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Green Infrastructure Network Identification at a Regional Scale: The Case of Nanjing Metropolitan Area, China

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Abstract: Clustered urban development has caused increasing fragmentation and islanding of regional ecological spaces. Creating a green infrastructure network (GIN) is a practical method of ensuring regional ecological security. This study proposed a method of GIN identification at the regional scale based on the Nanjing Metropolitan Area as an example. In this method, green hubs were identified using morphological spatial pattern analysis and connectivity indexes, green corridors were simulated based on the least-cost path model, and key optimization nodes were identified using circuit theory. The results indicated that green hubs covered an area of 5042.07 km^2, of which, 15.40% were cross-border, and the potential corridors were distributed in a network, with the key ecological nodes primarily narrowly situated. By comparing the hubs with the statutory green space protection area and the urban ecological control line, the identification results were more than 70% accurate, showing that the results were valid and reliable. This method not only made the identification of regional GIN more practical and replicable but also further identified key areas that need priority protection. This study provides a method for constructing regional GIN and serves as a strong guide for ecological and development planning of other urban clustered areas.

Keywords: green infrastructure; ecological network; regional scale; morphological spatial pattern analysis; circuit theory; Nanjing Metropolitan Area

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1. Introduction

Green infrastructure (GI) refers to natural or semi-natural green spaces [1], including forests, grasses, and parks. As one of the main habitats for animals, GI plays an important role in maintaining biodiversity and preserving the integrity of ecosystems [2]. However, with massive urbanization, GI has been encroached upon, which brings about serious fragmentation, islanding, and declining connectivity [3]. Of particular concern is the rise in clustered urban development, such as urban agglomerations and metropolitan areas, where rapid urban expansion and intense human activities have led to increasing depletion of GI, severe loss of biodiversity, and serious threats to the structure and function of green ecosystems [4,5]. Building a green infrastructure network (GIN) is ecologically important for biodiversity conservation and is an effective means of enhancing landscape connectivity [6,7].

Being able to identify a GIN has attracted widespread attention, and a research paradigm of "hubs identification-ecological corridors construction-network optimization" has progressively emerged [8–10]. Hubs provide habitats for animal survival and migration, and they are normally identified based on the biological habitat needs in terms of function or scale dimensions through ecosystem service evaluation, ecological sensitivity evaluation, landscape connectivity evaluation, etc. [11–13]. Corridors are areas in ecological networks that provide passage for animal migration. They are mostly constructed based on focal species, whose spatial locations, orientations, and widths are identified using model simulations such as the least-cost path, the minimum cumulative resistance, graph theory, and the ant colony algorithm [14–16]. Ecological nodes are key strategic points that have an important impact on ecosystem stability and connectivity, and most studies have selected ecologically sensitive areas or corridor narrows as ecological nodes through a spatial overlay with landscape components, such as road networks and construction land [7]. It is evident that most of the existing studies on GINs are constructed with focal species as the target, and the effectiveness of this construction technique was demonstrated [17,18].

However, the existing methods for identifying GINs are mostly applied at the urban scale and confined to specific administrative boundaries. Fewer studies have been carried out at the regional scale. In fact, the construction of GINs is not entirely constrained by administrative boundaries. The spatial continuity of green space patterns and the spatial mobility of ecosystem services dictate that the identification of a GIN requires the consideration of relevant influencing factors within a larger natural geographical context [16]. Traditional focal-species-based approaches to GIN construction are somewhat limited at the regional scale. First, the larger the area, the richer the species, and the habitat requirements of focal species and dispersal paths may not be representative of all species [19]. Second, animal dispersal behavior analysis is key to the use of this method, but the dispersal behavior of species is mostly uncertain [20]. The GI resource endowment, regional physical geography, and socio-economic conditions at the regional scale are even more variable, which could cause species dispersal behavior to be more unpredictable. Third, the method requires a large amount of data, including detailed species survey data and habitat quality assessment data, and is complex to calculate. As a result, its application to large-scale GIN construction takes a lot of time and effort [21].

The identification of hubs, corridors, and key ecological nodes at the regional scale is conducive to building a GIN that breaks through administrative boundary restrictions and can offer effective guidelines for building a GIN at the urban scale [17,22]. Some scholars have realized the importance of regional GINs and investigated the methods for their construction. The morphological spatial pattern analysis (MSPA) approach is based on graph theory [23] and uses image processing to identify GI elements that play an important role in maintaining ecological network connectivity [24]. This approach uses fewer data, emphasizes the structural connectivity of ecological networks, and preserves the continuity and integrity of landscape patterns; therefore, it has been applied in the construction of national- and urban-scale GINs [13,25]. The circuit theory (CT) defines the dispersal behavior of species as a stochastic behavior similar to the motion of electric charges, identifying ecological networks by assigning different ecological meanings to physical quantities, such as resistance, current, and voltage [26]. Without a need for the identification of focal species, CT could identify the corridors that meet the migratory needs of multiple species, thus being more suitable for species dispersal characteristics [27] and is broadly adaptable at several spatial scales [21,28].

The application of MSPA and CT has promoted the identification of GINs at the regional scale, but they have advantages in hubs selection and corridors identification, respectively. The combination of these two methods to identify regional GINs not only avoids the subjective interference of artificial hub selection but also obtains green corridors with structural connectivity and functional connectivity [7,29]. Therefore, the MSPA and CT method combined to study regional GINs is more scientific, which would provide more practical and accurate references for regional ecological planning. However, few studies have combined both methods [30], and relevant studies at the regional scale are even scarcer. Therefore, taking the Nanjing Metropolitan Area in China as an example, this study combined MSPA and CT to construct a methodological framework for identifying a regional GIN, including how to identify regional green hubs, how to create a resistance surface, and how to construct green corridors and identify key points; furthermore, the accuracy of the identified GIN is discussed. This study offers a detailed methodological framework for the construction of regional-scale GINs and a new perspective for regional-scale GIN planning.

2. Materials and Methods

2.1. Study Area

Located in the lower reaches of the Yangtze River of China, the Nanjing Metropolitan Area (29°57′ N–34°06′ N, 117°09′ E–119°59′ E) spans the provinces of Jiangsu and Anhui and consists of Nanjing, Zhenjiang, Yangzhou, Huai'an, Chuzhou, Ma'anshan, Wuhu, Xuancheng, and Changzhou (including Jintan District and Liyang District only), with a total area of approx. 66,000 km^2 (Figure 1). Principally located in the subtropical monsoon climate zone, this region features hot summers, warm winters, and abundant precipitation. The terrain is dominated by low hills and alluvial plains, which are higher in the south and lower in the north. The region is endowed with an excellent natural background, with mountains such as Mt. Huangshan, Mt. Tianmu, and Mt. Jiuhua in the south, and Ningzhen, Laoshan, and Maoshan mountain ranges in the center.

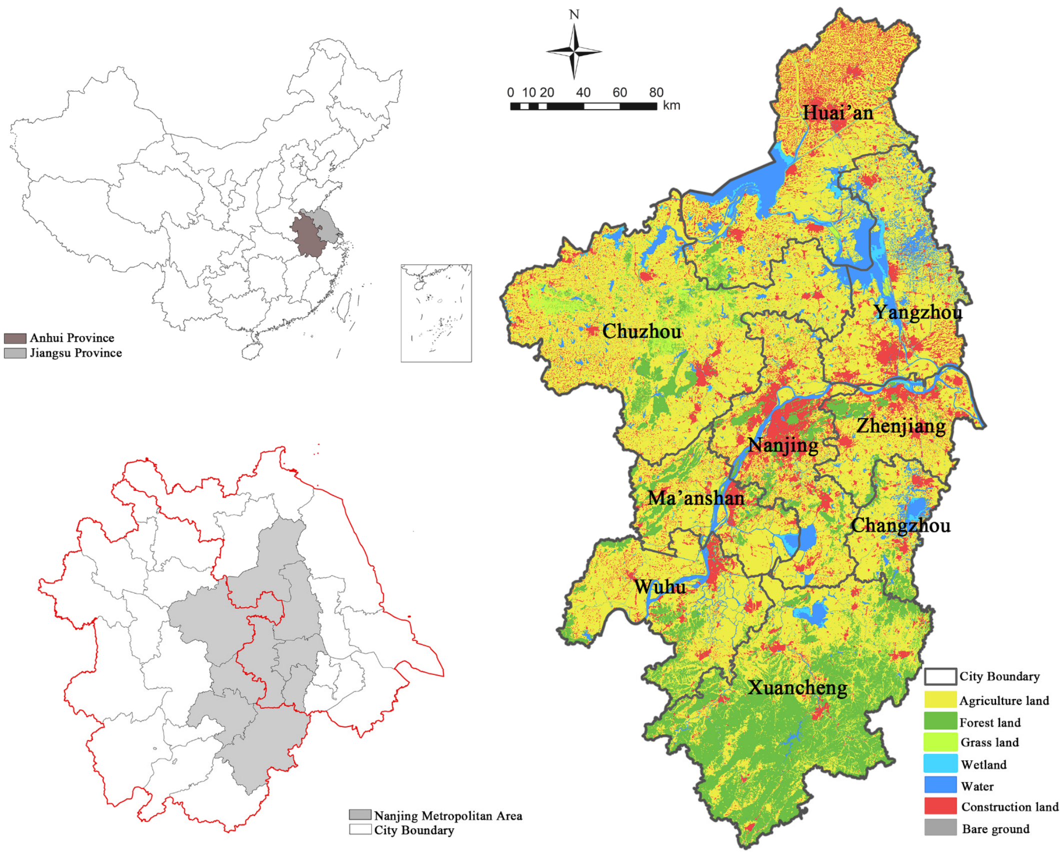


Figure 1. Location of the study area.

As a pivotal region linking eastern and central China, the Nanjing Metropolitan Area is an important part of China's Yangtze River Delta City Agglomeration and the first metropolitan area set up across provinces in China. By the end of 2019, it had a resident population of approx. 35 million and a gross domestic product per capita of RMB 113,000 [31], making it one of the most economically developed regions in China. In recent years, the vigorous development and construction of the Nanjing Metropolitan Area have brought about serious erosion of GI, a reduction in biodiversity, and increasing pressure on the regional ecological environment. Under the double pressure of clustered urban development and green spaces protection, Jiangsu and Anhui provinces jointly proposed to build a network of green corridors in Nanjing metropolitan area [31], providing a win–win solution for accelerating urbanization and protecting ecosystems. The results of this study can serve as a direct reference and data support for the construction of a regional GIN in the study area.

2.2. Data

The data sources used in this study principally included the 30 m resolution land cover classification data from 2020 (from http://www.globallandcover.com/ (accessed on 10 October 2021)) and the 30 m resolution DEM digital elevation model data (from http://www.gscloud.cn/ (accessed on 15 November 2021)). The study also referred to the Regional Planning for Ecological Space Control in Jiangsu Province (from http://www.jiangsu.gov.cn (accessed on 15 November 2021)) and the Ecological Protection Control Line of Anhui Province (from https://www.ah.gov.cn/ (accessed on 15 November 2021)) to extract the ecological protection control line within the study area.

The land cover classification data of Nanjing Metropolitan Area was divided into bare ground, shrub, grass, forest, agriculture, construction land, wetland, and water (Figure 1). To facilitate identification, shrub, grass, forest, and wetland were defined as the GI. In view of the fact that the vegetation type of agricultural land was relatively homogeneous, mostly dominated by cash crops with low biodiversity maintenance value [32], and that agricultural land is subject to a separate and strict protection regime in China, the study did not include agriculture within the GI.

2.3. Methods

In this study, a regional-scale GIN construction framework was proposed based on the research mode of "hubs identification-corridors construction-network optimization" by integrating approaches such as MSPA, least-cost path (LCP), and CT (Figure 2). The detailed process is described in the following sections.

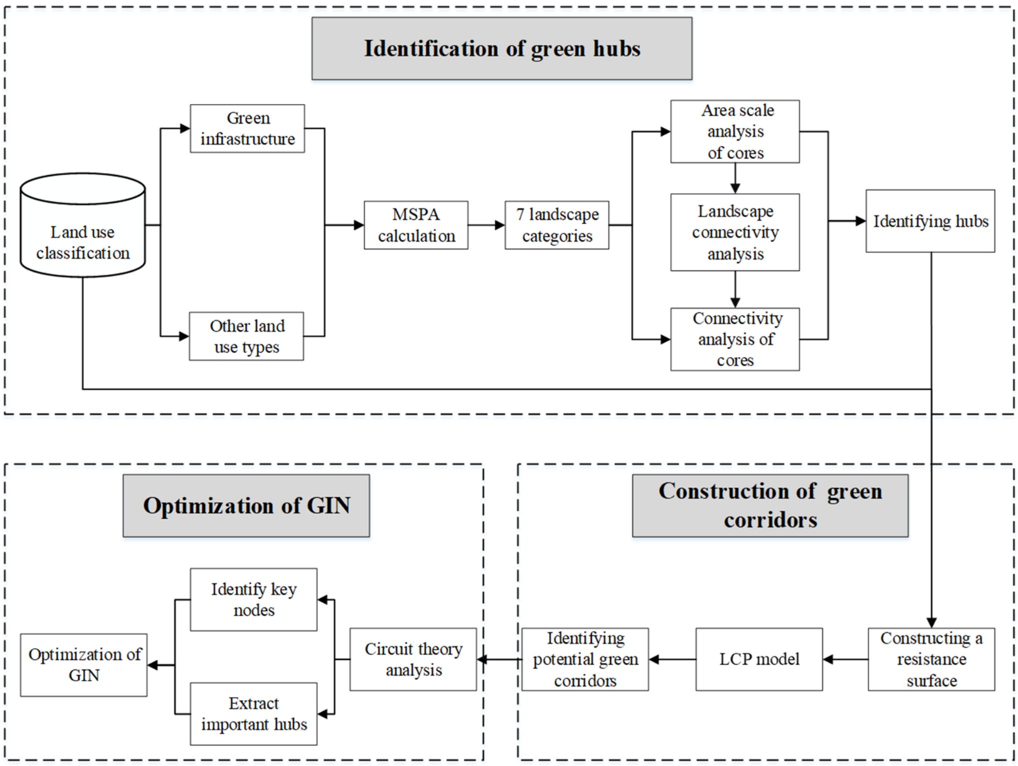


Figure 2. Flow chart of the study.

2.3.1. Identification of Landscape Elements Based on MSPA

Morphological spatial pattern analysis (MSPA) is an image-processing technique that measures, identifies, and segments the spatial pattern of a raster image based on mathematical morphological principles [33]. This method simplifies the process of determining landscape patterns and has been applied in the construction of regional-scale ecological grids [25]. First, the land use data was reclassified and converted into binary maps using the ArcGIS software, with the foreground set to the GI and the background set to other types of land. Second, with the help of the GuidosToolbox software, the binary raster data was analyzed by using the eight-neighborhood rule (edge width set to 1) to extract 7 types of MSPA landscapes, i.e., core, bridging, branch, perforation, islet, edge, and loop, which did not overlap with each other. The cores were mostly large GI patches that offered larger habitats for species and inform the screening of green hubs.

2.3.2. Hubs Extraction Based on Scale and Connectivity

The extraction of hubs requires consideration of both the size and the connectivity of the patch. The size of the core is decisive for habitat heterogeneity and species carrying capacity and scattered small patches play a limited role in the maintenance of regional ecosystem function. Therefore, larger core patches need to be selected as candidate hubs.

Connectivity refers to the degree to which horizontal movement of organisms or ecological processes is inhibited between landscape elements [34]. Cores with high connectivity offer higher survival of organisms. The integral index of connectivity (IIC), the possibility of connectivity (PC), and the connectivity importance index (dI) were chosen to determine the connectivity of candidate hubs and to identify cores of high importance as hubs. The specific formulae used for computation are as follows:

$$\mathrm{IIC} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\frac{a_i \times a_j}{1+nl_{ij}}}{A_L^2}, \quad (1)$$

where n refers to the total number of GI patches; a_i and a_j denote the area of core i and j, respectively; nl_{ij} represents the number of connections between cores i and j; and A_L stands for the total area of GI. The larger the IIC, the more suitable the core is as a habitat.

$$\mathrm{PC} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} P_{ij}^{*} \times a_i \times a_j}{A_L^2}, \quad (2)$$

where P_{ij}^{*} refers to the maximum product probability of all connections between cores i and j. The smaller the PC value, the lower connectivity between cores.

$$\mathrm{dI} = \frac{I - I'}{I} \times 100\%, \quad (3)$$

where dI represents the importance of the core; I denotes the connectivity index value of the core, namely, the IIC and PC values in the study; and I' stands for the connectivity index value after the removal of a certain core. The larger the dI value, the more important the core [35].

2.3.3. Corridors Construction Based on LCP

Corridors are important pathways for species migration and are carriers of material cycles and energy flows between hubs. The least-cost path (LCP) reflects the relative minimum cost consumed by a species during their migratory dispersal, and the corridors constructed on the basis of the LCP are theoretically the best pathways for species migration [2]. In the study, the Linkage Mapper corridor simulation software was used to construct potential least-cost green corridors between hubs. The key to the LCP is the setup of landscape resistance. The ecological resistance varies depending on the nature of the landscape unit. In most cases, the higher the habitat suitability of a landscape unit, the lower the ecological resistance. In this study, based on the results of the MSPA analysis, the value of resistance was determined by considering the natural environment of the region, different land-use types, and the level of human interference. On this basis, different resistance values were assigned, where larger values represent greater resistance (Table 1). Based on 30 experts' questionnaire responses and using hierarchical analysis, the weight coefficients of four resistance factors (i.e., MSPA landscape type, land-use type, topography, and human activities) were identified. It should be notable that the resistance values in Table 1 represent relative resistance only and not absolute resistance values for the landscape.

Table 1. Assignments and weights of landscape resistance factors.

Resistance	Weight Coefficient	Resistance Factor		Resistance Value
MSPA landscape type	0.38	Core	Hubs	1
			Other cores	5
		Bridge		10
		Other six MSPA types		50
		Background		600
Land-use type	0.25	GI		5
		Water (km^2)	River width >100 m, and lakes area >50	1000
			River width 50–100 m, lakes area <50 and >10	400
			Lakes area <10	40
		Agriculture land		60
		Construction land		1000
		Other types of land		600

Resistance	Weight Coefficient	Resistance Factor		Resistance Value
Topography	0.15	Elevation (m)	<50	5
			50–175	20
			175–350	60
			350–650	200
			>650	600
		Slope (°)	<5	5
			5–15	20
			15–25	200
			>25	600
Human activities	0.22	Distance from built-up area (km)	>2.5	5
			1.5–2.5	100
			1.0–1.5	500
			0.5–1.0	800
			<0.5	1000
		Distance from traffic artery (km)	>3.0	5
			2.0–3.0	100
			1.5–2.0	500
			0.5–1.5	800
			<0.5	1000

2.3.4. GI Optimization Based on CT

The circuit theory (CT) abstracts organisms as randomly traveling charges, while the landscape pattern is viewed as a conducting surface, where the current reflects the migration probability of organisms passing through corresponding pathways [26]. Circuit theory has been extensively used for ecological point identification. Based on CT, the study employed the Linkage Mapper plug-in in GIS10.6 software to generate hub-to-hub current densities to further identify important key areas that require priority protection or recovery.

1. Centrality identification

Centrality refers to the direct communication capability of the hub in the network and can reflect the importance of the hub in maintaining the overall connectivity of the network. Specifically, each hub is considered a node, the least-cost path between any two hubs is considered a circuit, and the cost weighted distance of each path is considered a resistance; then, a current of 1 ampere is fed into one hub and another hub is connected, and then the current value between the two hubs is calculated; finally, all hubs are iterated and the final cumulative current value for each hub is the centrality of that hub [36]. The higher the centrality (current value), the more important the hub is for maintaining the overall connectivity of the GIN. The study employed the Centrality Mapper tool in the Linkage Mapper plug-in to work out the centrality of each hub, setting the green corridor width at a weighted cost distance of 5000 and using a weighted cost distance of 20,000 as the corridor width.

2. Key ecological nodes identification

Key ecological points refer to the key nodes for material exchange between adjacent hubs [37], to which special attention should be given to strengthening the construction and protection. In this study, key ecological points were identified using the Pinchpoint Mapper tool. The areas with high currents, i.e., the areas with high degrees of ecological mobility, were identified by calculating the cumulative current value for each image element in the corridor and should be the key-point areas of corridors. Key-point areas are important for maintaining the connectivity of the entire GIN.

3. Results

3.1. Identification Analysis of Hubs

3.1.1. Landscape Pattern of the GI

The GI covered an area of 12,436 km^2, accounting for 19.00% of the total area of Nanjing Metropolitan Area. The core was about 7151.76 km^2, accounting for 57.51% of the GI (Table 2). Large cores were clustered in the south, while the central cores were distributed in strips. Sparse and fragmented cores were observed in the north, mostly wetlands, grasslands, or waterfront forest land (Figure 3). The bridge and branch are ecologically important for species migration and dispersal as structural linkages between cores. These two types accounted for only 14.98% of the GI, indicating that the cores were more scattered and independent of each other. Hence, it's necessary to carry out studies on the construction of regional GINs.

Table 2. Statistical description of MSPA landscape types.

Landscape Type of the GI	Area (km^2)	Proportion of the Area of the GI (%)	Proportion of the Area of the Study Region (%)
Core	7151.76	57.51	10.93
Bridge	1152.23	9.27	1.76
Islet	448.09	3.60	0.68
Perforation	148.96	1.20	0.23
Edge	2185.07	17.57	3.34
Loop	638.66	5.14	0.98
Branch	710.97	5.71	1.09

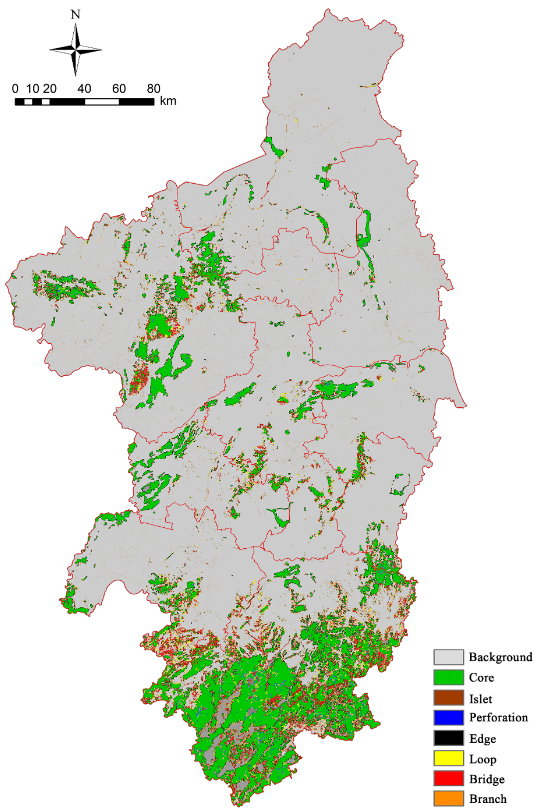


Figure 3. MSPA-based landscape classification map of the GI.

3.1.2. Identification of Hubs

There were 6208 cores, which varied greatly in size from 900 m^2 to 1811.70 km^2. According to Figure 4, it can be seen that along with the reduction in the area of patches, the number of patches increases rapidly, but the contribution to the core area decreased. The threshold of 10 km^2 preserved more than 80% of the core areas and less than 1.5% of the total number. Therefore, 90 cores that were larger than 10 km^2 were chosen as candidate hubs.

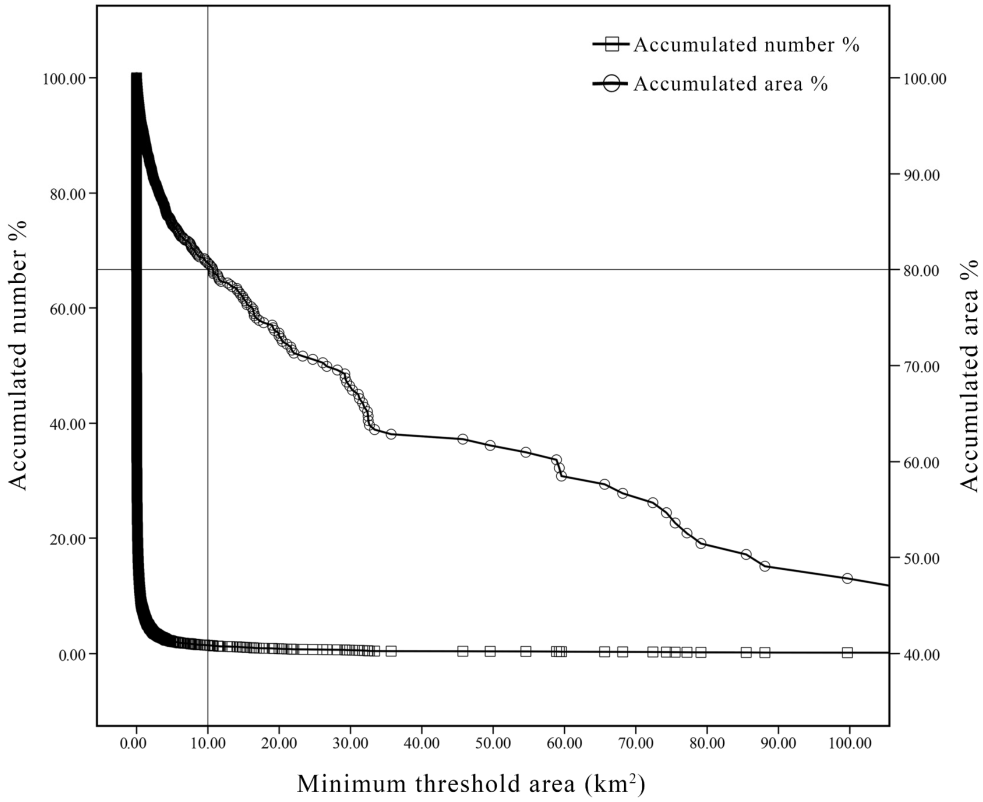


Figure 4. The results regarding candidate hub thresholds.

The landscape connectivity indexes among the 90 candidate hubs were calculated based on Confer 2.6 software. The distance threshold was set to 15 km and the connectivity probability was set to 0.5. The results were divided into three classes, i.e., high, medium, and low, using the natural breakpoint method. Then, 57 cores in the high and medium classes were chosen as green hubs. The largest hub covered an area of 1811.70 km^2, the minimum was 10.01 km^2, and the total was 5042.07 km^2, which accounted for 40.54% of the GI. As shown in Figure 5, the spatial pattern of hubs was similar to that of the core. The northern hubs were small in size with higher fragmentation than the southern ones. The hubs were principally large-scale green ecological patches, and forest land accounted for 82.7% of the total of the hubs, such as Qingliang Peak Nature Reserve, Banqiao Nature Reserve, and Laoshan National Forest Park, which can provide good habitats for living creatures. On the whole, hubs were distributed in nine cities, but Xuancheng accommodated the most and Yangzhou and Changzhou the least. The high distribution of hubs was due to the complicated mountain topography, abundant precipitation, and high vegetation coverages in Xuancheng. In contrast, the flat terrain, less precipitation, and intensive human activities in Yangzhou and Changzhou resulted in fewer green hubs. It should be notable that 15.40% of hubs were located on administrative boundaries, with the total size being 1237.92 km^2.

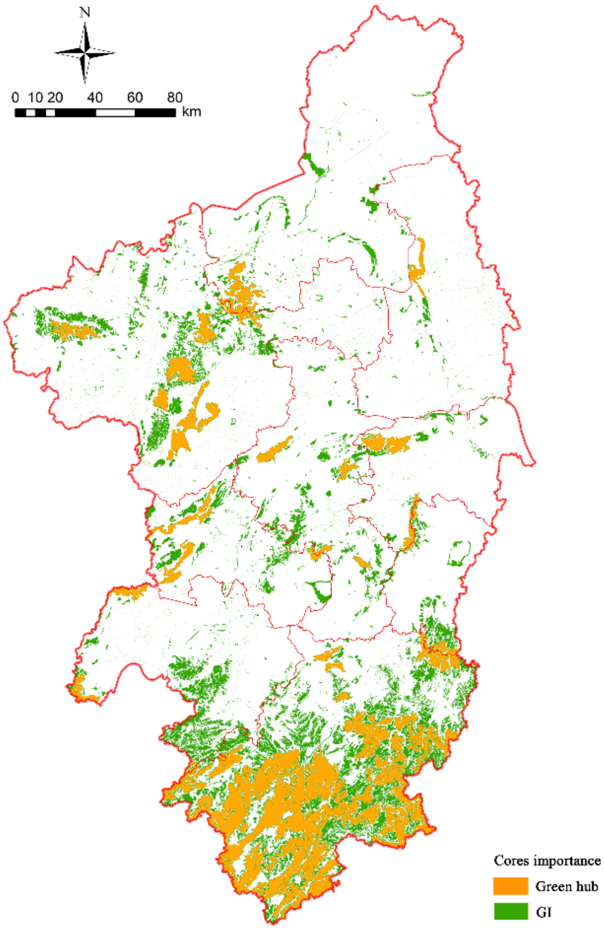


Figure 5. Spatial pattern of green hubs.

3.2. Construction of the GIN

In reference to each factor resistance surface, the final combined resistance surface was obtained using overlay analysis (Figure 6). Higher-resistance areas were principally located along the Yangtze River due to the fact that the dense towns, the developed economy, and the high level of land development along the river brought about high landscape resistance. In southern Xuancheng and central Chuzhou, low resistance was primarily due to a subtropical monsoon climate, which produced abundant rainfall and dense vegetation. Furthermore, human activities were constrained by the complicated geology and geomorphology, including mountains, hills, basins, tablelands, and plains. The hub-to-hub least-cost path was identified using an operational LCP model (Figure 7a). It was found that some of the hubs had two or more connecting paths to each other. The study ultimately identified 101 potential green corridors with a total length of 1961.85 km, with individual corridor lengths ranging from 120.45 km to 0.20 km (Figure 7b). Because of the scattered distribution of hubs, the green corridors were reticulated. From the green corridors distribution and number in each city (Figure 8), Xuancheng had the largest number of corridors (more than 70) and a shorter total length (only 270.32 km), which indicated that the GIN of Xuancheng was better with closely distributed hubs and shorter distance corridors. Nanjing had the longest total length of green corridors, over 500 km, but the number of corridors was only 32, indicating that its GIN was dominated by long-distance corridors. This may have been due to Nanjing being located in the center of the study area and the frequent material exchange between internal and external hubs, but with the high urbanization and the high value of landscape resistance, resulting in long corridor distances. There was only one green corridor in Huai'an. Huai'an was located in a flat area of Jianghuai Plain, which provided convenient conditions for urban development and agricultural production. As a result of dense construction and lack of green spaces, it was characterized by small sparsely green hubs, and the number and length of corridors were limited.

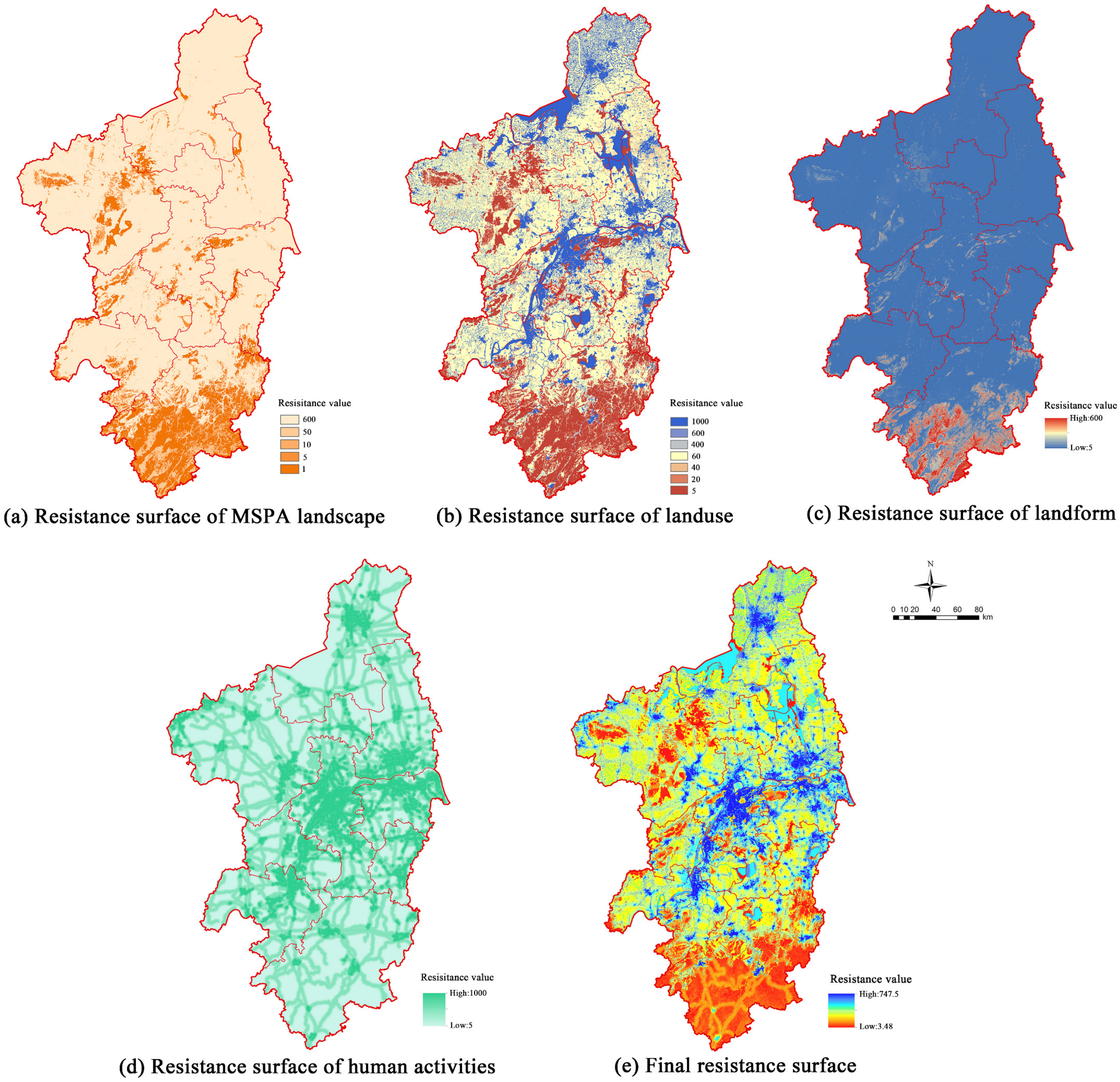
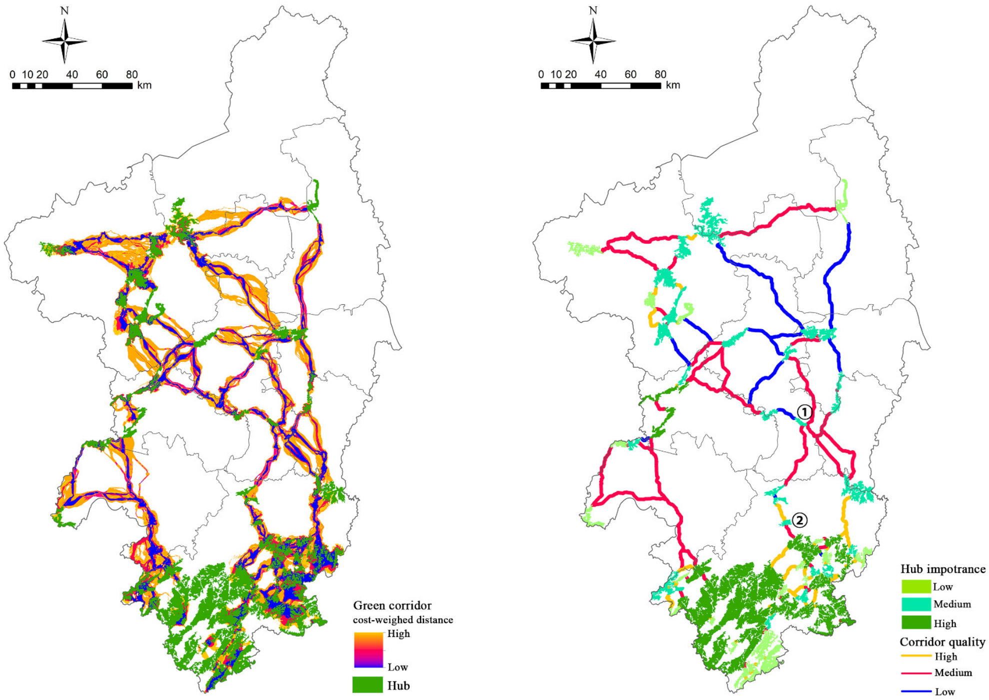


Figure 6. Landscape resistance surfaces.

To further learn about the importance of corridors, the ratio of the cost-weighted distance to the least-cost path length was employed to measure the quality of corridors. The lower the ratio, the smaller the relative resistance of the path and the better the quality of the corridor. The corridors were divided into three classes, i.e., high, medium, and low quality, using the natural breakpoint method. As shown in Figure 7b, more than 85% of the corridors were of medium-to-high quality, indicating that the quality of the corridors in the study area was better. Low-grade corridors were principally concentrated in the central areas, which were characterized by intensive land development, developed cross-area transportation facilities, and great resistance to the migration of organisms to the surrounding areas.



(a) The least-cost corridors in the landscape (b) Green infrastructure network

Figure 7. The GIN of the Nanjing Metropolitan Area. The number of the figure is the hub code.

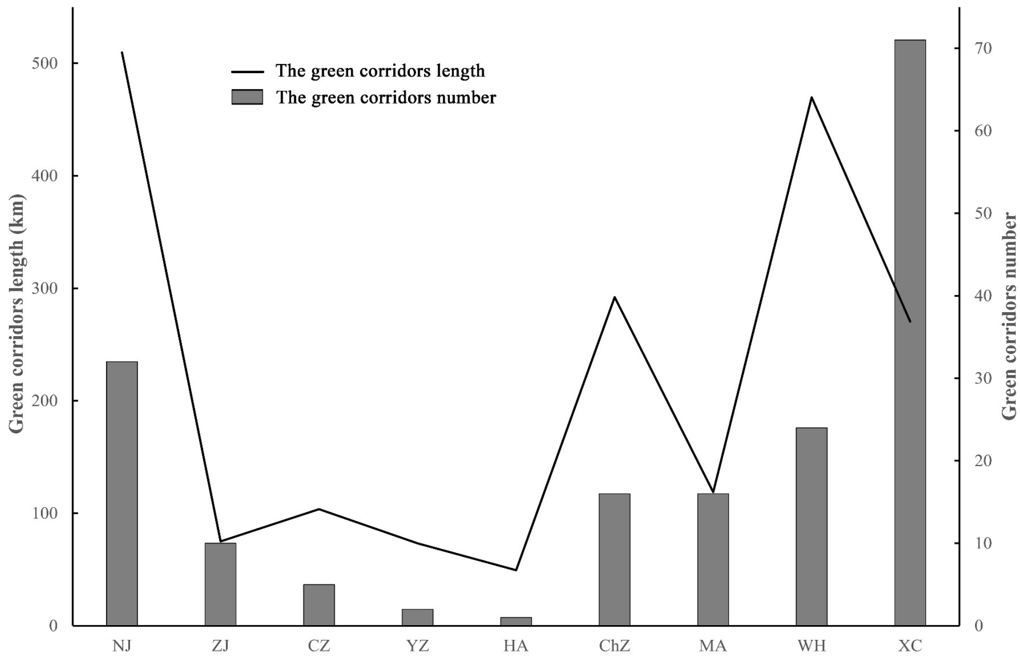


Figure 8. The length and number of green corridors in each city. NJ is Nanjing, ZJ is Zhenjiang, CZ is Changzhou, YZ is Yangzhou, HA is Huai'an, ChZ is Chuzhou, MA is Ma'anshan, WH is Wuhu, and XC is Xuancheng.

Based on the construction of GIN, the centrality of the hub was calculated to measure its importance. The results were also divided into the high, medium, and low classes. As shown in Figure 7b, there were only 10 high-class hubs, which were concentrated in the southern mountainous areas; the number of medium-class hubs was 26, which could be found in all cities except Yangzhou; the number of low-class hubs was 21 with a scattered distribution. In terms of size, the high-class hubs had the largest area, with a total of 2829.70 km^2, accounting for 56.12% of the total area of the hubs; the low-class hubs had the smallest area, with a total area of 852.80 km^2, accounting for 16.91% of the total hubs. It should be notable that some of the smaller hubs, such as hubs 1 and 2, were of the medium class, indicating that they were highly capable of material exchange despite their small size.

3.3. Identification of Key Ecological Nodes

The study identified the key ecological nodes in the network by calculating the current values for each raster of the potential corridor. A total of 26 key nodes were extracted (Figure 9). Most of the nodes were predominantly long and narrow. The land-cover types corresponding to key nodes were principally small forest, agricultural land, and grassland, which were located in small-sized, low-resistance sites. According to Figure 6d, traffic networks passed through several ecological nodes. For instance, nodes 2 and 14 were passed through by expressways, while there were railways passing through nodes 12 and 15 (Appendix A Figure A1). Linear transportation facilities had a restrictive effect on the flow of organisms.

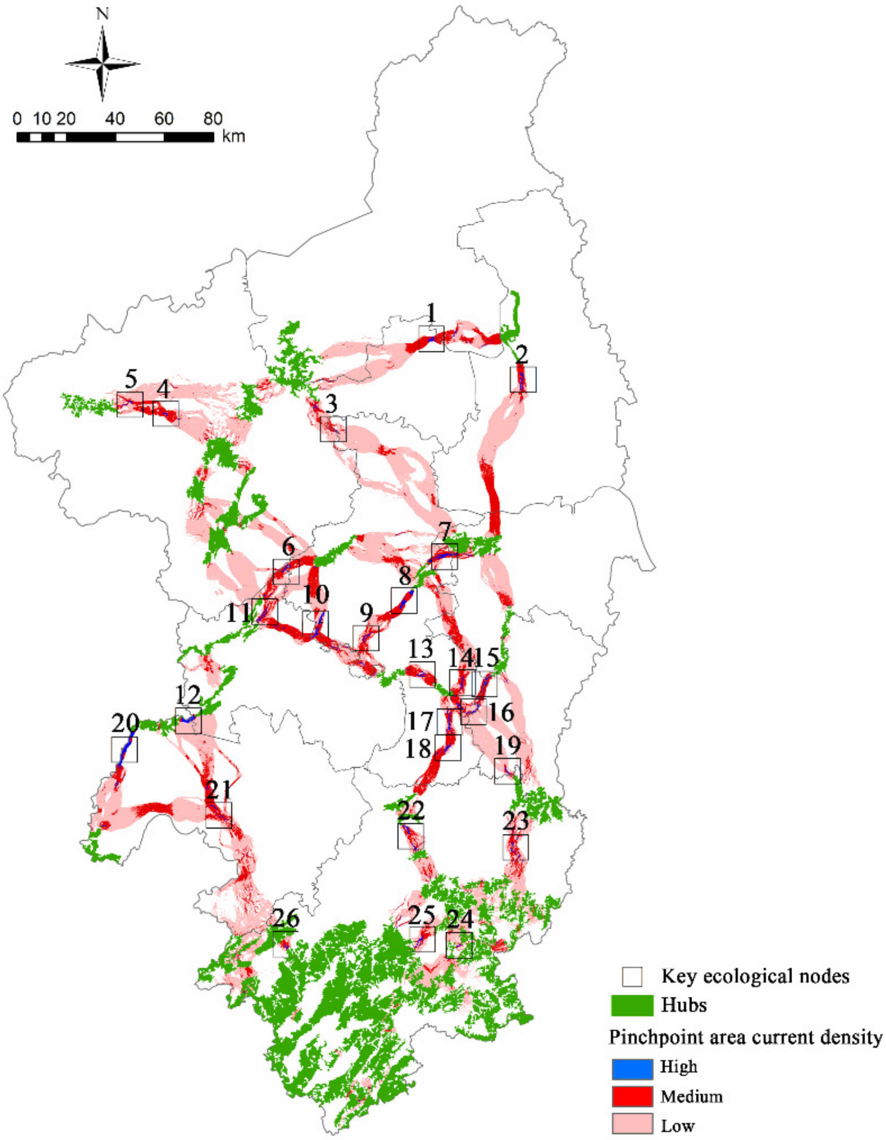


Figure 9. Result of the identification of the key ecological nodes. The number of the figure is the node code.

Approx. 46.2% of the key nodes were located in Nanjing. As a key zone of connection, Nanjing had a high probability of communication with surrounding species. Nodes 22–26 were concentrated in Xuancheng. This area was characterized by many hubs, a high probability of biological dispersal, and a high current density, which brought about several key ecological nodes. However, there were fewer nodes in Yangzhou, Zhenjiang, and Huaian due to the lack of hubs and the large construction cost distance of corridors such that the biological dispersal and migration were more susceptible to threats. Hence, more attention should be paid to these nodes and their protection should be enhanced.

4. Discussion

4.1. Effectiveness of the Identification of the GIN

The Nanjing Metropolitan Area contains 76 statutory green space reserves, including provincial and higher-level nature reserves, forest parks, and wetland parks, which are the most important regional GI. After overlaying a GIN and the statutory green space reserves, it was observed that the location match between the hubs and the green space reserves of over 10 km^2 was 72.50% (Figure 10), which illustrated that it was highly reliable for selecting the green hubs. This view was consistent with the results of previous studies [7,30], having offered a further basis for MSPA and landscape connectivity indexes to identify the hubs of GI on a regional scale.

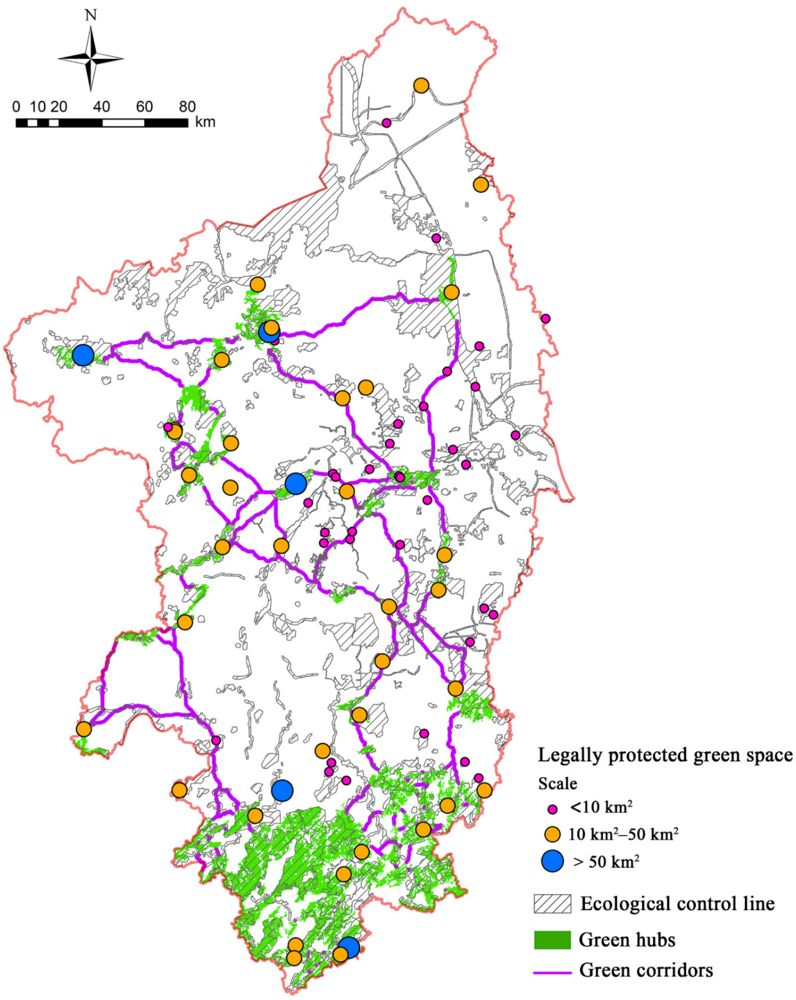


Figure 10. Overlay map of the GIN, statutory green space protection areas, and ecological control lines.

Urban ecological control lines are the bottom lines for each city to preserve its ecological security [38]. After overlaying the GIN and the ecological control lines of each member city, it was observed that the hubs within the control lines covered an area of 3653.57 km^2, which accounted for 72.46% of all hubs; only less than 30% of hubs were outside the control lines. Almost hubs outside control lines were situated around such lines, perhaps because the ecological control lines of China were normally composed of the core and conservation areas of ecological space, and the surrounding green spaces were not included. In contrast, the hubs identified in this study from spatial pattern and connectivity completely and continuously depicted the scope of individual green spaces.

Since the study area was dominated by low mountains, hills, and plains where agriculture was well-developed, agricultural land accounted for a large proportion of the green corridors. However, agriculture was not included in the ecological control line program of China; therefore, only 640.12 km of the corridors were located within the control lines, accounting for 32.63% of all corridors. In the ecological control lines and the statutory green space reserves, the present linear GI acted as ecological corridors, but this existing GI alone may result in poor hub-to-hub connectivity [7]. The corridors identified in the study are playing an important role in the stability of the ecosystem and the connectivity of the ecological network, and thus, they are a powerful supplement to ecological planning for the Nanjing Metropolitan Area.

The GIN identified in this study is highly consistent with the ecological control lines and statutory reserves. The hubs were favorably intact, while the corridors could effectively supplement existing ecological control lines, and guarantee the stability and connectivity of the ecosystem.

4.2. Theoretical and Practical Implications of the Study

4.2.1. Methodological Advantages

In this work, a regional-scale GIN identification method was proposed by combining methods such as MSPA, LCP, and CT (Figure 2). The method followed the paradigm of "hubs identification-corridors construction-network optimization". First, hubs were identified using land-use data as input data based on the scale and connectivity with the help of MSPA and connectivity indexes; furthermore, landscape resistance surfaces were determined by considering landscape types, land-cover types, topography, and human activities; then, the spatial locations of corridors were identified using LCP models; third, the CT was introduced to determine the corridor and hub levels and identify the key points of optimization affecting the network connectivity.

The GIN identified in the study combined structural and functional connectivity [30]; however, when compared with the GIN constructed for certain protected species, the identification results of our study may miss some small-scale quality habitats. Nevertheless, the identification method of the study still offers the following advantages: First, this method principally employs land-cover data. It requires fewer data that are easier to obtain and calculate, making it easier to build a large-scale GIN. Second, the method eliminates the need to select focal species and the simulated ecological corridors can accommodate multi-species migration. In the absence of basic species survey data, it is still possible to construct ecological networks with favorable connectivity [21]. Third, the method proposed in this study can determine the location and pattern of key areas in the GIN that need priority protection. In summary, this study provides a practical and replicable methodological framework for identifying a regional-scale GIN.

4.2.2. Policy Implications

China has entered its model of coordinated regional development with metropolitan areas as the mainstay. Compared to the urban scale, the identification of a GIN at the regional scale breaks through the constraints of urban boundaries, helping to provide a macro contextual grasp of regional ecological security and supporting the development of win–win ecological planning for individual member cities [39]. While regional GIN planning is not yet mandatory in China, more and more scholars and government agencies are becoming aware of its importance. For example, Shi and Qing obtained the key elements of the Zhengzhou–Kaifeng metropolitan area GIN [40], and Zhang et al. attempted to identify landscape ecological security patterns in the Beijing–Tianjin–Hebei region [22]. Moreover, state authorities also advocated building regional GINs to resolve conflicts between land development and ecological protection. In 2019, the Guidance for Fostering the Development of Modern Metropolitan Areas was promulgated by the National Development and Reform Commission, which requires strengthening the regional green corridors' connectivity [41].

As the first inter-provincial metropolitan area in China, the Nanjing Metropolitan Area is faced with litmus tests in terms of regional environmental protection. The study serves as a reference for the Nanjing Metropolitan Area and its similar fast-growing urban clusters in formulating development policies to better deal with the contradictions between regional ecological protection and economic development. Approx. 15.40% of the hubs were found to span at least two cities in the study. This was because the administrative boundaries of Chinese cities are usually defined on the basis of natural elements, such as rivers and mountains, and there is plenty of GI at the junctions of cities. Such transboundary GI is generally large and has excellent ecological environments, making it suitable for containing large habitat patches, thereby turning into important components of GIN on a regional scale. However, during the development, GI erosion is often more serious in transboundary areas because of low land costs, weak government governance, and strong development vitality. The GI in these areas should be paid special attention, and targeted strategies should be provided from the perspective of regional coordination to gradually eliminate administrative control barriers and promote the protection of regional hubs.

There were relatively few green hubs, poor quality ecological corridors, and high cumulative resistance in the north of the Nanjing Metropolitan Area; therefore, it is necessary to set the identified hubs and corridors as no-build areas. Some hubs in particular play an important role in maintaining network connectivity out of proportion to their size. Hence, it is essential to enhance the investment in them and create buffer zones around them to minimize human activities. The key ecological nodes may be sensitive and vulnerable due to the lack of large types of low-resistance land cover, the disturbance by transport networks, etc. The narrowness of the ecological nodes indicates bottlenecks in network connectivity, where these nodes and their surroundings are critical to the connectivity of networks [42]. The identified key nodes should be investigated on the spot to learn the exact causes of each ecological point and formulate targeted protective and mitigating measures. For example, at nodes 12 and 15 (Figure 10), animal overpasses or underpasses could be established based on ecological assessments to provide more alternative pathways for species dispersal. For the high-quality corridors, it is essential to have strict control over the development intensity and pattern, reduce ecological stress, and optimize the regional GIN.

4.3. Threshold Uncertainties and Study Limitations

This study used MSPA and landscape connectivity indexes to identify green hubs and avoid the subjectivity of artificial selection that is frequently observed in previous studies. However, MSPA is very sensitive to the landscape scale [43], and thus the size of the input data image element may directly affect the recognition result. Since the study focused on a regional-scale GIN, a 30 m $\times$ 30 m scale was chosen to preserve the key elements of the GI [25,44]. Moreover, the edge width of MSPA represents the edge effect of a patch, and the setting of its value affects the sizes of core areas. Such a value is normally set in related studies based on protected species [13], but the high species richness at the regional scale complicates edge effects; hence, the default value of 1 was set to address the needs of most species [45].

When patch importance is calculated with the Confer software, the connectivity distance threshold needs to be defined. Patches are considered disconnected when the distance between them is greater than this threshold. As the GI in the study area consisted mainly of forest lands, wetlands, and grasslands, a threshold distance of 15 km with a connectivity probability of 0.5 was chosen [46], based on a consideration of the dispersal distances of mammals, terrestrial birds, etc. [30,47]. In addition, Pinchpoint Mapper was used to identify the ecological points by setting a "width" threshold of the cost-weighted corridor. This threshold merely affects the current density at pinch points and does not affect the determination of locations of ecological points [26,48]. To identify the locations of ecological points more efficiently and conveniently, a threshold of 5000 m was chosen for the study.

For the calculation in the study, most of the thresholds were defined based on previous studies, but the applicability of such thresholds for the study area has not been verified. These thresholds should be further studied and discussed in the subsequent steps. The selection of resistance surfaces and the assignment of weights for the landscape does not refer to the resistance to the actual landscape, but rather indicates the relative resistance, which has flexibility in application and is adjustable depending on the characteristics of the region of interest. In addition, the way to optimize and implement the identified GIN through concrete measures is a complex and worthwhile research topic. This study did not offer an in-depth analysis of this topic, and future studies are expected to address it intensively.

5. Conclusions

Identification of regional GINs is essential for the sustainable development of regions and the maintenance of regional ecological security. In the study, a method for identifying regional-scale GINs was established using MSPA, connectivity indexes, LCP, and CT, and the identification results were validated with reference to statutory green space reserves and urban ecological control lines by taking the Nanjing Metropolitan Area as an example. The results of regional-scale hubs identified using MSPA integrated landscape connectivity indexes are more reliable. The GIN of Nanjing Metropolitan Area was composed of green hubs that were mainly dominated by forest land, and reticulated green corridors were dense in the south and sparse in the north. There were 57 green hubs, 101 potential green corridors, and 26 key ecological nodes in the Nanjing Metropolitan Area. The important hubs and quality corridors were concentrated in the south of the study area, while they were unsatisfactory in the north. About 15.40% of hubs were across administrative boundaries. Furthermore, most ecological nodes were long and narrow and were mainly located in small-sized and low-resistance sites.

As an exploration of the method for identifying regional GINs, this study provides a new way of thinking about construction at the regional scale. In addition, the study makes suggestions for regional GIN conservation policy and planning formulation and provides a convincing reference for ecological planning and development planning of other rapidly developing city clusters. On this basis, the method of GIN identification proposed in this study can be used to identify and manage the ecological spaces, including designating, expanding, upgrading, and strengthening management. In addition, it can indicate what areas need priority protection and can be used in conjunction with habitat evaluation to determine the timing of the restoration of regional ecological resources. Moreover, this method requires less data, is easier to replicate, and can be used as a long-term monitoring tool for the implementation of GIN planning. Once regional GIN planning has been developed, realistic GINs can be identified in the future using the same approaches at fixed time intervals. By comparing the identified and planned GINs, it is possible to reveal the areas that comply with the plan, lag behind the plan, and violate the plan, which helps to judge the completion of GIN planning and management decisions can be promptly adjusted.

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Appendix A

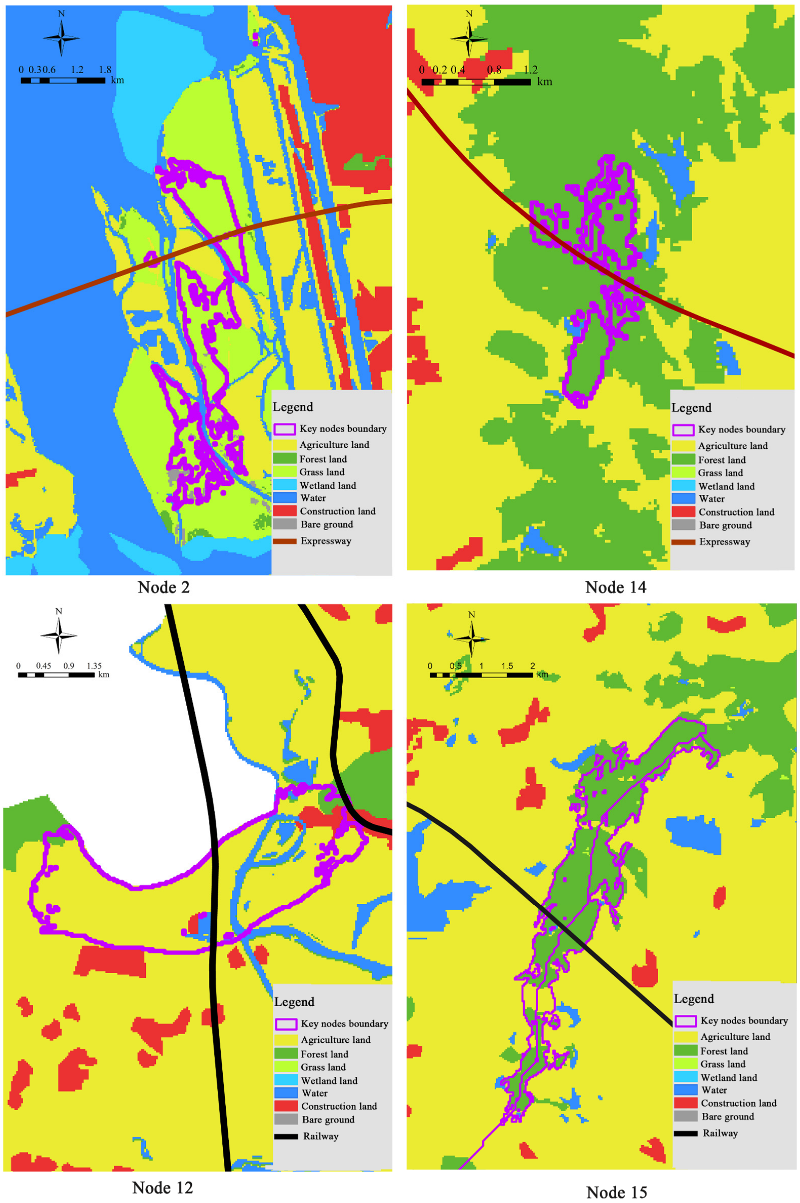

Figure A1. Land-use composition of key nodes.

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