EVOLUTION AND OPTIMIZATION OF POTENTIAL ECOLOGICAL CORRIDORS AMONG FOREST PATCHES IN CHINA'S HUNAN PROVINCE FROM 2000 TO 2019

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Abstract. Accelerating urbanization in China's Hunan Province has fragmented natural landscapes through road and railway construction. Will this affect the potential ecological corridors between forests? Taking 42 forests with an area greater than 100 km² in Hunan Province from 2000 to 2019 as the research objects, land type, night light, and vegetation cover index were selected as resistance factors. Based on the theory of the minimum cumulative resistance model, a potential ecological corridor network for forests was constructed. The Kruskal and K-Means algorithms were utilized to optimize the ecological corridors between forest patches. The results indicated that from 2000 to 2019, the length of forest ecological corridors in Hunan Province increased by 12.39%. Some potential ecological corridors gradually disappeared, and the number of potential ecological corridors around cities was significantly lower than in rural areas. Furthermore, the density of potential ecological corridors in southwestern Hunan was higher than in northeastern Hunan. After optimization, the total length of potential ecological corridors between forests in Hunan Province was significantly reduced. Compared to Kruskal's algorithm, the number of corridors forming a "closed loop" between forests increased, enhancing the mutual connectivity of geographically close forests.
Keywords: *construction of potential ecological corridor, K-Means clustering algorithm, Kruskal computation, ecological corridor optimization, MCR theory*

Introduction

Urbanization accelerates the decline in connectivity of biotic and abiotic habitat patches, intensifying landscape fragmentation and harming ecosystem health (Luo et al., 2020; Penghui et al., 2021). Constructing and optimizing ecological corridors connects dispersed ecological patches, promoting species migration, energy flow, and ecosystem stability (Xu et al., 2022).

Ecological corridors originate from the concept of "greenway" in foreign countries. Foreign scholars define an ecological corridor as a continuous and linear pathway that connects different ecosystems and provides channels for species migration, gene flow, and ecological processes (Reyes-Puig et al., 2019). As early as the 1980s, research on ecological corridor optimization primarily focused on the design and planning, functions and benefits, management, and protection of ecological corridors. Research on ecological corridors in China began later, focusing initially on urban greening, landscape aesthetics, and small-scale ecological protection. With the heightened awareness of ecological environment protection and biodiversity conservation, studies on ecological corridor optimization have garnered increasing attention (Guo et al., 2020). More scholars and experts in academia have embarked on extensive theoretical and practical exploration and research into the construction of ecological networks, and have basically established a paradigm for identifying ecological sources, constructing resistance surfaces, and extracting ecological corridors. This includes Morphological Spatial Pattern Analysis (MSPA) (An et al., 2021), circuit theory (Xie et al., 2022), graph theory (Cantwell et al., 1993), and the Minimum Cumulative Resistance (MCR) model (Li et al., 2015; Sun et al., 2022).

In recent years, due to the simplification of data structures and the rapid development of computational methods, the MCR model has been widely applied. It simulates the minimum cost path by calculating the minimum cumulative cost between the source patch and the target patch, seeking the optimal path for species migration or ecological process operation (Wang et al., 2019; Li et al., 2022). Dai et al. (2021) combined the MCR model with the Duranton and Overman index to establish a comprehensive evaluation method for ecological security networks. Taking Haikou City, an island city, as an example, Chen et al. (2020) used the MCR model to construct ecological resistance surfaces, obtain ecological corridors and nodes, and optimize the connectivity of urban ecological networks and landscape patches. Taking Changzhou, an important typical city in the Yangtze River Delta, as an example, Li et al. (2015) applied the MCR model and comprehensively considered the sources of ecological land and construction land, ecosystem service functions, resistance surfaces, and other factors to calculate the total amount of ecological land required to meet the needs of social and economic development and ecological protection. Zhang et al. (2021) identified ecological sources through the habitat quality module of the InVEST model and extracted ecological corridors, strategic ecological nodes, and stepping-stone patches based on the MCR model. Based on the theory of landscape ecology, Dong et al. (2015) studied the changes in landscape patterns in Nanjing over the past 20 years by selecting landscape pattern indices from TM images in 1990, 2000, and 2010 using remote sensing and Geographic Information System (GIS) technology, and constructed ecological networks based on the extraction of ecological nodes and MCR. Additionally, some researchers also used the MCR model to establish ecological corridors with ecological sources and resistance surfaces, achieving good results (Wang et al., 2022; Guan, 2023; Yang et al., 2023). Overall, potential ecological corridors between forest patches serve as the links connecting natural landscape spaces. Currently, most researchers primarily focus on the construction of potential ecological corridors between forest patches, with relatively few studies on the optimization of these corridors. Forests are indispensable and valuable resources on Earth, regulating climate, conserving water, preventing soil erosion, and acting as barriers against wind and sand. They are also the cradle of biodiversity and the largest biological gene pool on the planet. The construction of potential ecological corridors among forest patches can effectively improve the ecological environment quality of forest areas, promote biodiversity conservation, and enhance the overall connectivity and stability of forest ecosystems (Pugh et al., 2019; Nwachukwu et al., 2021).

In this study, we utilized the Minimum Cost Path (MCR) theory to construct potential ecological corridors among forest patches in Hunan Province. Additionally, Kruskal's and K-Means clustering algorithms were applied to analyze and study the potential ecological corridors among 42 forest patches in Hunan Province from 2000 to 2019. The aim of this paper is to elucidate the changing trends of potential ecological corridors among major forest patches in Hunan Province over the past two decades and to explore optimization strategies. These strategies aim to minimize the total length cost of ecological corridors and enhance the "closed loop number" of ecological corridors among adjacent forest patches, thereby providing insights for the construction and optimization of ecological corridors within the region.

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Materials and methods

Study area

Hunan Province, located in China, is situated between 108°47' and 114°15' east longitude, and 24°38' and 30°08' north latitude. It features diverse landforms and primarily has a continental subtropical monsoon humid climate. The climate exhibits significant seasonal variation: winters are cold, summers are hot, springs are characterized by fluctuating temperatures, and there is a pattern of rainy springs and summers followed by dry autumns and winters. The province is part of the tropical evergreen broad-leaved forest region. The main natural ecosystem types are forest and wetland ecosystems, covering over 12.67 million hectares of forest area. By the end of 2023, the forest coverage rate of the province will have reached 53.15%, the forest stock will have reached 655 million cubic meters, and the comprehensive vegetation coverage of grassland will have reached 86.87%.

In this paper, 42 forest areas with an area greater than 100 km² from 2000 to 2019 in Hunan Province were taken as the research object, and the area of such forests accounted for approximately 80.82% of the total forest area in Hunan Province. The specific distribution among forest patches is shown in *Fig. 1*.

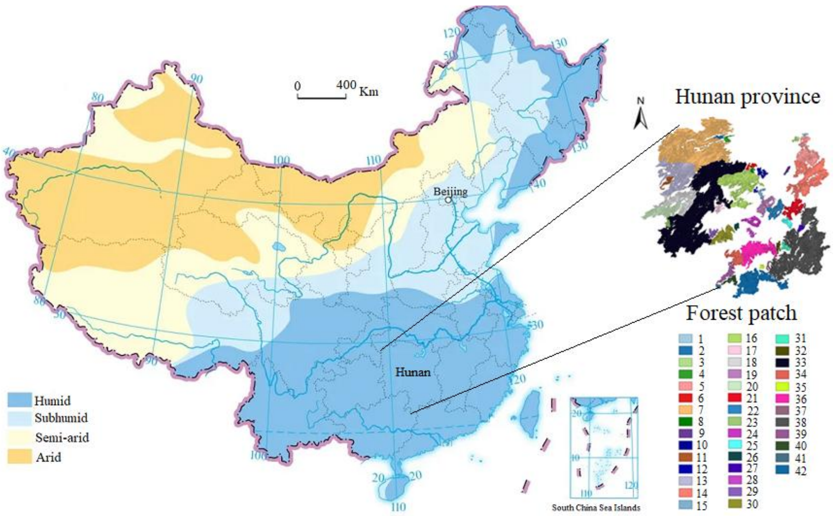

***Figure 1.** 42 forest patch research areas in Hunan Province*

Data sources

In this paper, land type, lighting, vegetation cover index, slope, elevation, etc., are selected as resistance factors. The amount of nighttime lighting data is sourced from the Resource and Environmental Science and Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/). NDVI, slope, and elevation data are all obtained from the Geospatial Data Cloud (http://www.gscloud.cn/). Land use type comes from the resource and environmental science and data center of the Chinese Academy of Sciences (https://www.resdc.cn/),Referring to the processing methods in the relevant literature (Liu et al., 2015; Gong et al., 2020), the land use types in this area are divided into forest, shrub, grassland, wetland, plowland, water area, impervious surface, wasteland, and the image resolution is set to 30 m×30 m. Furthermore, to facilitate the research, this paper calculates the centroid among forest patches using ArcGIS software, and connects the

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potential ecological corridors between different forest patches through their centroids. Due to slight differences in the centroid positions of some forest patches across different years, this paper unifies the centroid positions among forest patches across these years.

Research methods

Source point selection and resistance surface construction

The construction of source points and resistance surfaces provides clear insights into the source, transmission pathways, and consumption processes of energy and material within the ecosystem. In this paper, the centroid of each forest area is designated as an ecological source point and numbered accordingly. Resistance refers to the degree to which species migration is hindered by human activities or natural conditions. For the majority of terrestrial organisms, construction land, waters, and areas of high human activity can pose significant obstacles in the process of species migration and dispersion (Zuo et al., 2022). Drawing on the existing research of relevant scholars (Tang et al., 2020; Zhang et al., 2021), this paper selects land type, altitude, slope, NDVI, and nighttime light intensity as the environmental factors influencing resistance cost. It employs the reclassification technology in ArcGIS to assign specific resistance factor values to these variables (Li et al., 2021; Liu et al., 2021), determines the weight value of each resistance factor (Li et al., 2019), Subsequently, the grid calculator in ArcGIS software is employed to compute the corresponding comprehensive resistance value, thereby constructing the ecological resistance surface of Hunan Province. The formula for calculating the resistance value is *formula (1)*.

$$Cost_V = T \times 0.3 + D \times 0.25 + N \times 0.2 + P \times 0.15 + G \times 0.1 \quad \text{(Eq.1)}$$

where T is the landscape type, D is nightlight intensity, N is the vegetation index (e.g., NDVI), P is slope, and G is elevation.

The resistance and weight values assigned to each environmental factor are presented in *Table 1*.

Calculation method of potential ecological corridor based on MCR

The ecological corridor represents the most easily traversable low-resistance pathway connecting two adjacent "ecological sources" (Carlier et al., 2019). The Minimum Cumulative Resistance (MCR) model calculates the cumulative cost of ecological flow traversing the landscape, with the aim of identifying the path of least resistance, or the minimum cumulative resistance path, between two regions (Tang et al., 2020). The model is *formula (2)*.

$$MCR = f_{min} \sum_{j=n}^{i=m} D_{ij} R_i \quad \text{(Eq.2)}$$

where *MCR* is the minimum cumulative resistance distance from the source j to any point in space. The unit of *MCR* in this paper is km; f is the positive correlation function between the minimum cumulative resistance *MCR*, and Min is the minimum cumulative resistance cost of unit i for different ecological sources; D_{ij} is the spatial distance from the ecological source j to the destination unit i; R_i is the resistance coefficient of unit i to the movement of a species.

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Table 1. *Resistance surface index system and resistance weights*

Resistance factor	Unit	Resistance value								Weight
		5	**15**	**30**	**50**	**70**	**80**	**90**	**100**	
Land-use type	-	Forest	Shrub	Grassland	Wetland	Plowland	Water area	Impervious surface	Wasteland	0.3
Night light	-	<50	50-100	101-300	301-500	501-1000	1001-2000	2001-3000	>3000	0.25
NDVI (July every year)	-	0.81-1.00	0.61-0.80	0.51-0.60	0.41-0.50	0.31-0.40	0.21-0.30	0.10-0.20	<0.10	0.2
Slope	degrees	<10	11-15	16-20	21-25	26-30	31-35	36-50	>50	0.15
DEM	m	<100	101-200	201-300	301-500	501-600	601-700	701-900	>900	0.1

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Ecological corridor optimization based on K-means and Kruskal algorithm

Optimizing forest ecological corridor routes using the Kruskal algorithm alone

The Kruskal algorithm, proposed by Joseph Bernard Kruskal in 1956, is utilized to address the challenge of identifying a spanning tree that encompasses all vertices in a connected weighted undirected graph, while simultaneously minimizing the aggregate weight of its edges (Pop, 2020; Çalışkan et al., 2020). The detailed procedures of the fundamental Kruskal algorithm for determining the optimal ecological corridor path, encompassing vertex T and edge set V among forest patches, are outlined as *Step 1~ Step 6*.

Step 1: the cumulative resistance cost between any two forest patches serves as the weight for the corresponding edge, upon which a logical weighted connected graph is constructed, as illustrated in *Fig. 2*.

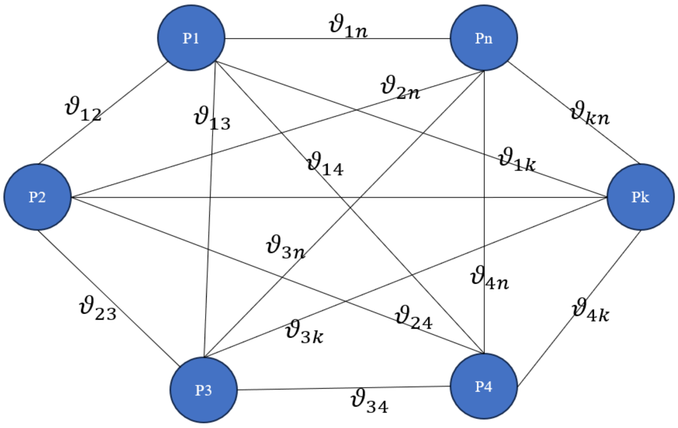

Figure 2. *Diagram of weighted logical connections in potential forest patch corridors. Where $P_1, P_2, P_k, \cdots P_n$ is the logical vertex of the forest patch, and $\vartheta_{12}, \vartheta_{13}, \cdots \vartheta_{kn}$, represents the minimum cumulative resistance path length between a pair of logical vertices, and this path length is used to determine the weights of the edges in the logical weighted connected graph representing the potential ecological corridor between the forest patches*

Step 2: Sort all edges in the graph in ascending order based on their weight values, and construct the *Ordering_Matrix* to store the sorted edges and their corresponding weight values. The data structure of the *Ordering_Matrix* is *formula (3)*.

$$Ordering\_Matrix = \begin{bmatrix} Edges & From & To & Weight \\ eg[1] & P_i & P_j & \vartheta_{ij} \\ eg[2] & P_j & P_f & \vartheta_{jf} \\ eg[z] & P_f & P_l & \vartheta_{fl} \\ eg[m] & P_i & P_m & \vartheta_{im} \end{bmatrix} \vartheta_{ij} \le \vartheta_{jf} \le \vartheta_{fl} \le \cdots \le \vartheta_{im} \quad \text{(Eq.3)}$$

where $m$is the number of edges in the logical weighted connected graph corresponding to the potential ecological corridors between forest patches; P_i, P_j and P_m are vertices in the weighted connected graph.

Step 3: Initialize the vertex set $T = \{\}$ for storing vertices on the optimal path and edge set $V = \{\}$ for storing edges.

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Step 4: Select the corresponding edge $eg[z]$ and vertex $Z = \{P_f, P_l\}$from the Ordering_matrix.

Step 5: Take the intersection of the sets T and Z ($T \cap Z$), if $T \cap Z \neq Z$, update $T = \{T, Z\}$and $V = \{V, eg[z]\}$.

Step 6: Repeat the *Step 5* according to the selection order of $eg[1] \to eg[2] \to \cdots \to eg[m]$ in *Ordering_Matrix*, and finally output the T and V.

Optimizing forest ecological corridor routes base on a hybrid algorithm combining K-Means and Kruskal

The Kruskal algorithm can effectively generate an optimal tree path for an ecological corridor between forest patches, but there may be forest patch nodes that, despite their close geographical proximity, lack direct connections between them. This situation is not conducive to energy exchange and species migration between the forest patches. The K-means clustering algorithm, an iterative dynamic clustering analysis algorithm, can classify similar objects into a single class (Sinaga et al., 2020). To construct a more scientifically sound potential ecological corridor between forest patches, this paper designs a three-step approach based on the K-means and Kruskal algorithms to find the potential optimal ecological corridor between forest patches.

Step 1: Use the Kruskal algorithm to construct an ecological corridor path, represented by a vertex set T and an edge set V, that includes all forest patches.

Step 2: Use the K-means algorithm to cluster all forest patches into k classes based on their geographical locations, and then use the Kruskal algorithm to solve for the ecological corridor path vertex set T_h and edge set $V_h (h = 1,2, \cdots k)$for each class among forest patches, respectively.

Step 3: Find the intersection of set T and T_h, and the intersection of set V and $V_h (T = T \cup T_{h,} V = V \cup V_h)$,the output sets T and $V$are the vertices and connecting edges in the optimal path of the forest patch ecological corridor.

Results

The spatial distribution of resistance values in Hunan Province from 2000-2019

From a spatial distribution perspective, the increase in resistance values is more pronounced in areas proximate to urban centers. The resistance values and ranges surrounding large and medium-sized cities, such as Changsha, Changde, Yueyang, and Hengyang, have significantly risen due to factors like high population density, intense land development, and a dense road network. In contrast, cities like Jishou (in Xiangxi Autonomous Prefecture), Zhangjiajie, Huaihua, and Chenzhou, which are relatively remote and boast a sound ecological base, exhibit smaller changes in resistance values. The disparity in resistance values among these cities is not solely attributable to the level of urbanization but may also be influenced by various factors, including topography, policy guidance, and ecological protection awareness. For instance, Zhangjiajie and Xiangxi Autonomous Prefecture are constrained by natural conditions like complex terrain, towering mountains, and remote waterways. Additionally, the government's ecotourism development strategy and stringent ecological protection policies contribute to relatively low resistance values and a narrow range of change in their ecological corridor construction. Conversely, economically developed cities like Changsha face high

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resistance and rapid growth in ecological corridor construction due to factors such as dense populations, scarce land resources, and strong economic development demands.

Amid the rapid pace of global urbanization, natural ecosystems are confronted with unprecedented challenges. As vital pathways connecting fragmented ecological patches, ecological corridors are crucial for preserving biodiversity and enhancing ecological security. According to the experimental results, the resistance value of ecological corridor construction in Hunan Province exhibited a linear upward trend from 2000 to 2019. The average resistance value increased from 16.75 to 18.84, with an average annual growth rate of 0.7%, indicating that as the economy and society develop and urbanization accelerates, the obstacles to ecological corridor construction in Hunan Province are mounting, the spatial distribution of resistance values in Hunan Province is shown in *Fig. 3*.

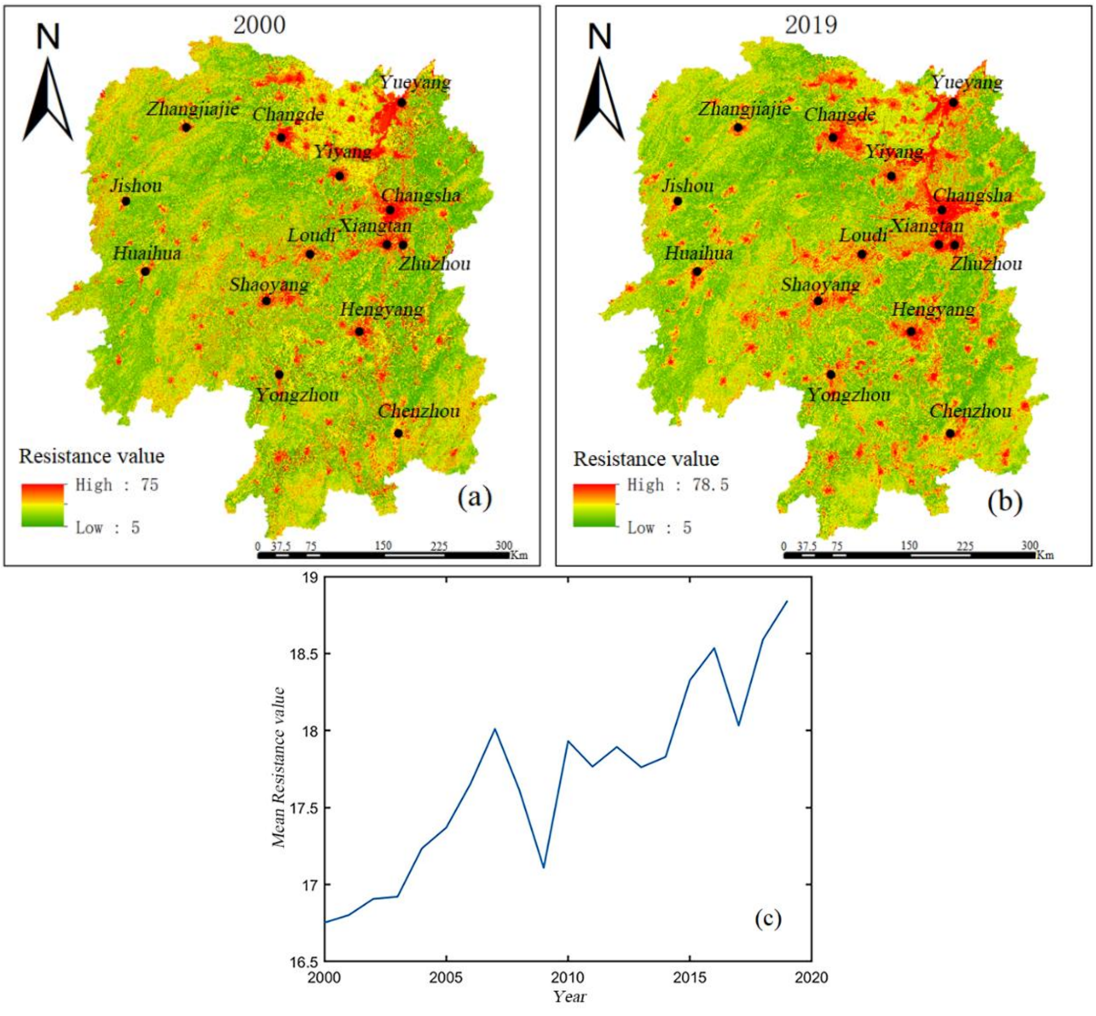

Figure 3. *Spatial Distribution of Resistance Surface and Annual Variation Trend of Average Resistance Value in Hunan Province. The figure consists of three parts: (a) displays the spatial distribution of the ecological resistance surface in Hunan Province in 2000, (b) presents the spatial distribution of the ecological resistance surface in Hunan Province in 2019, and (c) shows the trend of the average resistance value in Hunan Province from 2000 to 2019*

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Spatiotemporal analysis of basic characteristics of potential ecological corridors

Based on the experimental results, notable urban-rural disparities are evident in the spatial distribution of potential ecological corridors between forest patches in Hunan Province. Specifically, the line density of potential ecological corridors surrounding cities is markedly lower compared to that in rural areas. This can be attributed to the urban expansion that encroaches on natural ecological spaces, prompting most ecological corridors to circumvent urban regions. Furthermore, the number of potential forest ecological corridors in the northeast of Hunan Province is relatively scarce. Regarding regional variations, the line density of potential ecological corridors is generally lower in the eastern region than in the west, and lower in the north compared to the south. These disparities may stem from factors such as topography, climatic conditions, and the intensity of human activities prevalent in Hunan Province. For instance, the western region preserves more natural ecological space due to its rugged terrain and relatively limited human intervention (*as shown in Fig. 4*).

From a temporal perspective, the density of ecological corridor lines in 2000 was notably higher than that in 2019, suggesting a gradual decrease in the number of potential ecological connection pathways between forests in Hunan Province. Some ecological corridor lines are at risk of gradual disappearance. Additionally, the path length of ecological corridors between forest patches in Hunan Province exhibited a significant linear upward trend from 2000 to 2019. The total cost path length increased from 3,951,339.86 kilometers in 2000 to 4,441,056.47 kilometers in 2019, representing a 12.39% increase. Concurrently, the average length of ecological corridors between forest patches also lengthened, from 2,294.62 km to 2,579.01 km (*as shown in Table 2*). From a temporal viewpoint, the obstacles to species migration and diffusion intensified from 2000 to 2019, thereby influencing the material circulation and energy flow within the ecosystem among forest patches in Hunan Province.

The decrease in the line density of potential ecological corridors and the increase in the total path length between forest patches in Hunan Province can be attributed to the combined effects of various factors. Notably, with the acceleration of urbanization and changes in land use, some forests have been converted into farmland, urban land, or other non-ecological uses, leading to the severing or weakening of ecological connections between forest patches. For example, from 2000 to 2018, the urban built-up area in Hunan Province increased from 799.27 square kilometers to 1709.35 square kilometers. Moreover, the disruptions caused by climate change, natural disasters, and human activities on the ecological environment may also impact the stability of ecological corridor lines, resulting in a reduction in their number, as illustrated in *Fig. 4*.

Optimization analysis of potential ecological corridors in forest patches

It is evidently unrealistic to construct potential ecological corridors between every single forest patch, yet it is feasible to establish an ecological corridor network that interconnects all forest patches in Hunan Province. Such a network would integrate all forest patches within the province, ensuring the integrity and efficacy of ecological connections, facilitating species migration and energy flow, and preserving the holistic ecological connectivity. However, the primary challenge lies in selecting an ecological corridor network with the lowest construction cost amidst a myriad of potential options.

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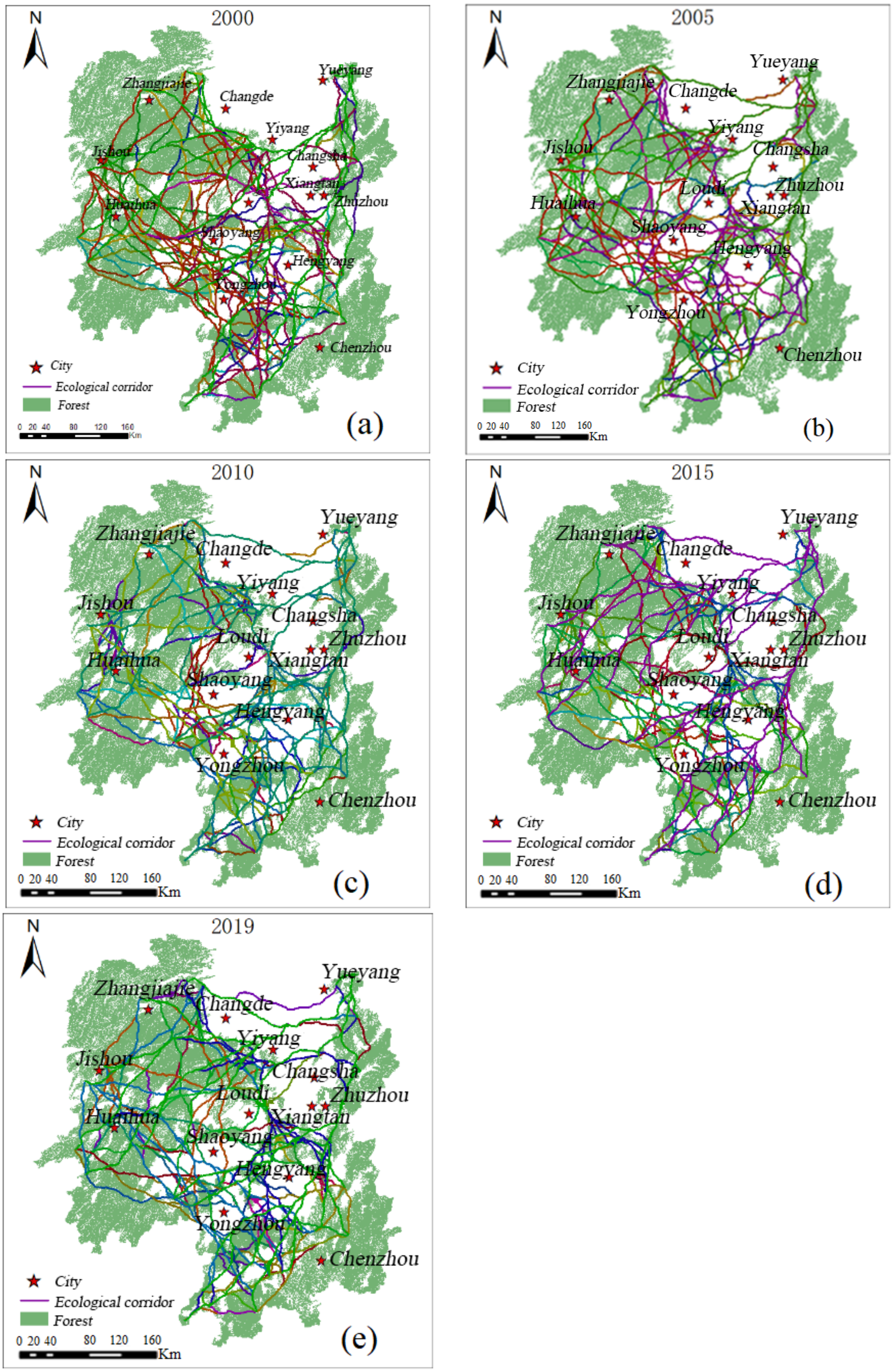

__Figure 4.__ Displays the spatial distribution of potential ecological corridors between forest patches in Hunan Province. Panels (a) through (e) in the figure depict the spatial distribution of these corridors in 2000, 2005, 2010, 2015, and 2019, respectively

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***Table 2.** The path length of potential ecological corridor cost among forest patches in Hunan Province*

Year	Total cost path length (km)	Average cost path length (km)
2000	3951339.86	2294.62
2005	4066727.22	2361.63
2010	4149765.2	2409.85
2015	4312911.63	2504.59
2019	4441056.47	2579.01

Currently, some researchers employ the Kruskal algorithm to optimize ecological corridors between forest patches, leveraging scientific algorithms to minimize unnecessary corridor construction, thereby reducing the vast number of potential corridors and associated high construction and maintenance costs. The Kruskal algorithm, a renowned minimum spanning tree algorithm, ensures that the resulting corridor network connects all forests while minimizing the overall path cost.

In this paper, we adopt the fundamental Kruskal algorithm outlined in Section *2.3.1* as the optimization strategy for ecological corridors. We optimize the potential ecological corridors between forest patches in Hunan Province from 2000 to 2019. The results indicate that, compared to a scenario where all potential corridors are constructed indiscriminately, the ecological corridor network optimized by the Kruskal algorithm significantly reduces construction costs while maintaining ecological flows and species migration between forests. This approach effectively enhances the overall stability and diversity protection of the regional ecosystem. The optimized routes of potential corridors between forest patches are illustrated in *Fig. 5.*

After applying the Kruskal algorithm to optimize the potential ecological corridors between forest regions, the total cost of the corridors was significantly reduced, effectively enhancing both the economic efficiency and ecological benefits. Although the Kruskal algorithm excels in global optimization, it still exhibits imperfections in local areas. For instance, there is a notable absence of directly connected corridors between forest areas with similar geographical locations, such as Jishou City and Zhangjiajie City, necessitating long-distance detours through other forests for energy flow and species migration, thereby substantially increasing the resistance and cost of ecological interactions.

To address these limitations, this article innovatively incorporates the k-Means clustering algorithm as a preparatory step, building upon the ecological corridor optimization design scheme based on K-means and Kruskal algorithms outlined in Section 1.2.3. Initially, 42 forest regions undergo geographical clustering analysis, grouping forests that are spatially proximate and share similar ecological characteristics into clusters. Subsequently, the Kruskal algorithm is employed to optimize the corridors within the overall forest and among various forest types within clusters, effectively minimizing corridor costs between regions that are geographically close yet exhibit weak ecological connections.

The research findings reveal that, post-optimization, all forest nodes across all years (*2000-2019*) have achieved full connectivity, with no isolated nodes (*as depicted in Fig. 6*). Direct corridors now exist between some geographically proximate forest patches, resolving the issue of proximity without direct corridor links, exemplified by forest patch nodes numbered 7 and 13.

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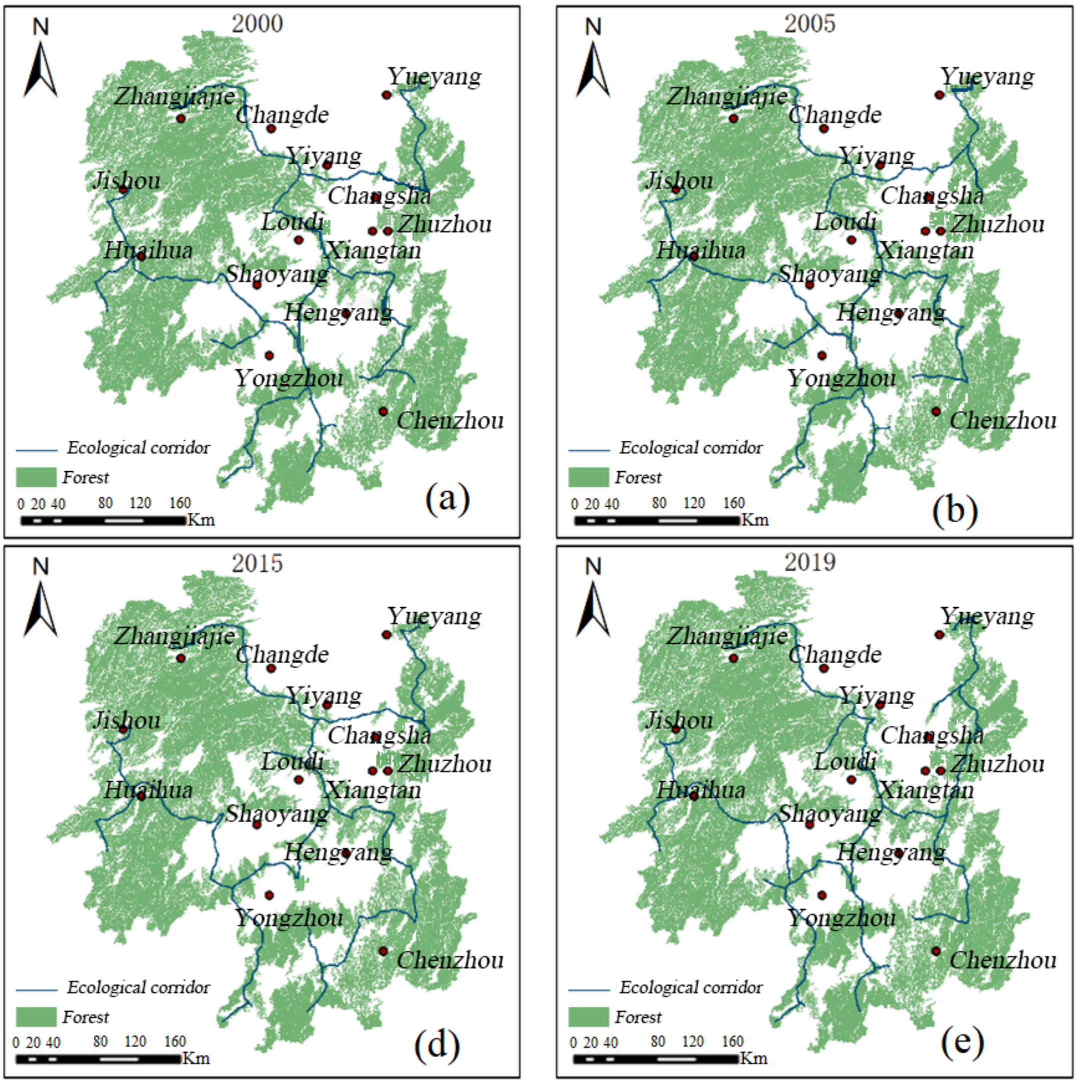

Figure 5. *Kruskal Algorithm for Solving the Optimal Route Maps of Potential Corridors between Forest Patches in Hunan Province. In the figure, panels (a) through (e) represent the optimal route maps of potential ecological corridors between forest patches in Hunan Province, as determined by the Kruskal algorithm, for the years 2000, 2005, 2010, 2015, and 2019, respectively*

Compared to the previous optimized version, the total cost of corridors between forest patches has been drastically reduced (*as shown in Table 3*, with a reduction rate exceeding 99.30%), indicating the effectiveness of the optimization strategy in lowering corridor construction costs, enhancing resource utilization efficiency, and fostering a more stable and efficient ecological corridor network structure.

However, on a temporal scale, the total length of ecological corridor construction between forest patches increased from 27,161.59 km in 2000 to 30,821.62 km in 2019, exhibiting a steady upward trend. This trend is likely attributable to the intensification of human activities, which have imposed greater pressure on the natural environment, leading to a corresponding increase in the potential cost of ecological corridors in forests. Furthermore, while the overall layout of potential forest corridors remains highly consistent across years, subtle changes are evident.

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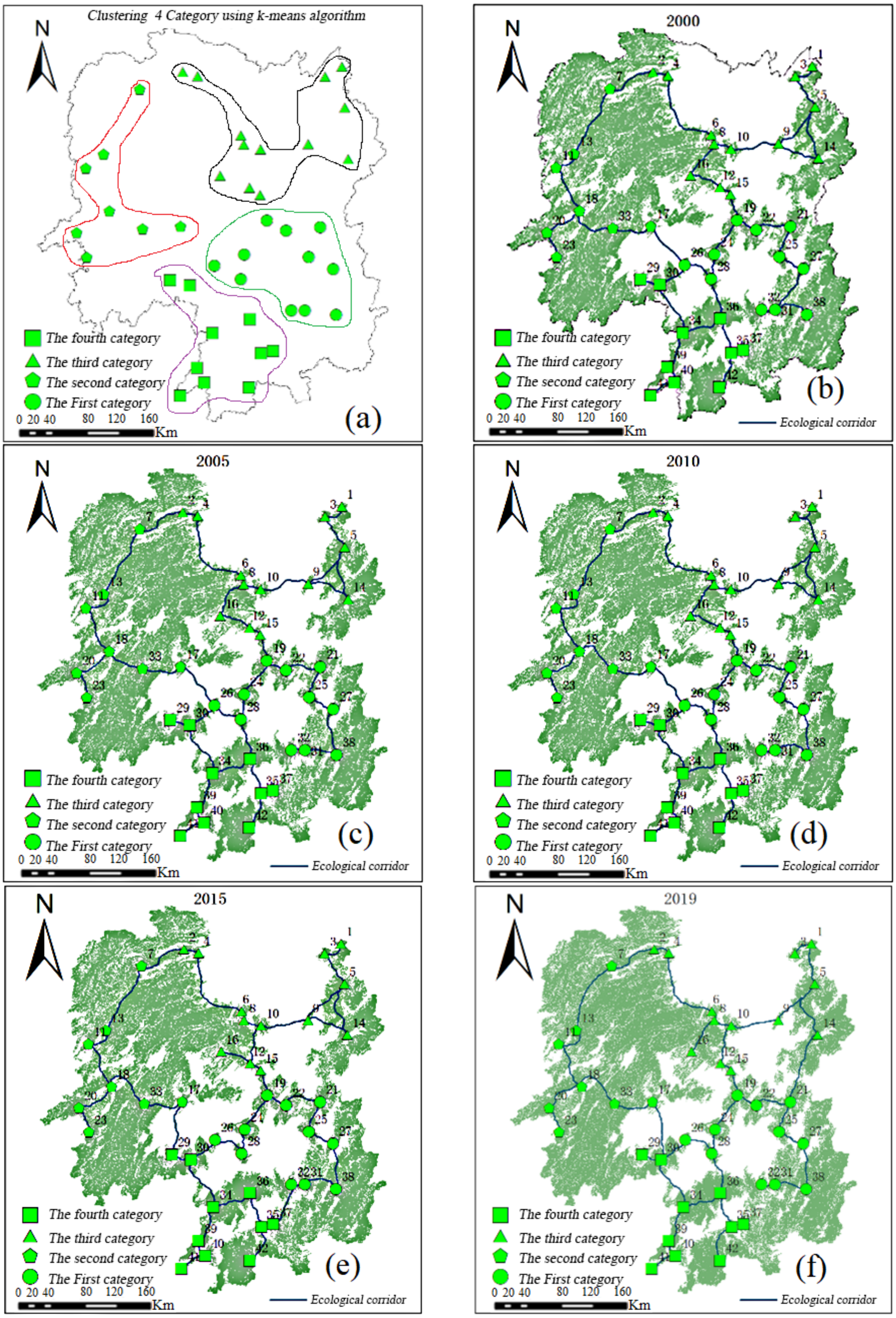

***Figure 6.** Optimized route map of potential corridors between Hunan forest patches via K-means and Kruskal algorithms. In Figure 6(a), the K-means algorithm is applied to identify areas containing more than 42 forest patches in Hunan Province. Figures 6(b) to 6(f) utilize both the K-means and Kruskal comprehensive algorithm to illustrate the optimized potential corridor route maps between forest patches in Hunan Province for the years 2000, 2005, 2010, 2015, and 2019, respectively*

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Table 3. *The total cost length of potential ecological corridors between forest patches, before and after optimization*

Year	Before optimization (km)	After optimization (km)	Reduction ratio
2000	3951339.86	27161.59	99.31%
2005	4066727.22	28153.22	99.31%
2010	4149765.2	28908.15	99.30%
2015	4312911.63	29824.87	99.31%
2019	4441056	30821.62	99.31%

For example, forest nodes 14 and 21, which were not directly connected prior to 2019, established direct corridors in that year, while the "closed loop" structure formed by specific node combinations (e.g., 9, 5, and 14) between 2000 and 2015 dissipated in 2019. These dynamic shifts underscore that the forest patch ecological corridor network evolves over time in response to human activities.

Additionally, an analysis of forest node connectivity revealed that nodes numbered 19, 18, 26, 30, 34, 9, 36, and 5 were all connected to three or more other forest patches post-optimization, signifying their pivotal role in fostering overall forest connectivity and serving as key hubs for linking potential ecological corridors. In subsequent forest management, these forest patch nodes should be prioritized for protection, and through scientific planning and rational management, their status as hubs within the ecological corridor network should be further consolidated and strengthened. The optimized route of potential corridors between forests is illustrated in *Fig. 6*.

Discussion

There are significant differences between urban and rural areas in the spatial distribution of potential ecological corridors among forest patches in Hunan Province, especially the notable decrease in the density of ecological corridors surrounding cities. Urban expansion not only results in the compression of ecological space but also impacts species migration and the material circulation and energy flow within ecosystems (Wei et al., 2022; Zhang et al., 2022). In the future urbanization process, balancing economic development and ecological protection is an urgent issue to address.

The disparity in the number of ecological corridors across different regions of Hunan Province, particularly the low density in the northeast and eastern regions, may stem from multiple factors such as topography, climate conditions, and the intensity of human activity. Due to the complex terrain and relatively sparse human activities, the western region of Hunan Province retains more natural ecological space, highlighting the significant influence of terrain and human disturbance on the distribution of ecological corridors (Gu et al., 2022). In future planning and management of ecological corridors, these regional differences should be thoroughly considered, and targeted protection measures should be implemented (Jiw, 2010; Justeau-Allaire et al., 2021). From a temporal perspective, the number of potential ecological corridors between forest patches in Hunan Province is gradually declining, whereas the path length is increasing. This trend reflects the ongoing impact of human activities on the natural environment and potential threats to ecosystems posed by natural factors like climate change. The reduction in the number of ecological corridors and the increase in path length heighten the resistance to species migration and ecological flow, posing a challenge to the stability and diversity of regional ecosystems (Barzan et al., 2015; Wang et al., 2022). The optimization effect of the Kruskal algorithm in localized forest ecological corridors still has certain limitations, as seen in Jishou City and Zhangjiajie City, which are geographically proximate yet lack direct connected corridors. The introduction of the K-means clustering algorithm as a preliminary processing step effectively reduces corridor costs between regions with close geographical proximity but weak ecological connections, enhancing the stability and efficiency of the ecological corridor network. The optimized corridor is the optimal route that can ensure the main forests in Hunan Province are connected with each other through multiple corridors, and It is the corridor line that needs to be protected in the future urban expansion or ecological corridor construction and maintenance.

In addition, through the analysis of the connectivity of forest nodes, it is found that some forest patch nodes are optimized to connect with other forest patches and become hubs in the ecological corridor network (such as forests numbered 16, 26 and 28). These nodes play a key role in enhancing the overall connectivity of the forest. In the follow-up forest management, these nodes should be taken as key protection targets, and their pivotal position in the ecological corridor network should be further consolidated and strengthened through scientific planning and rational management.

Conclusion

In this study, 42 forest patches with an area exceeding 100 km² in Hunan Province were selected as the research objects. Factors such as land type, lighting, vegetation cover index, slope, and elevation were chosen as resistance factors to construct a comprehensive resistance surface. Based on the theory of the minimum cumulative resistance model, a potential ecological corridor network connecting these forests was established, and the evolution characteristics of ecological corridors between forest patches in Hunan Province from 2000 to 2019 were analyzed. The Kruskal and k-means algorithms were employed to optimize the ecological corridors between forest patches. The primary research conclusions are as follows:

(1) Over the observation period from 2000 to 2019, the resistance to the establishment of potential ecological corridors between forest patches in Hunan Province continued to increase, with an average annual growth rate of 0.7%, particularly pronounced after 2010.

(2) There are notable differences in the spatial distribution of ecological corridors between urban and rural areas in Hunan Province. Overall, the line density of ecological corridors around urban areas in Hunan Province is significantly lower than that in rural areas. Ecological corridors are relatively scarce in the northeast and eastern regions of Hunan, while the number of potential corridors connecting forest patches in the western region is relatively high.

(3) From 2000 to 2019, the total number of potential ecological connection paths between forests in Hunan Province exhibited a declining trend, with some potential corridors between forest patches disappearing. However, the length of potential ecological corridor paths between forest patches demonstrated a marked increase, indicating a weakening of the connectivity between forest patches.

(4) The hybrid algorithm combining K-means and Kruskal addresses the issue of geographically close forest patches lacking direct corridor connections when solely relying on the Kruskal algorithm. This significantly enhances the stability and efficiency

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of the ecological corridor network, and remarkably reduces the total corridor cost compared to pre-optimization levels.

In future endeavors related to forest ecological protection and restoration, greater emphasis should be placed on safeguarding and rehabilitating ecological corridors between forests. By constructing ecological corridors, restoring degraded land, optimizing land use structures, and adopting other measures, it is crucial to reasonably plan urban expansion boundaries to avert further damage to ecological corridors. This will strengthen the ecological connections between forests, uphold the integrity and stability of the ecosystem, and ensure its continued vital role in maintaining ecological balance and facilitating species migration.

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REFERENCES

[1] An, Y., Liu, S., Sun, Y., Shi, F., Beazley, R. (2021): Construction and optimization of an ecological network based on morphological spatial pattern analysis and circuit theory. – Landscape Ecology 36: 2059-2076.

[2] Barzan, F. R., Baigorria, J. M. E., Bó, R. F. (2015): Bird Community Diversity in three Habitat Types in an Ecological Corridor in the Atlantic Forest of Misiones Province, Argentina. – Tropical Conservation Science 8(4): 955-974.

[3] Çalışkan, M., Anbaroğlu, B. (2020): Geo-MST: A geographical minimum spanning tree plugin for QGIS. – SoftwareX, 100553.

[4] Cantwell, M. D., Forman, R. T. T. (1993): Landscape graphs: Ecological modeling with graph theory to detect configurations common to diverse landscapes. – Landscape Ecology 8: 239-255.

[5] Carlier, J., Moran, J. (2019): Landscape typology and ecological connectivity assessment to inform Greenway design. – Science of The Total Environment 651: 3241-3252.

[6] Chen, C., Shi, L., Lu, Y., Yang, S., Liu, S. (2020): The Optimization of Urban Ecological Network Planning Based on the Minimum Cumulative Resistance Model and Granularity Reverse Method: A Case Study of Haikou, China. – IEEE Access 8: 43592-43605.

[7] Dai, L., Liu, Y., Luo, X. (2021): Integrating the MCR and DOI models to construct an ecological security network for the urban agglomeration around Poyang Lake, China. – Science of The Total Environment 754: 141868.

[8] Dong, J., Dai, W., Shao, G., Xu, J. (2015): Ecological Network Construction Based on Minimum Cumulative Resistance for the City of Nanjing, China. – ISPRS International Journal of Geo-Information 4(4): 2045-2060.

[9] Gong, P., Chen, B., Li, X., Liu, H., Wang, J., Bai, Y., … Xu, B. (2020): Mapping essential urban land use categories in China (EULUC-China): preliminary results for 2018. – Science Bulletin 65(3): 182-187.

[10] Gu, Y., Lin, N., Ye, X., Xu, M., Qiu, J., Zhang, K., Zou, C., Qiao, X., Xu, D. (2022): Assessing the impacts of human disturbance on ecosystem services under multiple scenarios in karst areas of China: Insight from ecological conservation red lines effectiveness. – Ecological Indicators 142: 109202.

[11] Guan, J. (2023): The impact of onshore wind farms on ecological corridors in Ningbo, China. – Environmental Research Communications 5: 015006.

[12] Guo, X., Zhang, X., Du, S., Li, C., Siu, Y. L., Rong, Y., Yang, H. (2020): The impact of onshore wind power projects on ecological corridors and landscape connectivity in Shanxi, China. – Journal of Cleaner Production 254: 120075.
[13] Jiang, P. H., Chen, D. S., Li, M. C. (2021): Farmland landscape fragmentation evolution and its driving mechanism from rural to urban: A case study of Changzhou City. – Journal of Rural Studies 82: 1-18.
[14] Jiw, W. (2010): The Research on the Urban Ecological Corridor Planning-With Daixi in Huzhou, Zhejing Province as Example. – Urban Studies, China.
[15] Justeau-Allaire, D., Vieilledent, G., Rinck, N., Vismara, P., Lorca, X., Birnbaum, P. (2021): Constrained optimization of landscape indices in conservation planning to support ecological restoration in New Caledonia. – Journal of Applied Ecology 58(4): 744-754.
[16] Li, F., Ye, Y., Song, B., Wang, R. (2015): Evaluation of urban suitable ecological land based on the minimum cumulative resistance model: A case study from Changzhou, China. – Ecological Modelling 318: 194-203.
[17] Li, H., Jia, M., Zhang, R., Ren, Y., Wen, X. (2019): Incorporating the Plant Phenological Trajectory into Mangrove Species Mapping with Dense Time Series Sentinel-2 Imagery and the Google Earth Engine Platform. – Remote Sensing 11(21): 2479.
[18] Li, Y., Wang, X., Dong, X. (2021): Delineating an Integrated Ecological and Cultural Corridor Network: A Case Study in Beijing, China. – Sustainability 13(1): 412.
[19] Li, Q., Zhou, Y., Yi, S. (2022): An integrated approach to constructing ecological security patterns and identifying ecological restoration and protection areas: A case study of Jingmen, China. – Ecological Indicators 137: 108723.
[20] Liu, H., Gong, P., Wang, J., Clinton, N., Bai, Y., Liang, S. (2020): Annual dynamics of global land cover and its long-term changes from 1982 to 2015. – Earth System Science Data 12(2): 1217-1243.
[21] Liu, Z., Huang, Q., Tang, G. (2021): Identification of urban flight corridors for migratory birds in the coastal regions of Shenzhen city based on three-dimensional landscapes. – Landscape Ecology 36(7): 2043-2057.
[22] Luo, Y., Wu, J., Wang, X., Wang, Z., Zhao, Y. (2020): Can policy maintain habitat connectivity under landscape fragmentation? A case study of Shenzhen, China. – Science of The Total Environment 715: 136829.
[23] Nwachukwu, C. M., Wang, C., Wetterlund, E. (2021): Exploring the role of forest biomass in abating fossil CO_2 emissions in the iron and steel industry - The case of Sweden. – Applied Energy 288: 116558.
[24] Pop, P. C. (2020): The generalized minimum spanning tree problem: An overview of formulations, solution procedures and latest advances. – European Journal of Operational Research 283(1): 1-15.
[25] Pugh, T. A. M., Lindeskog, M., Smith, B., Poulter, B., Arneth, A., Haverd, V., Calle, L. (2019): Role of forest regrowth in global carbon sink dynamics. – Proceedings of the National Academy of Sciences 116(10): 4382-4387.
[26] Reyes-Puig, J. P., Reyes-Puig, C., Ron, S., Ortega, J. A., Guayasamin, J. M., Goodrum, M., Yánez-Muñoz, M. H. (2019): A new species of terrestrial frog of the genus Noblella Barbour, 1930 (Amphibia: Strabomantidae) from the Llanganates-Sangay Ecological Corridor, Tungurahua, Ecuador. – PeerJ 7: e7405.
[27] Sinaga, K. P., Yang, M.-S. (2020): Unsupervised K-Means Clustering Algorithm. – IEEE Access 8: 80716-80727.
[28] Sun, J., Huang, J., Wang, Q., Zhou, H. (2022): A method of delineating ecological red lines based on gray relational analysis and the minimum cumulative resistance model: a case study of Shawan District, China. – Environmental Research Communications 4: 045009.
[29] Tang, Y., Gao, C., Wu, X. (2020): Urban Ecological Corridor Network Construction: An Integration of the Least Cost Path Model and the InVEST Model. – ISPRS International Journal of Geo-Information 9(1): 33.

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DOI: http://dx.doi.org/10.15666/aeer/2302_23932410

[30] Wang, H., Peng, P., Kong, X., Zhang, T., Yi, G. (2019): Evaluating the Suitability of Urban Expansion Based on the Logic Minimum Cumulative Resistance Model: A Case Study from Leshan, China. – ISPRS International Journal of Geo-Information 8(7): 291.
[31] Wang, Y., Qu, Z., Zhong, Q., Zhang, Q., Zhang, L., Zhang, R., Yi, Y., Zhang, G., Li, X., Liu, J. (2022): Delimitation of ecological corridors in a highly urbanizing region based on circuit theory and MSPA. – Ecological Indicators 142: 109258.
[32] Wei, L., Zhou, L., Sun, D., Yuan, B., Hu, F. (2022): Evaluating the impact of urban expansion on the habitat quality and constructing ecological security patterns: A case study of Jiziwan in the Yellow River Basin, China. – Ecological Indicators 145: 109544.
[33] Xie, P., Yang, J., Sun, W., Xiao, X., Xia, J. C. (2022): Urban scale ventilation analysis based on neighborhood normalized current model. – Sustainable Cities and Society 80: 103746.
[34] Xu, H., Wu, S., Diehl, J. A. (2022): The Influence of Harbin Forest–River Ecological Corridor Construction on the Restoration of Mollisols in Cold Regions of China. – Forests 13(5): 652.
[35] Yang, Y., Wang, Z., Li, B., Guan, J. (2023): The impact of photovoltaic projects on ecological corridors through the Least-Cost Path model. – Global Ecology and Conservation 42: e02381.
[36] Zhang, Y. Z., Jiang, Z. Y., Li, Y. Y., Yang, Z. G., Wang, X. H., Li, X. B. (2021): Construction and Optimization of an Urban Ecological Security Pattern Based on Habitat Quality Assessment and the Minimum Cumulative Resistance Model in Shenzhen City, China. – Forests 12(7): 847.
[37] Zhang, J., Jiao, G., Ye, Q., Gu, X. (2022): The Impact of Urban Expansion on the Urban Thermal Environment: A Case Study in Nanchang, Jiangxi, China. – Sustainability 14(24): 16531.
[38] Zuo, Q., Zhou, Y., Liu, J. (2022): Construction and Optimization Strategy of an Ecological Network in Mountainous Areas: A Case Study in Southwestern Hubei Province, China. – International Journal of Environmental Research and Public Health 19(15): 9582.

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