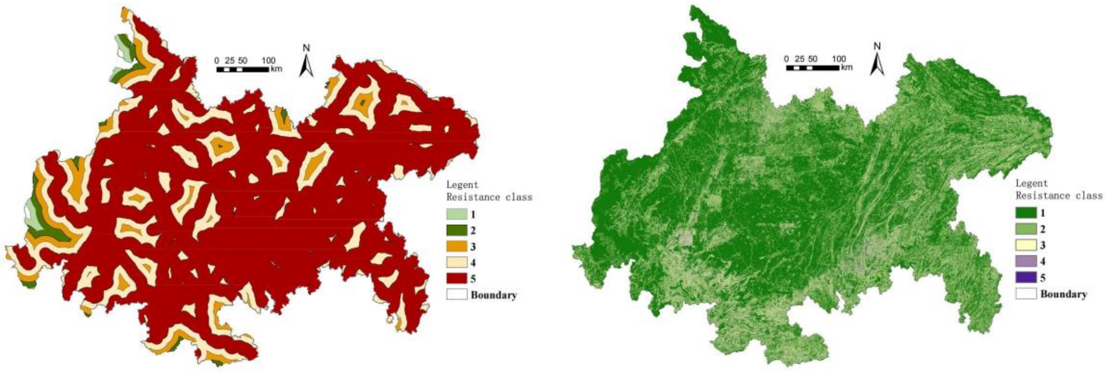
(a) DEM

(b) Slope



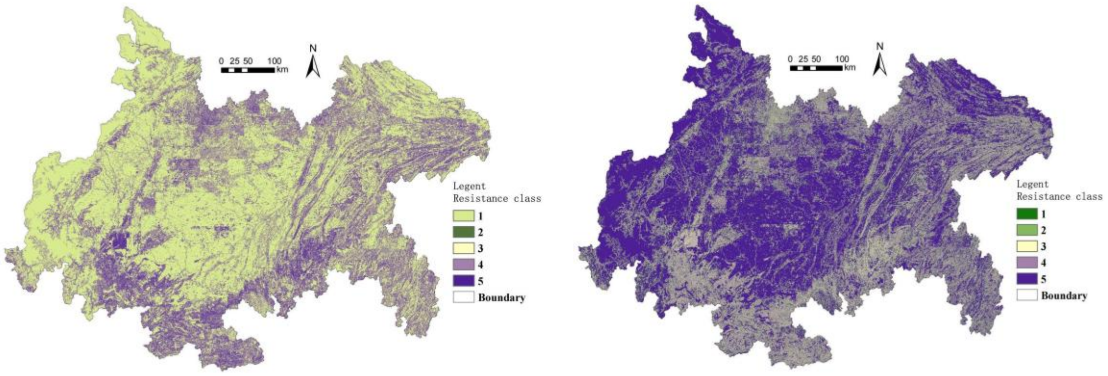
(c) Distance from water

(d) Distance from settlements



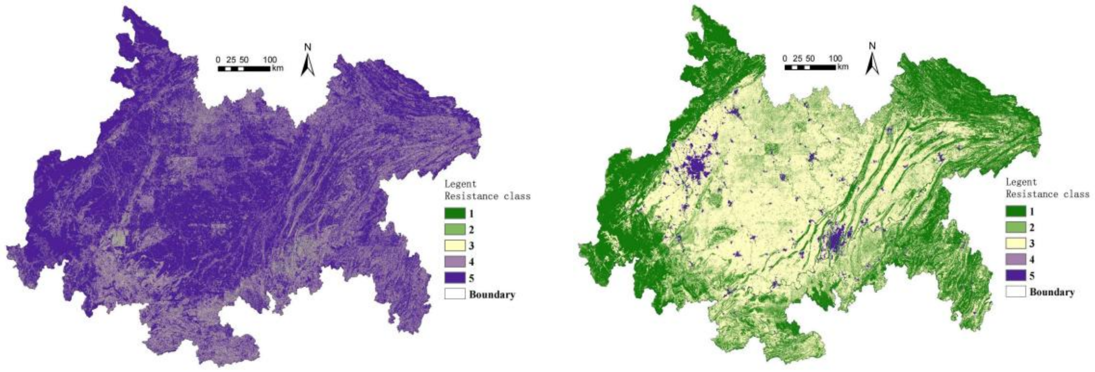
(e) Distance from road

(f) SHDI



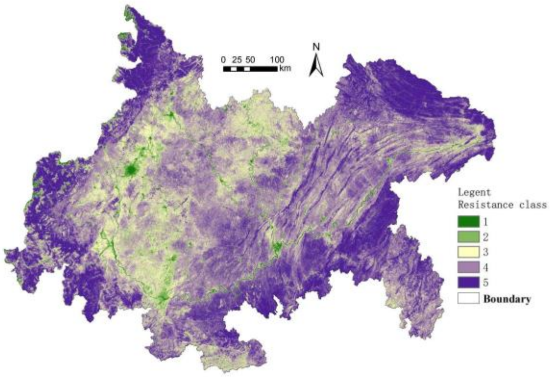
(g) SHEI

(h) CONTAG



(i) AI

(j) Land cover



(k) Vegetation coverage

Figure 6. *Ecological factor resistance surfaces and combined ecological resistance surfaces in the study area*

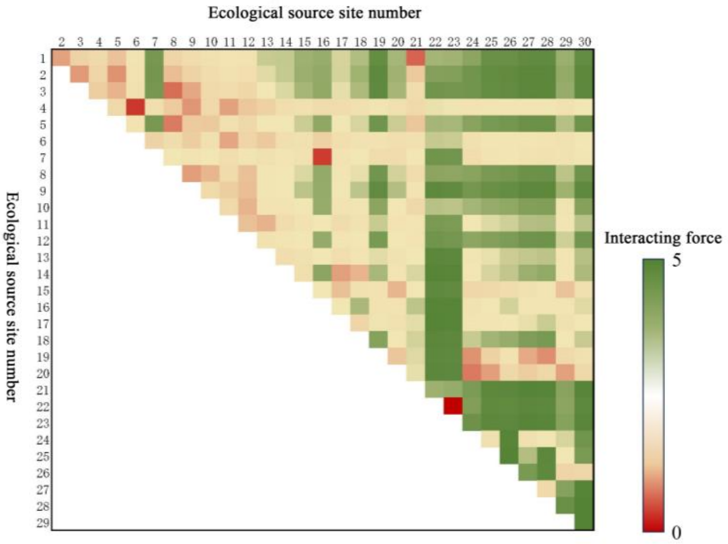


Figure 7. *Heat map of interaction forces between ecological source sites*

Construction of ecological networks

Relying on the ecological source and ecological resistance surface patterns of the China's Chengdu-Chongqing urban agglomeration, 435 general ecological corridors were constructed using the MCR model, with a total length of about 53,796.78 km, covering the paths from each source to the others, as shown in the general ecological corridors in *Figure 8* Influenced by the significant difference in gravitational force between the source sites, the interaction strength between the ecological source sites was calculated based on the gravity model under the principle of ensuring the interpenetration between the source sites, and based on the results, a heat map of the interaction force was plotted (*Fig. 7*), from which the corridors with an interaction force of more than 0.0001 were screened out as the essential ecological corridors, a total of 80 corridors, with the length of 7547.85km. In terms of area covered, the distribution of key ecological corridors in the China's Chengdu-Chongqing urban agglomeration can be categorized into three major regions, with the ecological corridors covering the first central region being densely populated, running from the west to the east; the second central region is distributed in the south, connecting the fragmented source areas in the south; and the third region connects two ecological sources in Xiushan. Spatially, ecological corridors are densely distributed in the region in a net-like structure, and their construction is dominated by grassland, followed by woodland. Among the essential ecological corridors, which are mainly composed of water bodies, roads, and green spaces, the protection and restoration of water ecosystems, the connectivity of green infrastructures, and the enhancement of woodland ecosystems need to be strengthened in the planning to promote the construction of ecological corridors.

This study identified the intersection points of resistance contours and key ecological corridors in the China's Chengdu-Chongqing urban agglomeration as ecological intersections, and 74 ecological intersections were obtained, finally constructing a complete ecological network (*Fig. 8*). ecological node in the China's Chengdu-Chongqing urban agglomeration in the south of Luzhou, the distribution of the most there are 36, especially in the China's Chengdu-Chongqing urban agglomeration in the south of the ecological source of the layout of the denser near the ecological resistance here is high, coupled with the land in the border zone is more needed through ecological restoration measures, to build a more stable ecosystem.

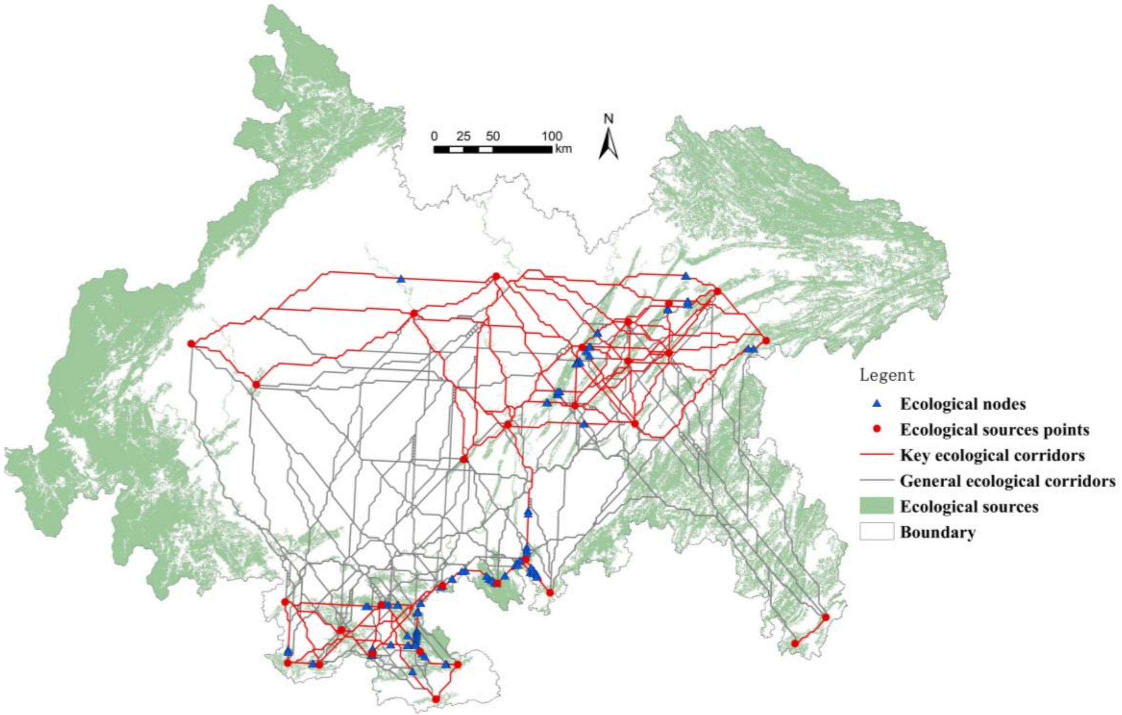


Figure 8. *The China's Chengdu-Chongqing city cluster ecological network*

The process of ecological planning can be based on the actual situation of further detailed selection of points, about ecological nodes set small or medium-sized green patches as ecological stepping stones; these patches can be parks, green spaces, wetlands, can enhance the stability and diversity of the ecosystem. The mesh layout of the ecological network of the China's Chengdu-Chongqing urban agglomeration not only promotes the free circulation of ecological elements in the region but strengthens

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the ecosystem's self-recovery and regulation capacity. Through this series of construction and optimization measures, the China's Chengdu-Chongqing urban agglomeration will form a three-dimensional landscape ecological network with the ecological network as the skeleton, ecological source as the core, ecological corridor as the link, and peripheral ecological barriers wrapping the built-up area of the city tightly. This network not only effectively alleviates the ecological pressure in the process of urbanization and enhances regional biodiversity but also provides strong ecological support for the high-quality development of urban agglomeration, realizes the harmonious symbiosis between economic growth and ecological protection, and walks out of a green development road with the China's Chengdu-Chongqing urban agglomeration characteristics.

Discussion

The integrated MSPA-MCR approach adopted in this study aligns with the prevailing paradigm for ecological network construction, as evidenced by applications in the Kunming (Chen et al., 2025) and Hebei-Tianjin coastal wetlands (F. Wang et al., 2023). Our identification of 30 ecological sources reflects a strategic emphasis on forest-dominated core areas, consistent with Pant al. (Pan et al., 2023), who prioritized large, contiguous patches as primary ecological anchors. However, the observed high fragmentation underscores a critical challenge: urban expansion has degraded connectivity, particularly in central regions where artificial surfaces dominate. This spatial imbalance echoes findings from Chang et al. (Chang et al., 2023), who noted similar core-periphery disparities in ecological resilience within the China's Chengdu-Chongqing urban agglomeration.

The 80 priority corridors identified via the gravity model (total length: 7547.85 km) highlight functional connectivity bottlenecks. Southeast corridors exhibited weaker interaction forces (*Fig. 7*), attributable to terrain complexity and anthropogenic barriers-a phenomenon also documented in the mountainous areas of the Pearl River Delta (Y. Tang et al., 2016). Our results advance methodological rigor by incorporating multi-dimensional resistance factors, addressing limitations in earlier single-factor models (Kim et al., 2019). Nevertheless, the hierarchical weighting approach may introduce subjectivity; future studies could integrate spatial principal component analysis to enhance objectivity, as demonstrated by Zhang et al. (F. Zhang et al., 2024).

Notably, the low density of ecological nodes in central urban clusters signals urgent need for stepping-stone habitats. This aligns with Zou et al. (Zou et al., 2024), who identified central the China's Chengdu-Chongqing urban agglomeration as an ecological vulnerability hotspot. Our proposal to establish peripheral ecological barriers ("hot springs-type layout") extends the "green vein-blue network" concept (J. Jiang et al., 2023), offering a spatially explicit strategy for mitigating urban encroachment.

Scale considerations remain pivotal. While large-scale analysis inherently sacrifices localized precision (Zhu et al., 2021), it captures cross-jurisdictional processes essential for regional planning-validating our choice to study the entire agglomeration. The 31.21% source area proportion warrants scrutiny; comparative studies suggest 35-40% is optimal for biodiversity maintenance in urban agglomerations (Judd et al., 2022). Strategic expansion of central woodlands, as proposed herein, could bridge this gap while enhancing network robustness.

Conclusion

This paper constructs the ecological network of the China’s Chengdu-Chongqing urban agglomeration based on MSPA and MCR models. According to the results of MSPA morphology analysis, the core area of the China’s Chengdu-Chongqing urban agglomeration accounts for 83.35%, which is mainly distributed in the periphery of the urban agglomeration. The Edge is 8.21% of the area, and the Core has many boundaries and is vulnerable to disturbance. the China’s Chengdu-Chongqing urban agglomeration has a better ecological conservation capacity in the east and west, where large and continuous Core areas are mainly distributed. At the same time, in the center, there are only a small number of fragmented source areas with a weaker conservation capacity. The results of the MSPA analysis identified 30 ecological source sites, mainly in the peripheral regions of the China’s Chengdu-Chongqing urban agglomeration and less in the interior. Four hundred thirty-five ecological corridors were identified, and then 80 key ecological corridors were screened based on the gravity model as key corridors for ecological flow and material exchange. Seventy-four ecological nodes were identified as reference selection points for ecological stepping stones, which help to enhance the stability and diversity of ecosystems and to communicate the core ecological sources in the east, center, and west.

Concerning internal areas with fewer ecological source areas, a strategy of precise policy application and scientific planning should be adopted to effectively increase the area of green space in the region and enhance the ecological service function through measures such as ecological restoration, afforestation, and wetland protection and restoration, to gradually narrow the gap between the ecological quality of the area and that of other regions and realize a balanced distribution of ecological source areas. Concurrently, reinforcing ecological sources within the China’s Chengdu-Chongqing urban agglomeration is pivotal in establishing a more robust and efficacious ecological network system. To achieve this objective, it is necessary to eliminate the administrative barriers in the planning process. Furthermore, cross-regional ecological cooperation must be promoted, and the joint construction of ecological corridors must be encouraged. Examples of such corridors include ecological greenways, river ecological buffer zones, and mountain forest protection zones. Implementing these measures will ensure the unimpeded circulation of ecological elements. It will form an ecological pattern “connected by a green vein and interconnected by a blue network.”

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