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Optimizing an Urban Green Space Ecological Network by Coupling Structural and Functional Connectivity: A Case for Biodiversity Conservation Planning

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Abstract: Strengthening and optimizing the spatial structure and functional connectivity of green space ecological networks can not only relieve the tight urban space and provide biodiversity protection but also promote the virtuous cycle of the urban ecosystem and provide a new method for the resilient development of the urban landscape. In this study, the central area of Chengdu was taken as the study area; Morphological Spatial Pattern Analysis (MSPA) with landscape metrics were combined to determine the optimal distance threshold and identify the ecological sources. Graph theory and circuit theory were applied to construct and optimize the green space ecological network with structural or functional connectivity, respectively. Based on the coupling effect, the optimization of the ecological network was put forward, and the network analysis method was used to evaluate the connectivity of three different types of ecological networks. The results were as follows: (1) The ecological network with structural connectivity was composed of 74 stepping stones, 43 protective sources, and 315 ecological corridors. The connectivity of green space structures gradually decreased from west to east and from periphery to center. (2) In the optimal ecological network with functional connectivity, 176 important ecological corridors were protected, and 40 pinch points and 48 protective sources were identified. The number of important corridors in the east and south was the largest, and the network structure was relatively complex. The barriers were divided into three different levels of ecological restoration areas. (3) The green ecological network with structural and functional connectivity has the best network connectivity. A green space ring network optimization pattern of one center, two belts, multi-points, multi-corridors, and multi-zones connected in a series was proposed. It was suggested to build a multi-level forest ecosystem in Longquan Mountain, develop eco-fruit agriculture and eco-tourism, enrich the biodiversity of the ecological source, and improve its anti-interference ability to the external environment. It is also important to increase ecological strategic points and stepping stones to strengthen the links between different ecological restoration areas, properly handle the use of cultivated land in different regions, strictly observe the red line of cultivated land, and maintain the integrity and diversity of ecological sources. Therefore, the optimization method of the green space ecological network in this study provides technical support for the effective determination of ecological protection areas, the accurate implementation of green space ecological networks, and a scientific planning strategy for decision-makers.

Keywords: structural connectivity; functional connectivity; coupling effect; green space ecological network; Chengdu

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1. Introduction

Recently, there has been unplanned growth of urban spaces, an imbalance in the urban–rural structure, decreasing landscape connectivity, and a sharp decline in biodiversity caused by rapid urban land expansion. Especially in the central city and densely populated cities, different degrees of human disturbance, ecosystem degradation, and landscape fragmentation have seriously hindered biological migration, and the service function of the urban green space ecosystem is poorly matched with the needs of urban sustainable development. Urban ecosystems are facing increasing pressure of urbanization [1]; how to reduce the impact of urbanization on the ecological environment and realize the sustainable development of the city has become the focus of urban planners and decision-makers [2,3]. At present, urban planning in China has changed from incremental planning to inventory planning, requiring the use of fine management concepts for urban renewal. As an important storage space resource in the central urban area, the connectivity of urban green space is relatively poor, and it does not connect and transition well with other urban spaces. As a result, the improvement brought by renewal is not comprehensive and complete enough to meet the needs of biodiversity protection and diversity of social activities. In the limited urban stock land space, how to rationally plan and effectively add urban green space and maximize the ecological service function of green space has become an important problem to be solved urgently. The optimization research of urban green space systems mainly focuses on single factors such as the green space quantity index, structure composition, urban park accessibility, and green space landscape pattern. Strengthening the systematization and integrity of the green space ecological network and improving the spatial connectivity of the ecological network are not only important ways to protect urban biodiversity but also important means to realize the optimization of the urban green space system. Studies have shown that an effective green space ecological network can not only connect isolated and fragmented green space patches and ecological corridors structurally and functionally but also relieve cramped urban conditions and effectively provide the service function of urban green space ecosystem to improve the safety and resilience of urban landscapes [4]. A perfect method of building a green space ecological network should not only consider the interaction between landscape patterns and landscape fragmentation but also consider improving the ability of species migration and enhancing the landscape connectivity between biological habitats. Connectivity originated in graph theory and has been applied to many research fields as a mathematical tool. Merriam first proposed the concept of landscape connectivity, which is used to measure the process of species migration and the exchange of matter and energy between landscape elements [5]. Landscape connectivity is the key condition and measurement index of biodiversity planning and plays an important role in maintaining key ecological processes and ecological network construction. It is usually divided into structural connectivity and functional connectivity.

Structural connectivity can be used to identify the spatial geometric characteristics of landscape units through various landscape pattern indexes; however, it cannot show the integrity of the landscape structure and the functional relationship between landscape spatial units. Morphological Spatial Pattern Analysis (MSPA) can identify the geometric characteristics of each landscape type [6], identify the location and type of important habitat patches and corridors, and construct an ecological network [2,7]. It is mainly used in forest pattern and biological protection research [8,9]. However, similar to the landscape pattern index, MSPA cannot directly and effectively reflect the connectivity between green patches [10]. In recent years, the graph theory has been widely used in the study of landscape patterns and processes, especially in the evaluation of habitat network connectivity [11]. They can reflect the effect of patches on landscape ecosystems by comprehensively considering species dispersal distance and behavioral responses. These are important indicators for measuring landscape patterns and functions [12,13]. In the graph theory, the ecological network structure can be composed of several nodes and connecting lines [14,15]. Each line connects two nodes. Within a certain threshold range, the connected body composed of multiple nodes connected with each other is called a component unit [16]. The graph theory analyzes the connectivity landscape metrics based on nodes, boundaries, and networks [15,17], which can be used for the connectivity evaluation and structural optimization of ecological networks and greatly enriches the application of the landscape connectivity index [18]. It is fast, efficient, and visual, which can provide technical support for national spatial planning.

Functional connectivity assessment can identify and protect ecological corridors that functionally connect multiple species, which is important for improving the spatial connectivity of green space ecological networks [19]. The commonly used evaluation models and methods include least-cost path (LCP) analysis, systematic conservation planning, and network analysis [20,21]. In practice, the variability of species migration and diffusion behavior is reflected by species diversity, and the optimal migration corridor simulated for a specific species may not be used by other species [18,19]. In addition, these methods often require substantial inputs of labor and resources to obtain ecological data. The lack of ecological data makes it difficult to effectively analyze the multipath diffusion probability of multiple species, and thus the measure of functional connectivity is not perfect [22,23]. The introduction of circuit theory can better solve the above problems, and it can make up for the lack of functional connectivity between MSPA and graph theory. McRae [24] was the first to integrate circuit theory from physics into landscape ecology, landscape genetics, and other fields [25]. Circuit theory links random walk theory with behavioral ecology and uses the electronic characteristics of random walk in the circuit to simulate the ecological process of random migration, diffusion of species, or gene flow in heterogeneous landscapes [9,18]. According to the value of the current density, important ecological patches and ecological corridors can be identified to build an ecological network. Circuit theory emphasizes functional connectivity, solving to some extent the limitation of the LCP method, which cannot clarify the specific scope and key areas of corridors. This method has been widely used in ecological network construction because it requires less ecological data, has a simple process, identifies functional corridors between habitat patches [22,26].

There is a complex dynamic coupling relationship between structural connectivity and functional connectivity. The spatial structure has a controlling effect on functional connectivity, and the changes in its position, area, shape, quantity, and other morphological structures will affect the flow of matter and energy in the ecological network and thus affect the realization of its functional role. The function can also react to landscape structure. Multiple ecological processes such as meteorological and climate, animal migration, and disturbance of human activities will cause changes in land cover types and then lead to changes in the shape and type of ecological network structure. The two interact and repeatedly cycle together to shape the overall dynamic process of the ecological network [4]. After continuous practice and exploration, "ecological source identification-comprehensive resistance surface construction-ecological network optimization" has become the basic model for the construction of green space ecological network patterns [2,4,9,18]. The areas with good habitat quality or the ecological land with a large area were generally selected as the ecological sources. The land use type, ecological service function, terrain, and nightscape lighting data were selected as resistance factors for constructing a comprehensive resistance surface [11,22,23,26]. The construction and optimization methods of ecological corridors mainly include the layered superposition method, the method of coupling the LCP and gravity model, the MSPA method, graph theory, circuit theory, etc. At present, most studies focus on structural connectivity or functional connectivity to construct and optimize green space ecological networks, but few research studies focus on their coupling effect to improve the ecological function and services of urban green space.

In this study, MSPA and graph theory-based landscape metrics were used to determine the optimal distance threshold between ecological patches and identify the ecological sources. Graph theory and circuit theory were used to construct and optimize green space networks with structural or functional connectivity. By coupling superposition analysis, an optimized ecological network with structural and functional connectivity was proposed in the central area of Chengdu. Therefore, the main issues in this study were (1) how to quickly identify the core ecological land and screen the optimal distance threshold conducive to urban green space connectivity; (2) how to construct an optimal green space ecological network with structural or functional connectivity, respectively; and (3) how to optimize an urban green space ecological network with the spatial coupling effect and construct the ecological security pattern of urban green space. The comprehensive method and results in this study can realize the coupling of green space structure planning and function improvement and construct a green ecological network with efficient connectivity by identifying key corridors, strategic points, and stepping stones that affect the spatial connectivity of urban green ecological networks.

2. Data and Methods

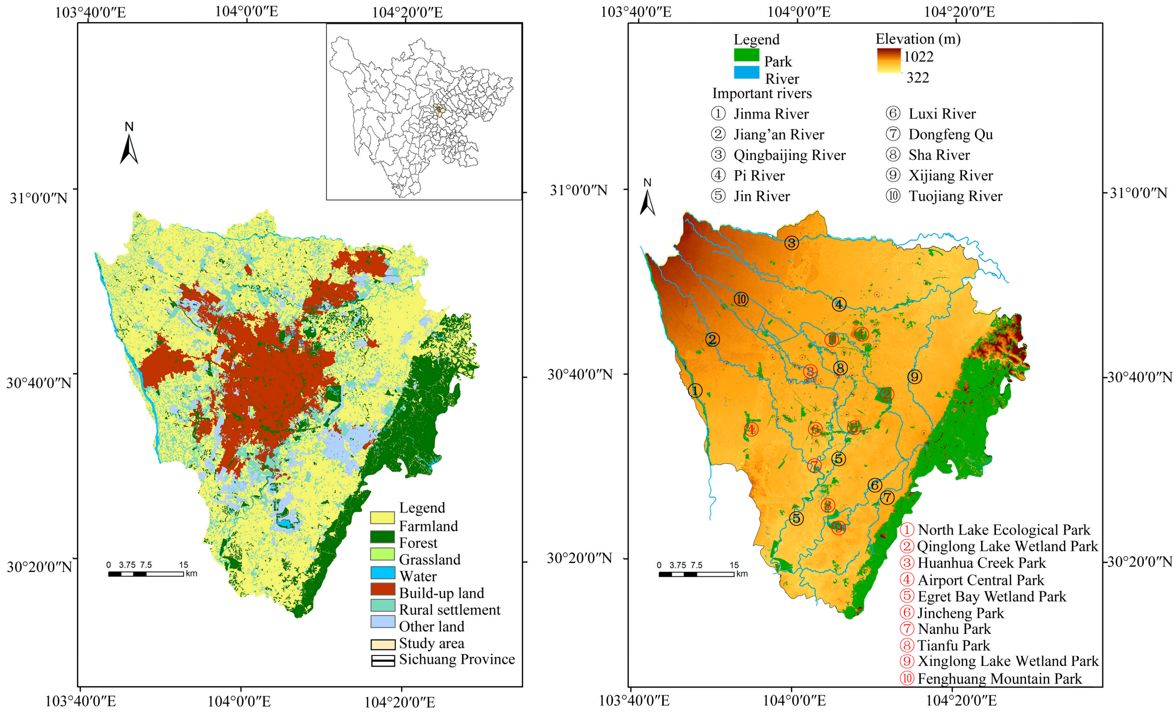
2.1. Study Area

Chengdu (102°54′–104°53′ E and 30°05′–31°26′ N) has a total area of 14,335 km^2, and the central area covers approximately 3677 km^2. As the capital city of Sichuan, it is a demonstration area for the implementation of the new development concept of a park city, with advantageous location and traffic conditions. There are multiple terrain changes and distinctive landscape characteristics. The river networks and canal systems are linked. The city has rich biodiversity and ecological resources that provide a natural ecological background for the construction of a park city.

Since the concept was first proposed in 2018, the city has explored pathways to construct a park city. The city has built 5327 km of greenways and built and renovated 184 parks of various types. The percentage of urban green land is 36.49%, the green coverage rate is 41.39%, and the per capita green area of the park is 14.23 m^2. Although the amount and structure of urban green space have been optimized and the per capita green space index has significantly improved, the maintenance of biodiversity (which is an important prerequisite for the ecological function of the urban green space network) has been somewhat neglected. Especially in the central urban area, which has a high population density, high urbanization levels, and increasing fragmentation of landscape patches, ecological problems are becoming more obvious. Therefore, the rapid expansion of urban scale has brought severe challenges to the sustainable development of urban ecological environment. There is an urgent need to optimize the ecological network pattern of green space to improve the ecological resilience and sustainable development capacity of the city.

2.2. Data Sources and Preprocessing

The data sources mainly include Landsat 8 OLI-TRI remote sensing satellite image data on 28 July 2020; digital elevation data with 30 m spatial resolution (http://www.gscloud.CN, accessed on 4 August 2020); high-resolution remote sensing image data at level 16 (http://www.bigemap.com/, accessed on 17 August 2020); the VIIRS Night lighting data in 2020 (http://resdc.cn, accessed on 25 September 2020), and urban planning atlas and social and economic statistics data of Chengdu. To identify the ecological green spaces, after a series of preprocessing steps, such as geometric correction for Landsat 8 OLI-TRI remote sensing images in the ENVI software platform, urban land use was divided into seven types, including forest land, grassland, water body, farmland, built-up land, rural settlement, and other land using supervised classification. With the help of high-resolution remote sensing images, the relevant planning atlas of Chengdu, and other data, we modified the land use data to obtain a current land use map of the central area of Chengdu in 2020 (Figure 1).



(a) (b)

Figure 1. (**a**) The location and current land use map; (**b**) the main parks and rivers in the center of Chengdu.

2.3. Multi-Objective Spatial Analysis Methods

Guidos 1.3 software was used to identify core patches, and Conefor Sensinode 2.6 software was used to calculate the graph theory-based landscape metrics to determine the optimal distance threshold and identify the ecological sources. The resistance surface was constructed based on the natural, social, and economic characteristics so as to construct a comprehensive resistance surface. Then, the ecological network with structural connectivity or functional connectivity was constructed using Graphab 2.6.1 and Circuitscape 4.0 software individually. Finally, the green space spatial security pattern with structural and functional connectivity was optimized. The method framework of this study is shown in Figure 2.

Stepping stones are the key patches to maintain the connectivity of adjacent patches in the ecological network and can be used as transit stations for biological migration and increase the connectivity between large patches. Pinch points are important patches selected by circuit theory simulation, which have high current density, are located in the narrow zone of ecological corridors, and have strong irreplaceability. Barrier points are areas where species are hindered by resistance when moving through a heterogeneous landscape. Structural connectivity corridor is an ecological corridor constructed based on landscape structure characteristics such as patch shape and size. Functional connectivity corridor is an ecological corridor constructed based on species migration or other landscape ecological processes between patches.

2.3.1. Extraction and Analysis of Core Ecological Patches Using MSPA

First, the raster data of the land use map of Chengdu were reclassified in ArcGIS10.3. In the study area, forest land, grassland, urban green spaces, and water bodies were assigned a value of 2. The remaining landscape types were assigned a value of 1, and blank areas were assigned a value of 0. These values were converted into binary raster data in TIFF format [6] in the Guidos. According to the actual needs, the analysis parameters were set to eight neighborhood connectivity analysis principles, and the edge width was set to 1 pixel (30 m). Finally, the core ecological patches determined using MSPA were input into the Graphab as the source patch so as to further analyze the spatial structural connectivity characteristics of urban green space.

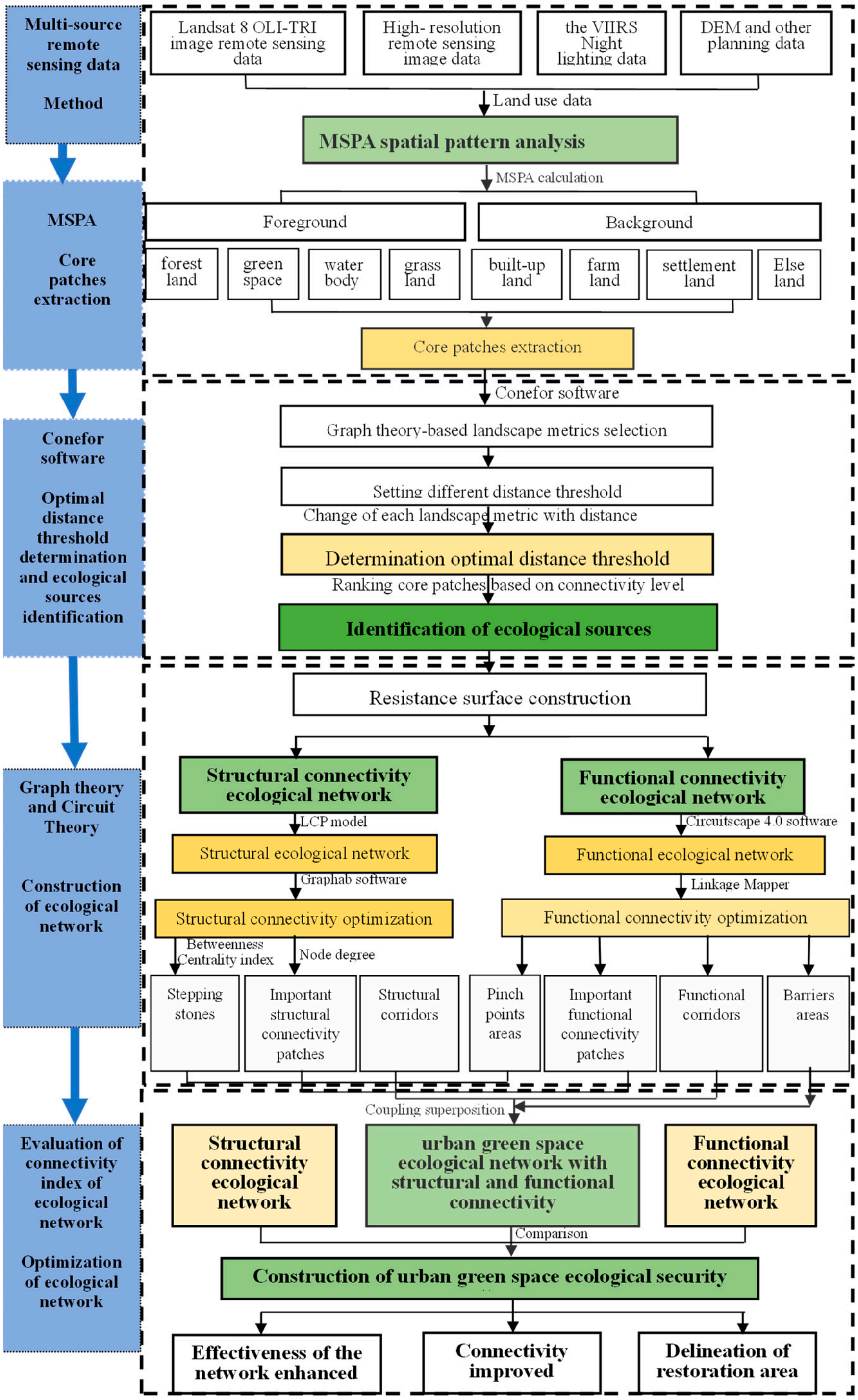


Figure 2. The methodological framework of this study.

2.3.2. Determining the Distance Threshold and Importance of Source Patches using Graph Theory Based-Landscape Metrics

The graph theory-based landscape metrics, such as the number of components (NC), the integral index of connectivity (IIC), probability of connectivity (PC), and importance index (dI), were calculated by Conefor to reflect the level of connectivity between important core patches [27]. The formula and ecological meaning can be found by referring to Table 1 [8,12,27] and Graphab 2.6 user manual. The distance threshold should be reasonably set based on the structural characteristics of landscape and ecological behavior of organisms to improve the applicability for planning. Therefore, in combination with the search and spread of key protected animals in the study area and the accessibility of habitat, ten distance thresholds (0.5 km,1 km, 2.5 km, 5 km, 7.5 km, 10 km, 15 km, 20 km, 25 km, 30 km) were set by calculating and analyzing the change in spatial connectivity and its stability with the distances change so as to determine the optimal distance threshold. Finally, according to the determined optimal distance threshold, dI′ value was calculated. On this basis, some core patches were selected as important ecological sources. These core patches will be used as the ecological sources for circuit theory analysis.

Table 1. The meaning and calculation formula of selected graph metrics.

Graph Metrics	Meaning	Scale	Formula
Integral Index of Connectivity (*IIC*)	$0 \leq IIC \leq 1$. The higher the *IIC* value, the higher the connectivity.	Global level, Delta	$IIC = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\frac{a_i a_j}{1+nl_{ij}}}{A_L^2}$
Node degree (*Dg*)	The larger the value, the more important the spatial connectivity.	Local level	$Dg_i = \lvert N_i \rvert$
Betweenness Centrality index (*BC*)	$BC \geq 0$. *BC* indicates the importance of a landscape patch as a stepping stone in most of the shortest paths.	Local level	$BC_i = \sum\limits_{j}\sum\limits_{k}\alpha_j^{\beta}\alpha_k^{\beta}e^{-adjk}$ $j,k \in \{1\ldots n\}, k < j, i \in P_{jk}$
Probability of Connectivity (*PC*)	$0 \leq PC \leq 1$. The higher the *PC* value, the higher the landscape connectivity.	Global level, Delta	$PC = \frac{1}{A^2}\sum\limits_{i-1}^{n}\sum\limits_{j=1}^{n} a_i a_j e^{-\alpha d_{ij}}$
Number of Components (*NC*)	$NC \geq 1$. The larger the number, the lower the global spatial connectivity.	Global level	$NC = nc$
Fractions of delta connectivity index (*dI*)	Rate of variation between connectivity index value of *I* (*PC* or *IIC*) and connectivity index value of I_{remove} corresponding to the removal of the patch *i*.	Delta	$dI = \frac{I - I_{\text{remove}}}{I} \times 100\%$ $dI' = 0.5 \times dIIC + 0.5 \times dPC$

Where A means area of the study zone, n means number of patches, nc means number of components, nl_{ij} means number of links between patches i and j, a_i generally means the surface area of the patch i, ac_k means total area of the patches comprising k, N_i means all patches close to patch i, d_{ij} generally means the least-cost distance between patches i and j, $e^{-\alpha d_{ij}}$ means probability of migration or diffusion between patches i and j, α means limit on movement distance, β means exponent to weight capacity, and P_{jk} means all the patches crossed by the shortest path between patches j and k [11,17].

2.3.3. Green Space Structural Connectivity Analysis Using LCP and Graph Theory

The LCP method based on Arcgis 10.3 and Garphab can achieve many-to-many ecological network construction. The construction process can be divided into three steps: the identification of ecological sources, the evaluation of landscape resistance and construction of comprehensive resistance surface, and the construction of ecological network.

Firstly, landscape resistance reflects the ease with which species can migrate and energy can flow between different landscape units [28]. For most organisms, factors such as the degree of human disturbance in built-up land, terrain slopes, water bodies, vegetation types, and social economy factors will have an important impact on species migration [18]. Based on the comprehensive status of land use in the central area of Chengdu and the availability of data, the resistance score of each factor (Table 2), such as built-up land and green spaces (including urban green spaces, forest land, grassland, etc.), was determined by referring to relevant research literature [4,22] and expert scoring methods. The lower the landscape resistance score, the higher the patch habitat suitability. Then, the single-factor resistance cost grid data were made in ArcGIS 10.3, and the resistance surface grid file was created by using the mosaic tool. Finally, the night lighting data and slope factor were used as correction factors and superimposed on the constructed resistance surface according to Formula (1) to obtain the final comprehensive resistance surface in the study area [29,30].

$$R_{fin} = \frac{L_i}{L_\alpha} \times R_i(1 + \beta \times S_i) \quad (1)$$

where R_{fin} is the final comprehensive resistance value of each grid in the study area after correction, R_i is the basic resistance value of grid i, L_i is the lighting index of grid i, L_α is the average lighting index of land use type corresponding to grid i, S_i is the percentage slope value of grid i, and β is the coefficient controlling slope; the value is 1 by reference to relevant literature.

Table 2. Resistance assignments of each landscape type.

Land Type	Grading Index	Resistance
Water body (area S)	$S \leq 10\ hm^2$	7
	$10\ hm^2 < S \leq 100\ hm^2$	20
	$S > 100\ hm^2$	600
Built-up land	$P^* < 1$	700
	$1 \leq P < 2$	800
	$2 \leq P < 3$	900
	$P \geq 3$	1000
Road land	Railway	700
	Fast way	600
	Primary way	500
	Secondary way	400
	Branch way	300
	Other road	550
Farm land	Paddy field	120
	Dry field	150
Green space (area S)	$S \leq 5\ hm^2$	5
	$5\ hm^2 < S \leq 10\ hm^2$	3
	$S > 10\ hm^2$	1

* P = 0.5 × building density/0.5 × building capacity.

Secondly, the tiff raster data of core ecological patches and the comprehensive resistance surface raster were imported into Graphab. The minimum patch area was set as 0, and patch connection was set as an eight-neighborhood rule. Then, the create graph tool was used to build the green space ecological network based on LCP simulation. Thirdly, based on the principle and algorithm of graph theory, Graphab was used to screen stepping stone patches and important ecological patches by selecting BC and Dg index at local level and IIC and PC using Delta mode to visually determine the priority protection level of core patches and the spatial connectivity of urban green space. Through comprehensive evaluation, an optimized green space ecological network with structural connectivity was constructed.

2.3.4. Constructing and Optimizing Green Space Ecological Network with Functional Connectivity Using Circuit Theory

In circuit theory, resistance means the value of different land cover types obstructs biological flow in the ecological network. Areas with high habitat quality that can promote gene flow, species migration, and frequent exchange of information were considered low-resistance surfaces with high permeability [31]. The resistance was assigned according to the relative habitat suitability of different land types, and then the conductivity surface of the study area was created using a similar process to the setting of landscape resistance and the construction of a resistance surface in graph theory.

Using Circuitscape 4.0 software, this study selected the pairwise mode and all-to-one mode to simulate and analyze the connectivity characteristics between ecological source areas and the relative importance of ecological corridors [29,30]. To better identify the functional ecological network of the green space, combined with relevant research results [32,33], the current study selected the top 30% grid pixels of the pairwise mode current density values as important functional connectivity corridors in combination with the zoning model. The top 20% of grid pixels of the all-to-one mode current density were regarded as important patches that functioned as stepping stones in the landscape [29,34].

The Linkage Mapper module of ArcGIS10.3 was used to optimize the green space ecological network. Firstly, the centrality mapper tool was used to calculate the patch importance. As the current centrality becomes more important, the contribution to maintaining the ecological network connectivity will increase. The linkage pathways tool was used to identify important ecological corridors based on the minimum cost-weighted distance using pairwise mode analysis. The pinchpoint mapper tool was used to obtain the pinch points. Pinch points are the key to optimizing the green space ecological network, which is equivalent to stepping stones in the ecological network, and they cannot be removed. Barrier points significantly hinder species migration or diffusion. Identifying and improving barriers will enhance the landscape connectivity of ecological networks [35]. The barrier mapper tool was used to set a search radius of 30 m so as to reflect the characteristics of the study area.

2.3.5. Coupling Effect Analysis of Structure and Function Connectivity and Optimization of Green Space Ecological Network

The optimization of ecological network depends on the improvement of connectivity, and the quality of ecological network can be improved by adding stepping stones and corridors. We can use the superposition method to analyze the differences between ecological network with structural connectivity and functional connectivity and find the important protective ecological sources with higher Dg and high centrality values, the important corridors with structural and functional connectivity, and patches with high BC values and ecological pinch points can be used as stepping stones. Based on the coupling effect, a composite green space ecological optimization network with structural and functional connectivity was constructed. Network analysis is a method used to evaluate the connectivity of ecological networks. It evaluates the complexity of ecological networks by measuring the connectivity between corridors and patches. Therefore, the network closeness (α index), network point line rate (β index), network connectivity (γ index), and average network consumption cost ratio ($C\gamma$ index) were selected to evaluate the three different optimized green space ecological networks. The formula is as follows:

$$\alpha = \frac{e - v + p}{2v - 5p} \tag{2}$$

$$\beta = \frac{e}{v} \tag{3}$$

$$\gamma = \frac{e}{3(v - 2p)} \tag{4}$$

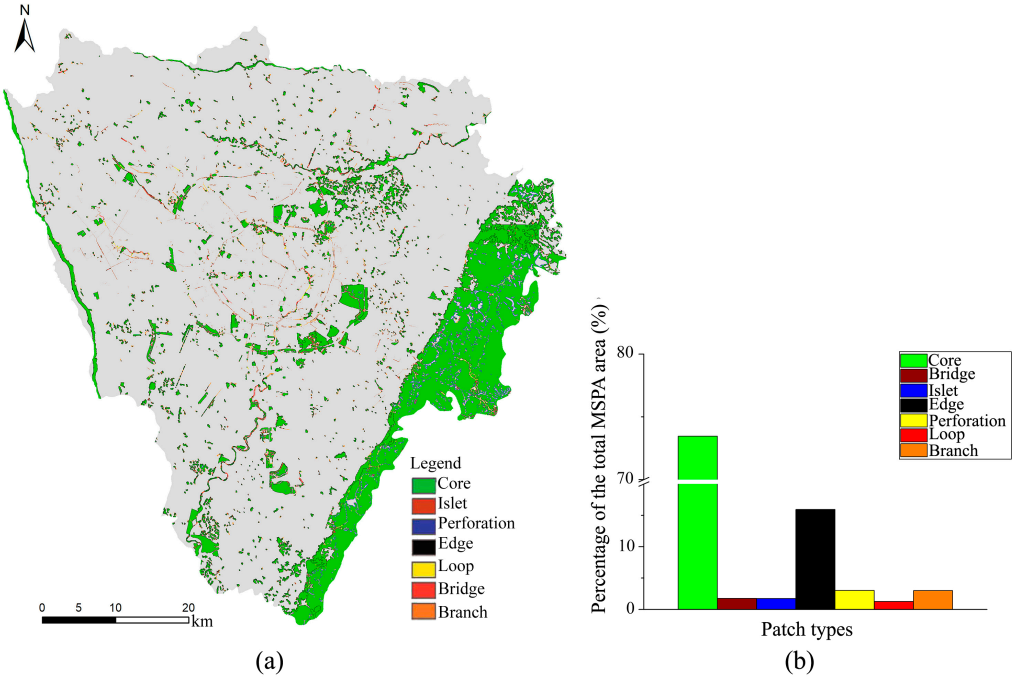
$$C_{\gamma} = 1 - (e/l) \tag{5}$$

where e represents the number of main corridors; v represents the number of nodes of the network; p represents the number of disconnected subgraphs in the network, generally 1; and l is the total length of the corridor. α index can measure the network closeness. The value is closer to 1, the better the network closeness is. β index can measure the network connectivity. The smaller the value, the lower the network structure perfection. γ index can measure the connectivity of the network. The value range is 0 to 1. The closer the value is to 1, the more connections exist between each node in the network. $C\gamma$ can reflect the effectiveness of the network.

3. Results

3.1. Extraction of Core Ecological Patches

The statistical analysis of the MSPA landscape types (Figure 3) shows that the core area of Central Chengdu in 2020 was approximately 606.29 km^2, about 73.46% of the total area of ecological elements, mainly distributed in the park green space, waterfront greenway of Jinjiang, Jinma River, Pi River, and the Longquan Mountains, with relatively good landscape connectivity. These elements provided important habitats for native species. The number of core patches in the northwest and north was relatively small; the patches were mostly islands, and the landscape connectivity was relatively poor.



(a) (b)

Figure 3. The landscape structure analysis map based on MSPA. (**a**) The map of seven landscape types; (**b**) the results of seven classification statistics.

3.2. The Determination of Optimal Distance and Classification of the Importance of Ecological Sources

It can be found that the NC value (Figure 4a) has continuous stability after 5 km, indicating that most core ecological patches can basically be interconnected at 5 km. IIC and PC values (Figure 4b) increase significantly in the range of 2.5–7.5 km, suggesting that the landscape connectivity between core ecological patches is growing fast. The dI′ value (Figure 4c) of most small and medium core patches stabilized after 5 km. Therefore, 5 km was finally determined as the optimal distance threshold of this study.

3.3. Constructing and Optimization of Green Space Ecological Network with Structural Connectivity

3.3.1. Construction of Green Space Ecological Network Using LCP

The ecological network of green space constructed using LCP included 1592 patches, 3115 corridors, and 439 components (Figure 5a). The degree of fragmentation of green patches in the old central urban area was relatively high, and the cumulative resistance cost distance was relatively large. This hindered the migration diffusion and energy flow of species. Most of the important corridors were in the south and east and consisted of river corridors in the Jinjiang, Sha River, and Pi River. In addition, some regional parts of the ecological network were distributed in clusters, with a complex network structure and fragmented habitats. The number of corridors was lowest in the west, and each patch was an independent island. There was potential for development in areas such as the Longquan

Mountains, Jinjiang ecological belt, Pi River and Jinma River, which could form the focus of ecological network optimization in the study area.

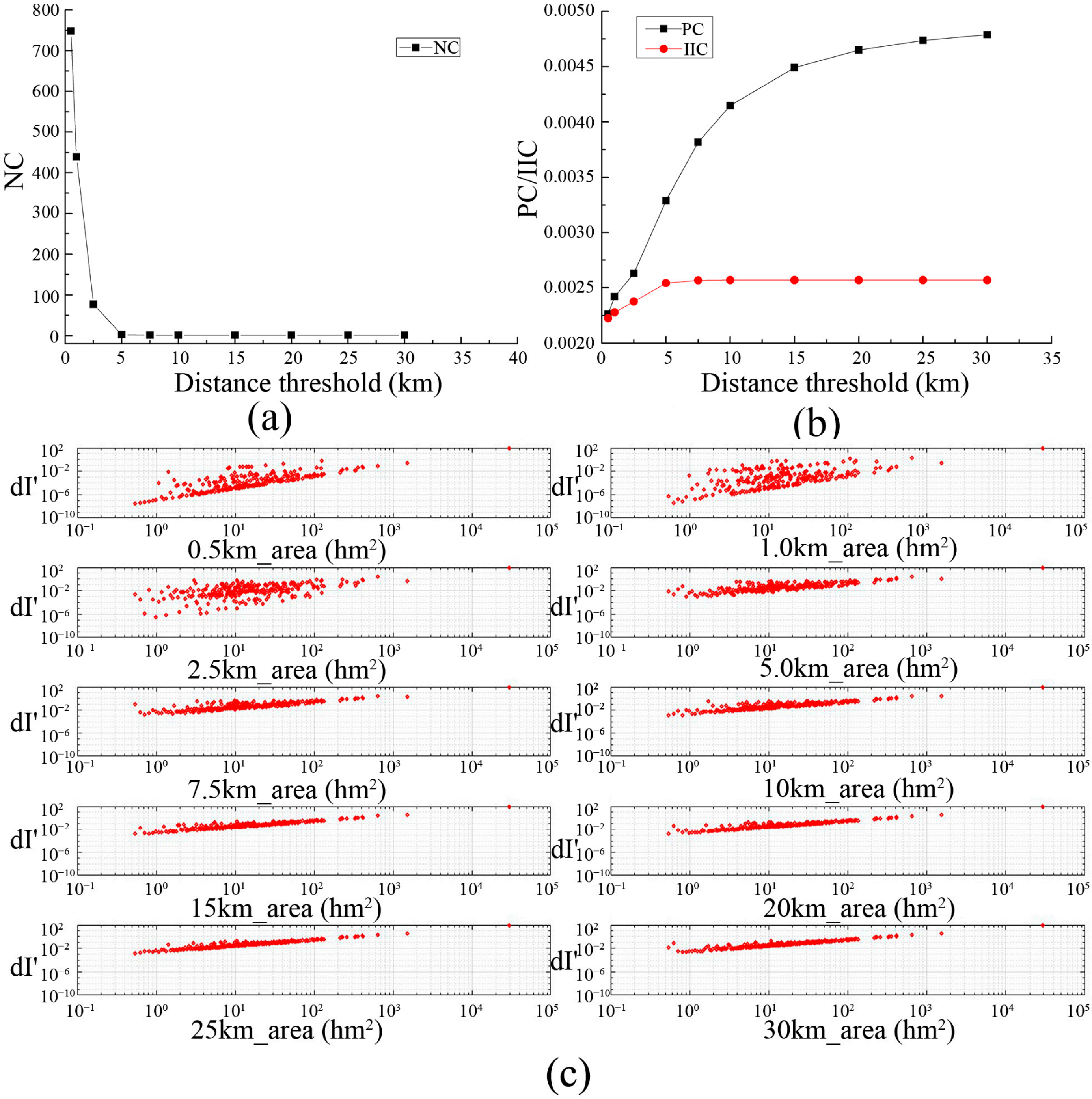


Figure 4. The different graph theory-based landscape metrics values with different distances. (**a**) The change in NC with distance threshold; (**b**) the change in PC and IIC with distance threshold; (**c**) the importance of individual patches of different sizes at different distances.

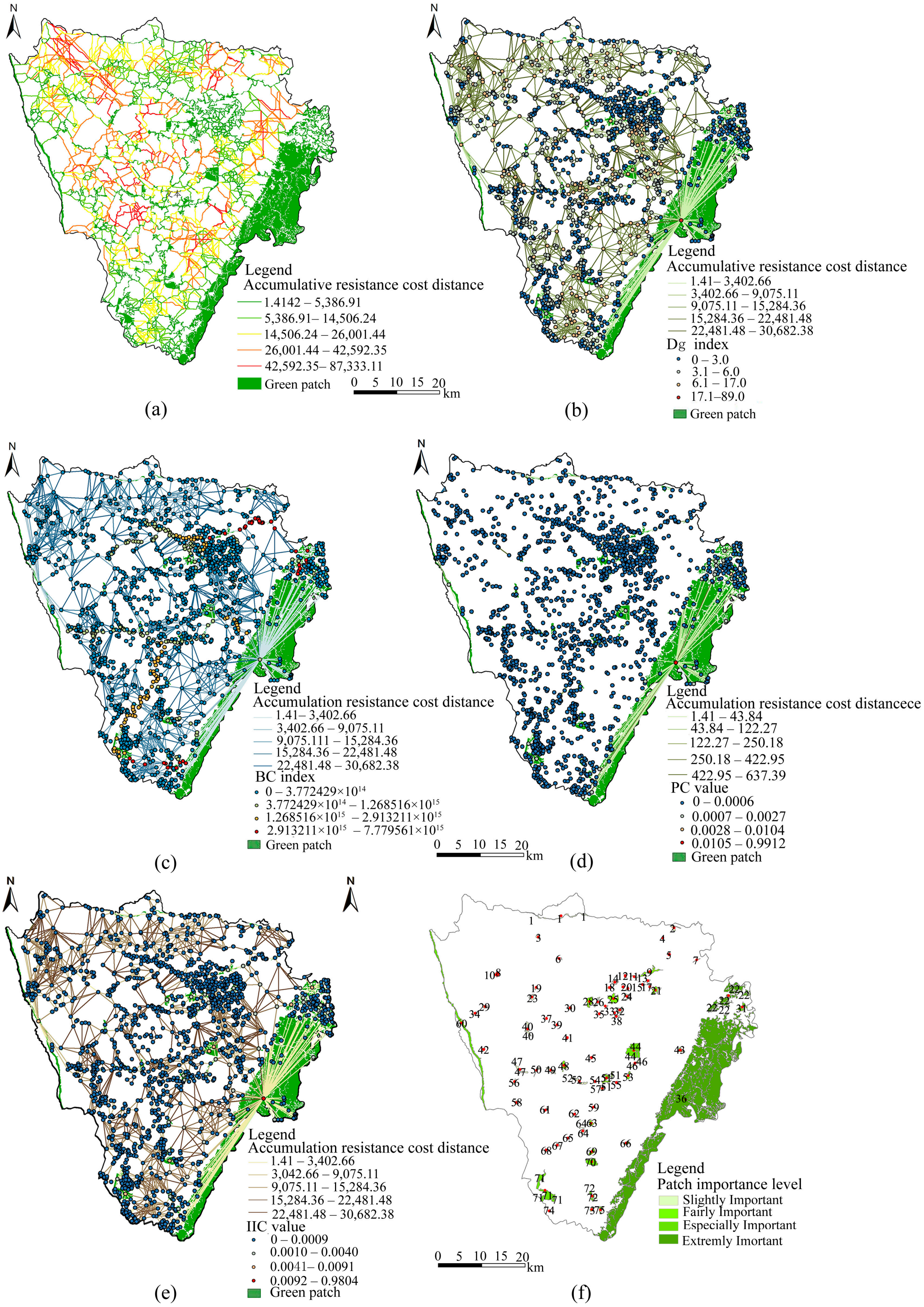


Figure 5. Evaluation of green space spatial connectivity at multiple levels. (**a**) Green space ecological network using LCP method; (**b**) distribution of node degree of green core patches; (**c**) distribution of betweenness centrality of green core patches; (**d**) importance level of green core patch and corridors based on PC; (**e**) importance level of green core patch and corridors based on IIC; (**f**) importance level of ecological sources.

3.3.2. Evaluation of Green Space Structural Connectivity and Optimization of Ecological Network

At a local level, the Dg and BC of patches can not only reflect the connectivity between patches but also indicate the importance of patches to the overall spatial connectivity and the intensity of the intermediary effect. Therefore, the BC index was used to screen green patches with important stepping stones in ecological networks. Figure 5b shows that there were 23 ecological patches with a Dg value higher than 10. The largest Dg value was in the Longquan Mountains area, which played a vital role in the overall green space connectivity, followed by Qinglong Lake Wetland Park, Jinma River, etc. The greater the Dg value of the core patch, the stronger the connectivity with other patches around and the greater the contribution to the overall green space spatial connectivity. At the same time, we found that there was a certain correlation between the area of core green patches and the Dg value, but it may not be the dominant factor. For example, the Xinglong Lake wetland park had an area of about 333.72 ha, but its Dg value was only 5. On the contrary, many small forest patches had relatively high Dg values. Therefore, the value of Dg is not only related to the green patches area but also to the spatial location and morphological structure of green patches. Figure 5c showed that the BC index of patches in the northeast of Longquan Mountain was the largest and that it played a key role in the connectivity between patches. Tianfu Park, Shahe Park, and other areas were adjacent to patches with a high Dg value. We focus on the protection and expansion of green patches with a large BC index with the role of a stepping stone to build and optimize the green ecological network with efficient circulation.

Figure 5d,e show the connectivity analysis of IIC and PC in Delta mode. By sorting the value of IIC and PC, the analysis results can directly screen and evaluate the important patches and connectivity corridors in the green space ecological network. According to the dI′ superposition results, the most important ecological patches in the study area were the Longquan Mountains, Bailu Bay Wetland Park, Xinglong Lake Wetland Park, etc. Therefore, this study sorted the core patches according to the size of the dI′ value, extracted the most important ecological patches as ecological sources, and classified the importance levels of patches. Figure 5f show the top 75 ecological sources ranked according to their dI′ value. Through comprehensive analysis and evaluation, the optimal green space ecological network with structural connectivity was composed of 74 stepping stone patches, 43 protective sources, 75 ecological sources, and 315 ecological corridors, which is shown in Figure 6.

3.4. Construction and Optimization of Green Space Network with Functional Connectivity

3.4.1. Construction of Green Space Network Using Circuit Theory

Figure 7a shows that multiple functional connectivity corridors had different widths. The eastern and southern regions had dense ecological source areas, and the Jinma River, Jinjiang River, and Pi River had the largest number of corresponding important functional corridors. The current density of riverside areas such as Jinjiang and Pi River was scattered because of the different quality and degree of connection of green patches in different sections. The corridors were mainly spread along rivers in a ring network distribution, which was consistent with the circular radial expansion mode of Chengdu. The ecological corridors formed natural green rings, which have a clear directional significance for the construction of green space ecological networks in the future. The area of extremely important corridors was 105.264 km^2, that of especially important corridors was 422.29 km^2, and that of fairly important corridors was 555.58 km^2 (Figure 7b).

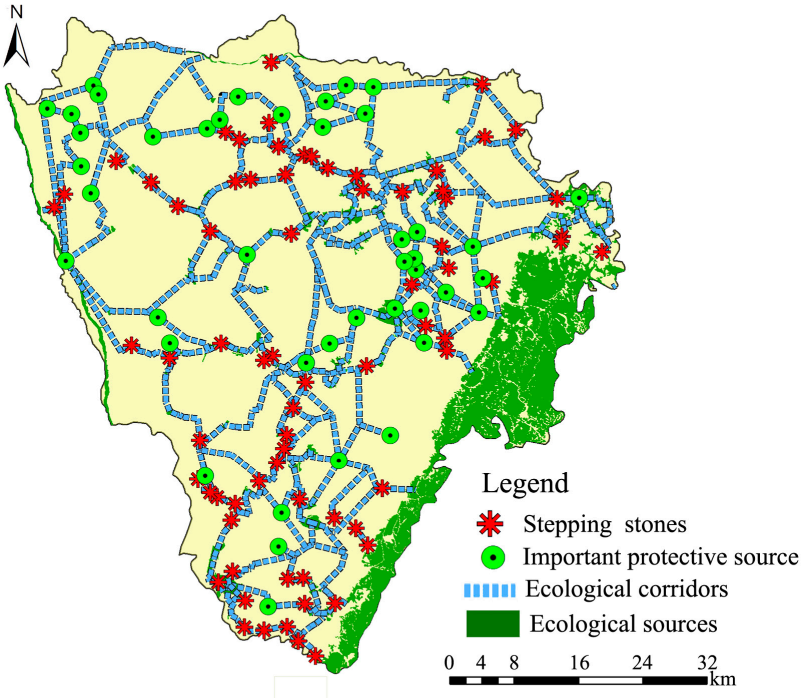
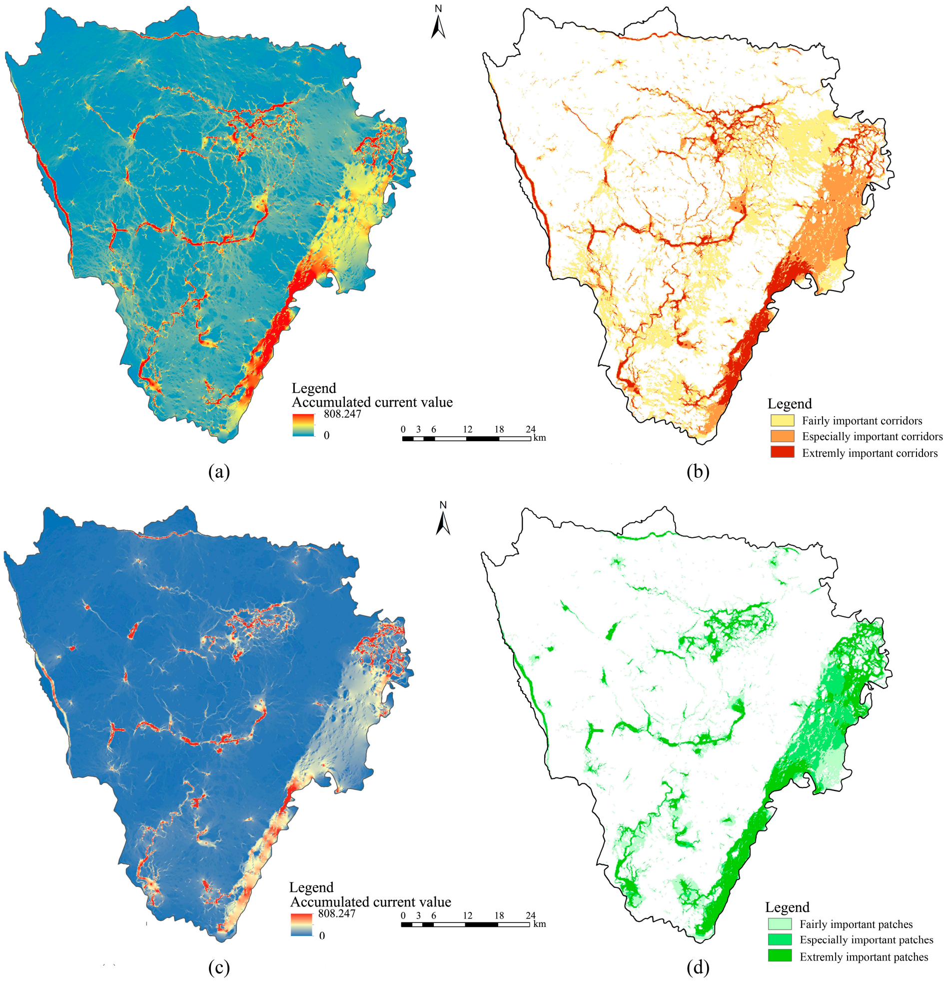


Figure 6. The optimal green space ecological network with structural connectivity.



(a) (b)

(c) (d)

Figure 7. Circuit theory simulation results. (**a**) Paired simulation results; (**b**) important corridors distribution; (**c**) all-to-one simulation results; (**d**) important patches distribution.

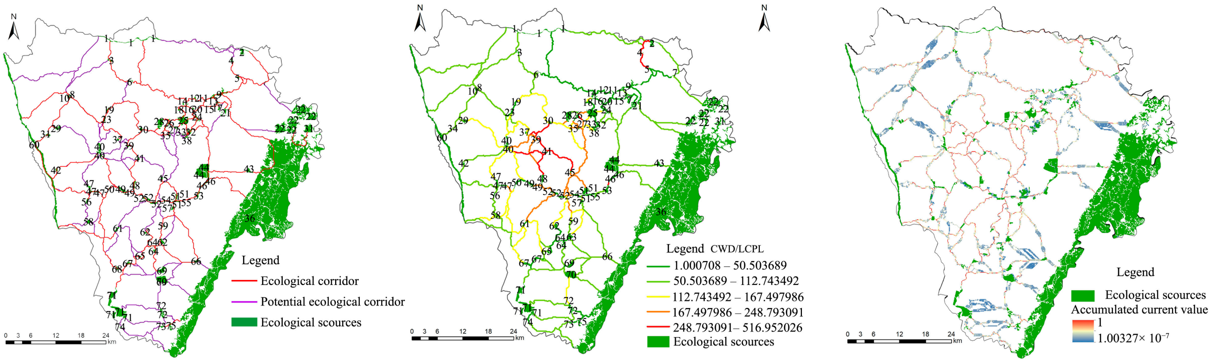
Figure 7c shows that the landscape fragmentation of the entire central urban area was relatively high. The quality of the green space network in the east and south was better than that in the west and north, and the difference was significant. According to the visual expression of the current density, we found that the ecological source of the Longquan Mountains was relatively isolated. On the one hand, the Dongfeng Canal and Luxi River obstructed ecological processes such as terrestrial biological migration. On the other hand, the eastern region of the Longquan Mountains was rugged terrain with large slope changes within the study area, which also hindered the activities of terrestrial species to a certain extent. The area of the extremely important patches, in terms of current value, was 191.59 km^2, that of the especially important patches was 237.99 km^2, and that of the fairly important patches was 248.38 km^2 (Figure 7d). The three levels of patches provide an important foundation for the connectivity of the ecological network.

3.4.2. Optimizing Green Space Functional Connectivity

A total of 160 ecological corridors were obtained through the simulation (Figure 8a), and 81 potential corridors were identified that could link ecological source areas. In the east, the Longquan Mountains and Qinglong Lake Wetland Park were the centers that connected the surrounding green patches; in the west, the Jinma River was the center that connected the surrounding patches; in the south, the Jinjiang River and other water systems and large green patches were connected. Connectivity between ecological sources can be reflected by the ratio of CWD/least cost path length (LCPL). As the ratio increased, the relative resistance of the path increased; that is, the connectivity between the two sources decreased. By comparing the visualization results (Figure 8b), we found that the CWD/LCPL values of the 81 potential ecological corridors were relatively small; that is, the connectivity between their corresponding ecological sources was relatively high. The improvement in connectivity plays a key role in effective ecological green spaces, and the ecological corridors identified here need to be a focus in the optimization of the security pattern.

Using the natural breakpoint method to classify the simulation results of ecological source centrality (Figure 8c), we found the central values of 75 ecological sources; Longquan Mountain, had the highest centrality. Widespread pinch points were found to be among the ecological sources within the research area (Figure 8d). Many more concentrated pinch points were observed in the west and south; these were crucial for species migration, whereas few pinch points were observed in the east and north, and the connectivity was relatively poor.

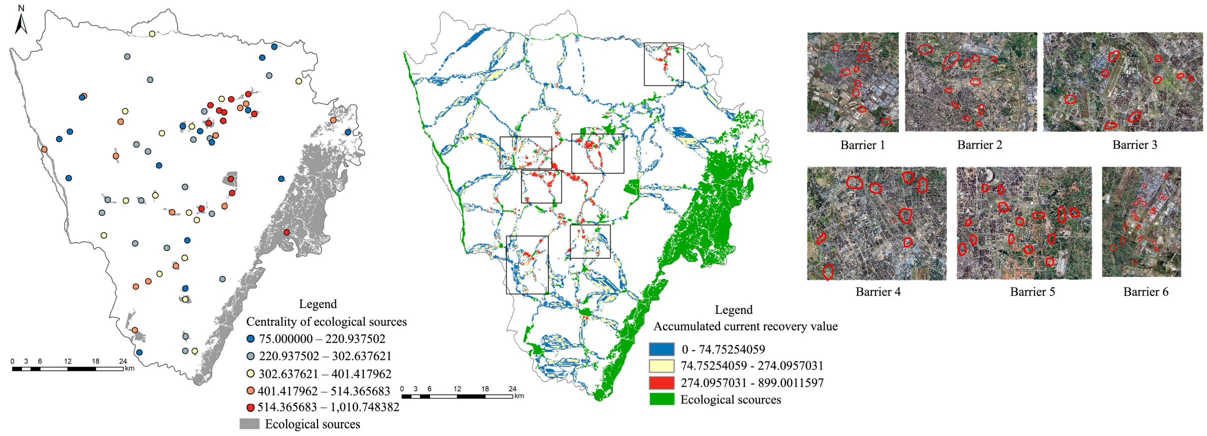
Many barriers were distributed in a point-like or strip-like distribution over a large area (Figure 8e). In the old central area, with high building density, it was difficult to improve the landscape connectivity. There was more space for improvement in landscape connectivity in other areas. By comparing the images, most of the barrier points can be seen to be built-up land (barriers 1 and 4) and road land (barrier 2), although some barrier points appear in the areas, including rivers, farmland, and forest land (barriers 5 and 6). Built-up land is the main site of human activities. Owing to the change in underlying surface, other built-up land, such as housing, roads, and impervious ground, hinder the migration of species to varying degrees, reflecting the negative interference of human beings on the landscape ecological process. Therefore, the improvement and restoration of barriers are important to optimize the functional connectivity of the green space ecological network. Through comprehensive analysis and evaluation, the optimal green space ecological network with functional connectivity was composed of 40 stepping stone patches, 48 protective sources, and 176 ecological corridors, which are shown in Figure 9.



(a) Distribution of ecological corridor

(b) Ratio of cost weighted distance (CWD) to least cost path length (LCPL)

(c)Distribution of pinch points for threshold 200



(d) Centrality of ecological sources

(e)Distribution of barriers and underlying surface local detail

Figure 8. Optimization of urban green space ecological with function connectivity using Linkage Mapper. (**a**) Distribution of ecological corridors; (**b**) ratio of cost-weighted distance (CWD) to least cost path length (LCPL); (**c**) distribution of pinch points; (**d**) centrality of ecological sources; (**e**) distribution of barriers and underlying surface local detail.

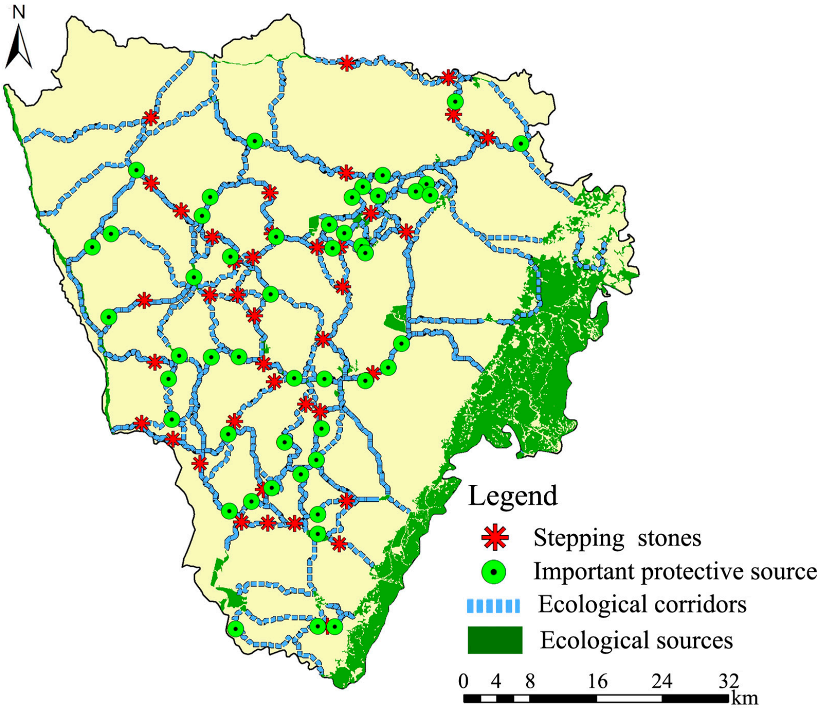


Figure 9. The optimal green space ecological network with functional connectivity.

3.5. Coupling Effect of Green Space Ecological Network with Structural and Functional Connectivity

It can be found that there were some differences between the landscape measurements based on graph theory and those based on circuit theory. For example, except for a few ecological source areas—such as Longquan Mountain and the forest land in the north of Longquan Mountain, Qinglong Lake Wetland Park, Jinma River, etc., which not only have high centrality but also a high Dg value—the landscape measurement values of other ecological source areas have certain differences. The main reason for this may be that graph theory focuses on the calculation of landscape structure connectivity from the aspects of patch shape, location, area size, etc., while circuit theory focuses on the vegetation type of green space, the contribution rate to species migration and diffusion, etc. (Figure 10a). Most of the points with high BC values screened by graph theory and the pinch points screened by circuit theory coincide with each other, which were mainly distributed in the river corridors such as Pihe River and Jinjiang River, indicating that these patches play an important role both in structural and functional connectivity (Figure 10b). Similarly, there were many overlaps between the structural corridors and the functional corridors in the central area of the city. In addition, most of the structural connectivity corridors were mainly distributed in the urban fringe, which organically connects the green patches in the suburb. The structural corridors and the functional corridors complement and perfect each other, thus forming a relatively more optimized corridor network system (Figure 10c). Therefore, in the construction of a composite green space ecological network, it is necessary to integrate graph theory and circuit theory to jointly screen the key sources and corridors so as to enhance the efficiency of material and energy flow in the green space ecological network and improve the probability of species' successful diffusion and migration. Finally, based on the coupling effect, the ecological network of composite green space was composed of 114 stepping stone patches, 91 important protection patches, and 446 ecological corridors (Figure 11).

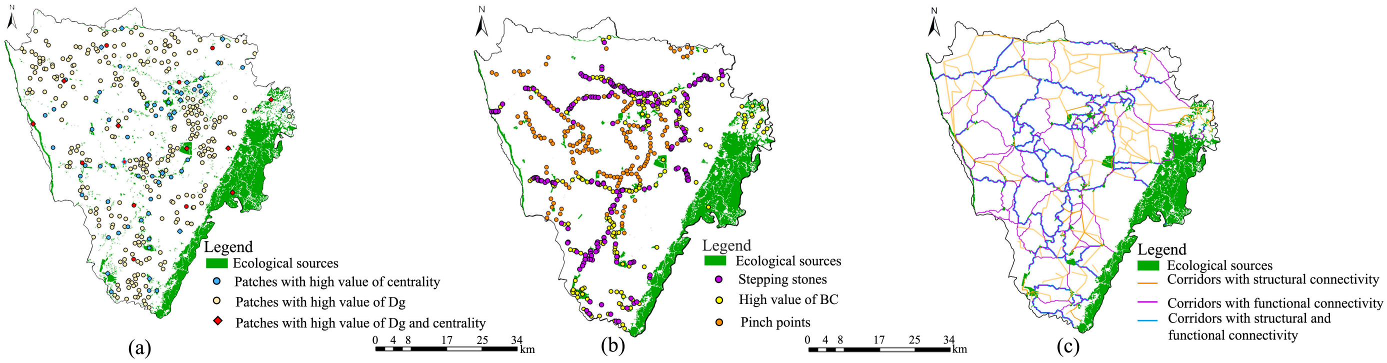


Figure 10. The coupling effect of structural and functional connectivity. (**a**) The coupling effect of high value of centrality and Dg; (**b**) the coupling effect of pinch points and BC; (**c**) the coupling effect of structural and functional corridors.

The three different types of optimized ecological networks were compared and analyzed (Table 3). The results showed that the cost value of the optimized ecological network by coupling structural and functional connectivity was relatively increased, but the other three indicators, the α index, β index, and γ index, were significantly improved compared with the other two ecological networks, which indicates that the reasonable increase in ecological stepping stones and ecological corridors by improving structural and functional connectivity is of great significance to the connectivity of regional networks.

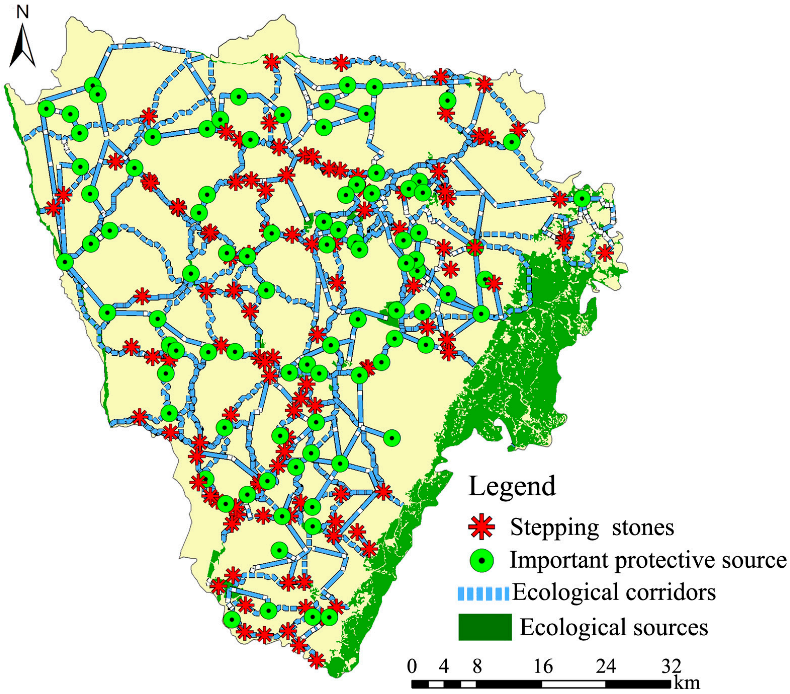


Figure 11. Green space ecological network coupling structural and functional connectivity.

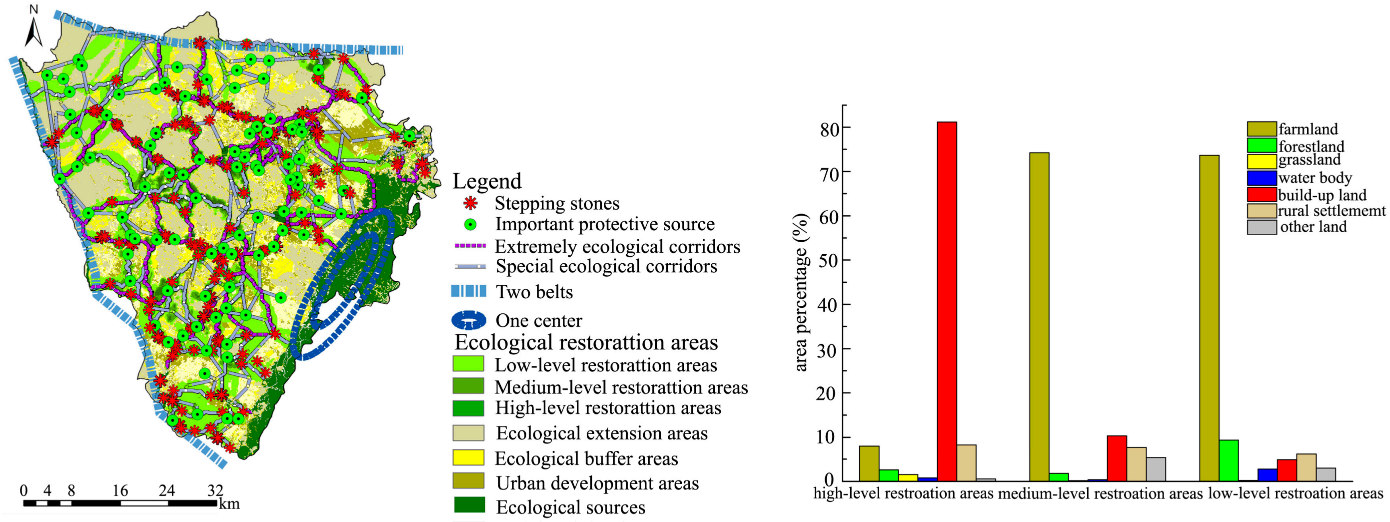
Table 3. Comparison of ecological network connectivity index of different optimization ecological networks.

Index	Ecological Network with Structural Connectivity	Ecological Network with Functional Connectivity	Ecological Network Coupling with Structural and Functional Connectivity
α index	0.33	0.25	0.46
B index	1.64	1.49	1.91
γ index	0.57	0.51	0.64
Cγ index	0.56	0.88	0.82

3.6. Optimization Strategy for Urban Green Space Ecological Security Pattern

In order to improve the spatial connectivity of urban green space and build an urban ecological security pattern, an optimization pattern of a ringed green ecological network with one center, two belts, multiple points, multiple corridors, and multiple zones connected in series was proposed on the basis of comprehensive overlay analysis of green space landscape structural and functional connectivity (Figure 12a).

The "one core" refers to the Longquan Mountain area, which has an important ecological radiation function, and priority should be given to ecological security protection. Therefore, we recommend that it is strictly forbidden to carry out high-intensity development and productive construction activities in the Longquan Mountains, and measures such as optimization of forest land community allocation and closing mountains for afforestation should be undertaken to strengthen the protection and maintenance of environmental quality of forest ecosystem. The "two belts" refer to the ecological green belts along the Qingbai River and Jinma River. There are different land use types, including farmland, forest land, and wetland. They have a good ecological foundation but are often affected by human activities. Different types of parks can be built to form landscape belts that integrate culture, entertainment, and economic industry to meet the needs of residents for recreation and promote rural economic development. The "multi-zone" concept is based on circuit theory and defines different levels of ecological restoration areas, ecological expansion areas, ecological buffer zones, peripheral development areas, and urban construction areas. According to their importance for connectivity, the barriers were divided into three levels of restoration areas (Figure 12b), including high-level restoration areas of 27.93 km^2, medium-level restoration areas of 166.94 km^2, and low-level restoration areas of 240.92 km^2. The high-level restoration areas are mainly distributed in urban built-up land (81.17%). These areas are also landscape areas seriously disturbed by human beings. The improvement in high-level restoration areas is very urgent, but it is difficult to implement ecological engineering construction here. We recommend setting up green belts on both sides of the roads and increasing vertical and roof greening to implement ecological engineering construction. The areas for medium-level restoration are mainly farmland (74.25%), followed by built-up land (10.43%) and rural settlement (7.68%). Ecological construction should focus on the barrier points and adopt diversified techniques to optimize ecological elements. The low-level restoration areas are mainly farmland (73.96%), followed by forest land (9.35%). The low-level restoration area is an important component of the green space ecological network and has good ecological restoration potential. The ecological expansion area is the outward expansion area of natural habitats, which represents the outermost area of the free migration of species, and it is the area required to ensure stable material and energy flow for species. The buffer area represents the separation between the habitat area and the built-up area. It is the natural buffer zone around the junction of the city and suburbs.



(a) (b)

Figure 12. Optimized map of green space ecological security pattern (**a**) and its land use proportions of restoration areas (**b**).

According to the comprehensive analysis, 114 ecological patches were selected as stepping-stone patches. The patches with the higher Dg value and highest centrality are important protective ecological sources, and suitable optimization measures can be taken for them that are easily disturbed and destroyed by human activity, including the establishment of buffer belts on both sides of rivers to protect habitat quality. Different types of ecological sources, including street green space and stepping stones woodland, should be added near the important protective ecological sources to reduce the barrier effect of urban built-up land. The width of ecological corridors, especially potential ecological corridors, should be increased as much as possible to enhance their contribution to network connectivity so as to meet the dual needs of biological migration and resident recreation. Together, all the landscape elements form an urban green space ecological security pattern that provides urban planners with a comprehensive ecological strategy.

4. Discussion

4.1. Advantage of Construction of Compound Green Space Ecological Network Coupling MSPA, Graph Theory, and Circuit Theory

In this study, by comprehensively analyzing the coupling effect of landscape connectivity, it can be found that the landscape has high structural connectivity, not necessarily high functional connectivity. Therefore, the planning of a green space ecological network integrating structural and functional connectivity is an important way to effectively protect biodiversity and ecological functions. By integrating MSPA, graph theory, and circuit theory analysis methods, this paper puts forward a research framework to build a green space ecological network with composite functions. Most other studies [22,23] have identified pinch points or barriers based on the current density of circuit theory to optimize the ecological pattern of green spaces without comprehensively considering the significance of the connectivity characteristics of green space structure to the optimization of green space ecological network. Graph theory can be used to analyze the connectivity of green space structures from different scales and find out the distribution characteristics of important patches and ecological corridors. Using graph theory-based landscape metrics to evaluate green space ecological networks and select the important ecological sources is more scientific and reasonable [11,14]. We make full use of the advantages of Graphab and Conefor software so as to improve operational efficiency. Graphab was used to optimize the structural connectivity of the green space ecological network, and at the same time, the optimal distance threshold was set to realize the transition and connection from structural connectivity to functional connectivity of green space via Conefor. Compared with previous results [3,7,27], we found that the optimal distance threshold for different areas was also different. The main reasons were mainly related to the scope of the study area, the spatial distribution and area of natural ecological environment elements, the urban spatial pattern and other factors being closely related, etc. Therefore, for other regions, we should select a variety of distances according to the diffusion characteristics of species to analyze and compare the network graph maps and reasonably select the distance threshold so as to build an ecological network that is most consistent with the habitat. The green space ecological network approach framework proposed in this study comprehensively considers the characteristics of spatial structural connectivity and functional connectivity of green space and scientifically identifies the landscape elements and key areas that have an important impact on landscape connectivity. This not only can promote the coupling between the structural planning and function improvement of the green space system so as to systematically improve the ecological service function of urban green space but also will help to further refine the pattern of green space ecological network and ensure the accurate implementation of ecological protection and construction, thus providing a new research idea for protection planning of green space ecological networks.

4.2. The Difference and Relation with Urban Network Theory Model

The city is an open, complex system; the spatial elements are connected and interdependent through the exchange of material, energy, and information [36]. Since Christopher Alexander proposed the semi-lattice city theory in his book “A City is not a Tree” in the 1960s [37], many scholars have continuously explored the complexity, internal correlation, interaction, and research model of the ideal city of urban space and urban system based on self-organizing theories such as dissipative structure theory, synergy theory, mutation theory, and nonlinear theory and formed the urban complexity paradigm based on topology, self-organizing theory, and nonlinear theory. In particular, Fractal City [38], Space Syntax [39], Self-Organizing City [40], and other studies are representative. In recent years, Nikos Salingaros understood the urban system as a complex system formed by the self-organization evolution of some simple rules and proposed the Urban Web Theory model to describe the overall complexity of cities. He simulated the urban spatial structure as a network and the urban spatial elements as nodes and modules of the network, which interact and influence in the urban system to simulate the phenomena and laws that spontaneously emerge in the city. Different urban spatial elements are connected to each other through paths to form the edges of the network, which is represented by the easiest or optimal accessibility between nodes [36,41]. Meanwhile, Nikos Salingaros and Michael Mehaffy conducted a series of studies using complexity theory and self-organization theory.

With the acceleration of the urbanization process, facing the threat of extreme climate, loss of biological habitat, and reduction in biodiversity, improving the landscape connectivity among urban landscape elements is one of the most effective ways to combat these issues. As an important node of a complex urban network system, urban green space plays an important role in maintaining urban ecological balance and improving ecological environment quality. Unlike the Urban Web Theory model that focuses on multiple spatial elements in a city and comprehensively reflects their interactions and impacts, this study focuses on urban green space elements and constructs an urban green space ecological network using graph theory and circuit theory based on landscape ecological models and processes. Using graph theory to study the structure and optimization of ecological networks is considered to be an effective method to improve the ecological quality of urban open space systems [11,18,29]. It can simplify the complex urban green space system and abstract green patches as nodes and green corridors as connections. Therefore, an urban green space system can be simplified into a network composed of nodes and connections in the sense of graph theory, and their topology, connectivity, and complexity can be further quantitatively measured [42]. The comprehensive analysis shows that the ecological network model based on graph theory is the continuation and expansion of the Urban Web Theory model.

4.3. Coordinating Urban Development and Ecological Protection

There is a complex coupling relationship between urbanization and the ecological environment, and how to coordinate the relationship between urbanization and the ecological environment has become a global strategic scientific problem [43]. Coordinating the relationship between rapid urban expansion and the protection of ecological resources is the key to sustainable urban development. In the process of ecological planning, it is necessary to divide the ecological management and control approaches of different eco-systems in the study area, define core protected areas in combination with stepping stones, restore barrier areas in stages to reduce landscape resistance, increase the number of nodes, and connect potential ecological corridors [2,9,18]. This will reduce the degree of fragmentation of green space and enhance ecosystem services. Circuit theory and graph theory can achieve this goal well. Therefore, in order to better guide green space ecological planning and further improve the accuracy of the model simulation, long-term monitoring of the ecological and social environment in urban central areas can be carried out to construct the optimal pattern of urban ecological security, and the model can be corrected and optimized according to the monitoring data in the future.

4.4. Challenges in the Process of Urban Green Space Ecological Network Construction

The selection of ecological sources and setting of the landscape resistance value are important challenges in the construction of a green space ecological network. The identification of ecological sources generally selects ecological land with a large area or based on habitat quality assessment or MSPA and landscape connectivity. Research on the selection of ecological sources by considering the ecological value of different landscape types, such as urban green space, is less involved. Different landscape types have certain differences in ecological values, such as protecting biodiversity, improving environmental quality, regulating climate, and maintaining community stability. The seasonal changes of urban green space, forest land, cultivated land, etc., will also have a certain impact on the assessment of ecological value. The effect of ecological value on the selection of ecological sources was not considered in this study. In the next study, remote sensing technology can be used to conduct comprehensive and long-term dynamic monitoring of urban land types in different seasons, especially green space, so as to quantitatively evaluate the different ecosystem service functions of landscape elements and obtain the results of the importance of ecosystem services. Based on the comprehensive assessment of the importance of ecosystem services, habitat quality, and landscape connectivity, the ecological lands with high ecological value, high stability, and high connectivity were selected as the ecological sources so as to improve the scientific accuracy of ecological source selection. In this study, the construction of a comprehensive resistance surface mainly used land use type, terrain slope, and other factors, but there was still some subjectivity. When determining the resistance value, the characteristics of species dispersal and the influence of different seasons on the migration resistance value of species in heterogeneous landscapes were not fully considered. In future studies, the seasonal migration characteristics of species in heterogeneous landscapes, ecosystem service functions, and social and human factors will be comprehensively considered to construct a comprehensive resistance surface reflecting the regional ecological environment.

5. Conclusions

The overall aim of this paper was to build an integrated green ecological network optimization pattern with the dual effectiveness of structural and functional connectivity based on biodiversity conservation, identify the ecological land and key ecological corridors that need to be prioritized for protection in the territorial spatial planning for relevant urban planning departments, and put forward suggestions for regional ecological protection management for the improvement areas to ensure the implementation of development and protection policies. Based on the current green space in the central area of Chengdu, this study analyzed the spatial coupling relationship between structural and functional connectivity and determined the priority protection sequence of important ecological sources, ecological corridors with key connectivity functions, key strategic points in urgent need of protection, and ecological restoration areas. The optimization strategy and planning implementation of ecological network security patterns were discussed so that regional biodiversity conservation planning policies could be more accurately connected. The green space network optimization method based on MSPA, graph theory, and circuit theory will provide a new conceptual framework for planning and construction of ecological networks in the study area and the optimization of the pattern of territorial space development and protection so as to realize the overall restoration and comprehensive function improvement of natural ecosystems, as well as provide methodological support for the preparation of other urban ecological planning. The main conclusions were as follows:

1. On the basis of setting the optimal distance threshold of 5 km, the ecological sources, ecological corridors, stepping stones, and the whole green space ecological network of the study area were identified. The optimal green space ecological network with structural connectivity was composed of 74 stepping stone patches, 43 protective sources, 75 ecological sources, and 315 ecological corridors. The connectivity of green space structures gradually decreased from west to east and from periphery to center. There was potential for development in areas such as the Longquan Mountains and the Jinjiang ecological belt, which could form the focus of ecological network optimization in the study area. The number of green patches in the central and southern areas was large and scattered, the number of important corridors in the east and south was the largest, and the number of important corridors in the west was the lowest.
2. In the optimal green space ecological network with functional connectivity, there were 40 pinch points, 48 protective sources, and 176 important ecological corridors in the study area, involving forest land, grassland, etc. There were obvious regional differences in functional connectivity corridors. In particular, there were relatively few functional connectivity corridors between Longquan Mountain and the central urban area, and more barriers overlapped with different types of urban construction land. According to the resistance value of barrier points, it was divided into high-level restoration areas covering 27.93 km^2, medium-level restoration areas covering 166.94 km^2, and low-level restoration areas covering 240.92 km^2. The division of the

restoration area is important for the sequential construction of Chengdu's central urban area.

3. Through the analysis of the coupling effect of landscape structural and functional connectivity, the ecological network of composite green space was composed of 114 stepping stone patches, 91 important protection patches, and 446 ecological corridors. Longquan Mountain, Qinglong Lake Wetland Park, Jinma River, Pihe River, and other patches play an important role both in structural and functional connectivity. There were many overlapped stepping stones and corridors in the central area of the city. By comparing the connectivity of the three different types of optimized green space ecological networks, the α index, β index, γ index, and $C\gamma$ index of ecological networks with coupling structural and functional connectivity were 0.61, 2.21, 0.74, and 0.82, respectively, and its connectivity was the best by comparing to the other ecological network.
4. A ring network optimization security pattern of one center, two belts, multiple points, multiple corridors, and multiple zones connected in series was proposed, which provides spatial guidance for urban ecological protection planning. It was suggested to build a multi-level forest and multi-type composite forest ecosystem in Longquan Mountain, strengthen the conservation of vegetation resources and biodiversity, and develop eco-fruit agriculture and eco-tourism. Increasing the protection radiation range of ecological sources can improve its anti-interference ability to the external environment. A buffer zone can be set around key strategic points to alleviate the interference of human activities on strategic points in the process of urban development. It is important to strictly control the development mode and construction intensity of ecological corridors with synergistic effects and set up diversified corridor protection modes. In the process of ecological restoration, based on the current situation of urban land use and the development and construction planning of Chengdu, the feasibility of ecological restoration area construction should be reasonably assessed, and corresponding supplementary and coordinated policies should be made. The use of cultivated land in different regions should be properly handled, the protection of cultivated land should be given priority, and the integrity and diversity of ecological sources should be maintained.

It should be noted that this study uses circuit theory to identify all potential functional corridors and analyze their relative importance, providing a simple and feasible methodological framework for the construction and optimization of urban green space ecological networks. However, the circuit theory model abstracts and simplifies the migration parameters of species in heterogeneous landscapes, so it is necessary to further observe the migration characteristics of different species and use experimental data to modify the model to improve the accuracy of the circuit theory simulation. On the other hand, the dynamic changes in urban landscape patterns and the spatial scale effect will also have an important impact on the spatial connectivity of green space. This study did not fully reflect the dynamic coupling relationship between structural and functional connectivity, and it is necessary to continuously explore diversified model methods to track the coupling relationship between them so as to promote the optimization of green space ecological security patterns. At the same time, the green space ecological network is multi-scale. It is of great practical significance for the implementation of ecological networks to pay attention to the coupling and connection of multi-spatial and temporal scales of green space ecological networks and select appropriate spatial scales for research. Therefore, we will analyze the landscape dynamic change trend and multi-scale change process in the next research work, clarify the relationship between green space ecological network pattern and ecological process at different scales, and reveal the internal causes (changes in the total amount, distribution characteristics of green space, etc.) and external causes (the impact of government decisions on the expansion of green space). This paper provides an important reference for the construction and optimization of a composite green space ecological network.

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