Li *et al. Ecol Process (2021) 10:63*
https://doi.org/10.1186/s13717-021-00332-2

Ecological Processes

RESEARCH
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Integrating morphological spatial pattern analysis and the minimal cumulative resistance model to optimize urban ecological networks: a case study in Shenzhen City, China

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Abstract

Background: With the increasing fragmentation of landscape induced by rapid urbanization, the construction of ecological networks is of great significance to alleviate the degradation of urban habitats and protect natural environments. However, there is considerable uncertainty when constructing ecological networks, especially the different approaches to selecting ecological sources. We used the southern Chinese city of Shenzhen as a study area to construct and optimize ecological networks using a coupling approach. Ecological source areas were extracted using morphological spatial pattern analysis (MSPA) and the landscape index method. Ecological networks were constructed using the minimal cumulative resistance (MCR) model and the gravity model. Stepping stones and ecological fault points were added in corridors to optimize the ecological network.

Results: Ten core areas with maximum importance patch values were extracted by the landscape index method as ecological source areas according to MSPA, after which corridors between ecological sources were constructed based on the MCR model. The constructed ecological networks were optimized using 35 stepping stones and 17 ecological fault points. The optimized ecological networks included 11 important corridors, 34 general corridors, and seven potential corridors. The results of corridor landscape-type analysis showed that a suitable ecological corridor is 60 to 200 m wide.

Conclusions: Overall, our results imply that ecological source areas can be identified virtually, and that ecological networks can be significantly optimized by combining MSPA and MCR models. These results provide a methodological reference for constructing ecological networks, and they will be useful for urban planning and biodiversity protection in Shenzhen and other similar regions around the world.

Keywords: MSPA analysis, MCR model, Ecological corridor, Ecological resistance surface, Shenzhen City

Introduction

Since the twentieth century, urbanization induced by increasing population migration has dramatically altered land-cover patterns, resulting in the fragmentation of landscapes and the deterioration of ecosystems (Carrete et al. 2009). This poses a threat to ecological security around the world (Su et al. 2016; Ng et al. 2018). Natural ecosystems have become impervious surfaces under the intensive pressure of anthropogenic activities (Alberti 1999). This process has radically changed the flow paths of material and energy and it has degraded habitat quality (Liu et al. 2017; Oliveira et al. 2018). As a result, urban

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ecological fragmentation and degradation has become an increasingly serious challenge. It increases patch islanding, reduces landscape connectivity, and hinders the ecological functioning of ecosystems (Saunders et al. 1991; Heller and Zavaleta 2009) which causes inducing diverse eco-environmental problems such as biodiversity loss, heat islands, air pollution, and urban waterlogging (Steeneveld et al. 2011; Cheng et al. 2018). Methods of balancing urban development and ecological restoration must be explored urgently.

The ecological network, as an ecological security pattern based on the optimization theory of landscape patterns, has been regarded as an effective approach to achieve a sustainable landscape within a fragmented urban environment (Opdam et al. 2006; Blasi et al. 2008; Estrada-Carmona et al. 2019). An ecological network consists of ecological sources (including core areas and buffer zones), ecological nodes, and ecological corridors, which constitute a network system for connecting space (Bascompte 2010; Cui et al. 2020). Fragmented habitats can then be connected by the ecological networks, facilitating material and energy circulation, and strengthening the structural stability of the ecosystem (Cunha and Magalhaes 2019). Accordingly, the construction and application of ecological networks have been widely studied for diverse purposes, such as protecting species biodiversity (Opdam et al. 2006; Baguette et al. 2013), optimizing urban green space (Kong et al. 2010; Cui et al. 2020), evaluating urban ecological risk (Zhang et al. 2020), formulating sustainable land-use policy (Vuilleumier and Prelaz-Droux 2002; Yang et al. 2020), and maintaining regional ecosystem services (Peng et al. 2019).

Even though a number of approaches have been introduced for constructing ecological networks, such as island biogeography theory (Ahern 1995), metapopulation theory (Opdam et al. 1995), circuit theory (McRae et al. 2008), source–sink theory (Liu and Chang 2015), graph theory (Peng et al. 2017), and habitat suitability models (Dondina et al. 2018; Piri Sahragard et al. 2021), the results of different methods vary widely (Théau et al. 2015). By contrast, the minimum cumulative resistance (MCR) model has been favored in many previous studies due to its operability and practicality (Peng et al. 2017; Tang et al. 2020; Zhang et al. 2021). It was developed based on source–sink theory, and has been widely used to construct ecological networks. It offers advantages in terms of identifying ecological sources, calculating resistance surfaces, and extracting ecological nodes and corridors using GIS-based technology (Kong and Yin 2008). The MCR model can also comprehensively couple many factors, such as terrain, landforms, environment, and human disturbance; it uses relatively little data, and offers map-expressed results. As such, it has become a mainstream tool for constructing ecological networks (Peng et al. 2018). For example, Dai et al. (2021) integrated the MCR and the Duranton and Overman Index (DOI) to construct an ecological security network of urban agglomeration around Poyang Lake in China. Yang et al. (2018) used the MCR model to construct an ecological network in Guangzhou City and provided scientific guidance for urban planning and design. However, the selection of ecological sources, which is a key step in constructing an ecological corridor, has been regarded subjectively in many previous studies. New methods are needed that can objectively identify ecological sources based on a comprehensive index system (García-Feced et al. 2011; Ersoy et al. 2019). The morphological spatial pattern analysis (MSPA) approach, which is based on the use of binary graphs in the recognition process, can accurately identify ecological sources objectively based only on land-cover data. This approach has since been widely used in ecological network analysis (Vogt et al. 2009; An et al. 2021). This method was designed to divide the foreground into seven classes of patterns (viz., the core area, edge, bridge, branch, loop, perforation, and islet) to identify the spatial pattern needed to sustain landscape connectivity. This enhances the rationality of selecting ecological sources and offsets the disadvantages of the MCR model (Clerici and Vogt 2013; Peng et al. 2017). The MSPA method and MCR model are both based on the phase element level, are theoretically useful, and can accurately reflect the characteristics of landscapes. Combining these two method can improve the efficiency of ecological planning. This is a promising means of constructing and optimizing ecological networks.

Ecological corridors and so-called stepping stones are the two main strategies used to connect important patches in ecological networks (Lynch 2019). Currently, most studies in this area have been conducted from the perspective of ecological corridor. The optimization of ecological networks from the perspective of stepping stones has been neglected (Dai et al. 2021; Luo et al. 2021). Ecological stepping stones are small habitats that can act as corridors for the movement of biological species in the natural landscape (Saura et al. 2014). In fragmented cities, stepping stones have become a vital scheme of connectivity, by offering habitats that are more practical and conducive to urban ecosystems (An et al. 2021; Luo et al. 2021). Therefore, stepping stones should be identified and considered when constructing and optimizing urban ecological networks, even though relevant case studies are still lacking.

Shenzhen City the first Special Economic Zone of China, established in 1979 has undergone fast economic growth and rapid urbanization since the Reform and

Opening-up of China. Once a small town, it is now one of the main economic centers in China (Song et al. 2021). With rapid urban expansion, land-use change has been unprecedented, leading to serious deterioration of the ecological and environmental quality of the atmosphere, vegetation, soil, and water (Shi and Yu 2014; Yi et al. 2018). Among these impacts, landscape fragmentation induced by urban development has recently become increasingly prominent (Peng et al. 2015; Liu et al. 2020). For example, Gong et al. (2013) found that urban forest fragmentation was extremely serious in Shenzhen, with urban structural changes triggered by an industry-related economic boom and the increasing migrant population. Moreover, biodiversity, such as migratory bird habitats, has greatly decreased in recent decades (Liu et al. 2020). The Shenzhen government has adopted a series of policies for improving green infrastructure, such as demarcating the first eco-control line in China and implementing urban green belt systems since 2005 (Song et al. 2021). Recently, an increasing number of researchers have sought to protect ecological landscapes or construct ecological security patterns based on various methods (Peng et al. 2015; Liu et al. 2020; Zhang et al. 2021). To our knowledge, however, a clear ecological network of local landscape features is still lacking for this astonishing city. Therefore, Shenzhen City was selected as the study area with the following objectives: (1) classifying landscape types and identifying ecological landscape patterns by MSPA analysis; and (2) constructing and optimizing the ecological network by coupling MSPA analysis and the MCR model. This research can serve as a methodological reference for constructing ecological networks, and the results can be meaningful for urban planning in Shenzhen and other similar cities around the world.

Materials and methods

Study area and data sources

Shenzhen (22° 26′–22° 51′ N, 113° 45′–114° 37′ E) is a coastal megacity located in the Pearl River Delta in southern China (Fig. 1). The land area of this city is about 1997.47 km^2, with a total coastline of 260 km. The city is situated in a subtropical marine climate zone, with an average mean temperature of 22.4 °C and an average mean annual precipitation of 1933 mm (Yu et al. 2015). The total number of sunshine hours is 2011 per year. Shenzhen is also rich in plant resources and wild animals. Zonal vegetation types include tropical evergreen monsoon forests in the south and subtropical seasonal evergreen broadleaf forests in the north (Shi and Yu 2014). There are 509 species of terrestrial wild animals, including 31 amphibians, 76 reptiles, 366 birds, and 36 mammals, with 83 species of first and second-class key animals under state protection and 55 species under provincial protection. The soil types are latosolic red soil, paddy soil, coastal sand, and coastal saline marsh soil.

The data used in this research included the following main components: land-cover data with 30 m spatial resolution in 2017 produced by a Tsinghua University research team that have been verified and widely applied in many studies (http://data.ess.tsinghua.edu.cn/) (Gong et al. 2019), ASTER GDFM elevation data with 30 m resolution (Geospatial data cloud sites, http://www.gscloud.cn/), the administrative boundary vector map of Shenzhen (Resources and Environmental Science Data Center, Chinese Academy of Sciences, http://www.resdc.cn/), and a high-definition urban road network map of Shenzhen (http://www.bigemap.com/).

The vector map of the administrative boundary of Shenzhen was used to select land-cover data, yielding a land-cover map of Shenzhen. Seven landscape types were obtained through reclassification using raster values (Fig. 1): cropland, forest, grassland, shrub, water area, impervious area, and bare land. Using the surface analysis function in the Spatial Analyst tool of ArcGIS 10.2, a slope value distribution map of the study area was generated. Based on the road network data of the BIGEMAP downloader, the highways, railways, and general roads of the study area were vectorized in ArcGIS 10.2.

Landscape pattern analysis and identification of ecological source areas

The MSPA approach was used to analyze the land-cover data in 2017 (Fig. 2). Based on land-cover maps of the study area, forest was used as the foreground for MSPA, and other land-cover types were used as the background. The data were then converted to a 30 × 30 m binary raster in “.tiff” format. The eight-neighborhood analysis method was used to analyze the landscape pattern in Guidos 2.6, and seven landscape types were obtained: branch, edge, perforation, islet, core, bridge, and loop.

The landscape-type diagrams were overlaid with the Intersect module in ArcGIS 10.2, and the areas of the eight landscape categories were determined. To analyze the morphological features of the landscape, Fragstats 4.2 software was used to calculate the landscape pattern indices of the core areas obtained through MSPA analysis. The shape, density, and edge indices of the patches in the core area were calculated, including patch density (PD), largest patch index (LPI), landscape shape index (LSI), interspersion and juxtaposition index (IJI), patch cohesion index (PCI), and aggregation index (AI).

Conefor 2.6 software was used to calculate the landscape connectivity index of the core area, considering the 40 largest patches that had been extracted. With reference to previous studies (Zhu et al. 2005; Yang et al. 2018;

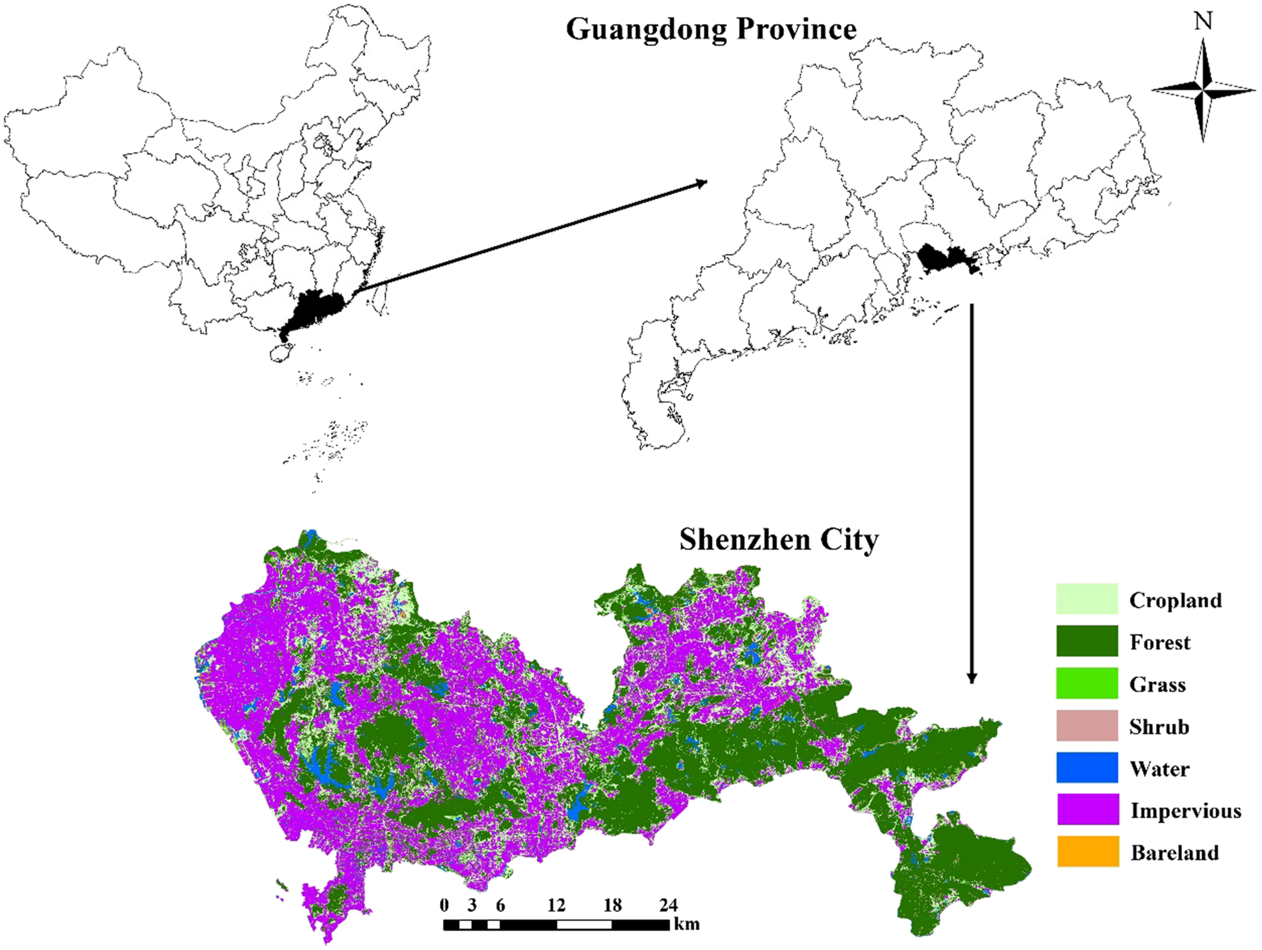

Fig. 1 Location and land-cover of the study area. The top-left subgraph shows an administrative map of China and the geographical location of Guangdong province. The top-right shows an administrative map of Guangdong province and the geographical location of Shenzhen City. And the bottom map shows land-cover in Shenzhen City

Liu et al. 2020), the threshold value of the patch connectivity distance was set to 1000 m, and the probability of connectivity was set to 0.5. The importance values of a patch (dPC) of the evaluation results were ranked and ten core patches with the highest dPC values were selected as the ecological source areas of Shenzhen based on the integral index of connectivity (IIC) and probability of connectivity (PC). The geometric center of each ecological source was also calculated as the ecological source point using ArcGIS 10.2 software.

Construction of the ecological resistance surface

The resistance surface has a major impact on the simulation of corridors (Graves et al. 2014), and accurate calculation remains challenging (Xiao et al. 2020). Since the resistance surface may be influenced by multiple factors, a system of evaluation indices was established by considering two groups of variables: natural conditions and human interference. Natural conditions were represented by elevation, slope, and land-use type, while human interference was mainly expressed as an obstacle in the outward development of the ecological sources. We chose the distance from the road to reflect this resistance (Dai et al. 2021). In addition to land-cover type, resistance was then classified into five grades using quantile classification. We used 1–5 to represent the different levels of resistance, with 1 being the lowest and 5 the highest as a subjective determination (Peng et al. 2018). Rare and endangered species in Shenzhen include certain amphibians, reptiles, and birds. Therefore, the resistance of the land-cover type was set mainly by considering terrestrial animals (Zhang et al. 2021). Forest land was assigned the lowest value of 1 because it had the highest vegetation coverage and least human interference, and grassland ranked second, with a score of 2, due to its coefficient

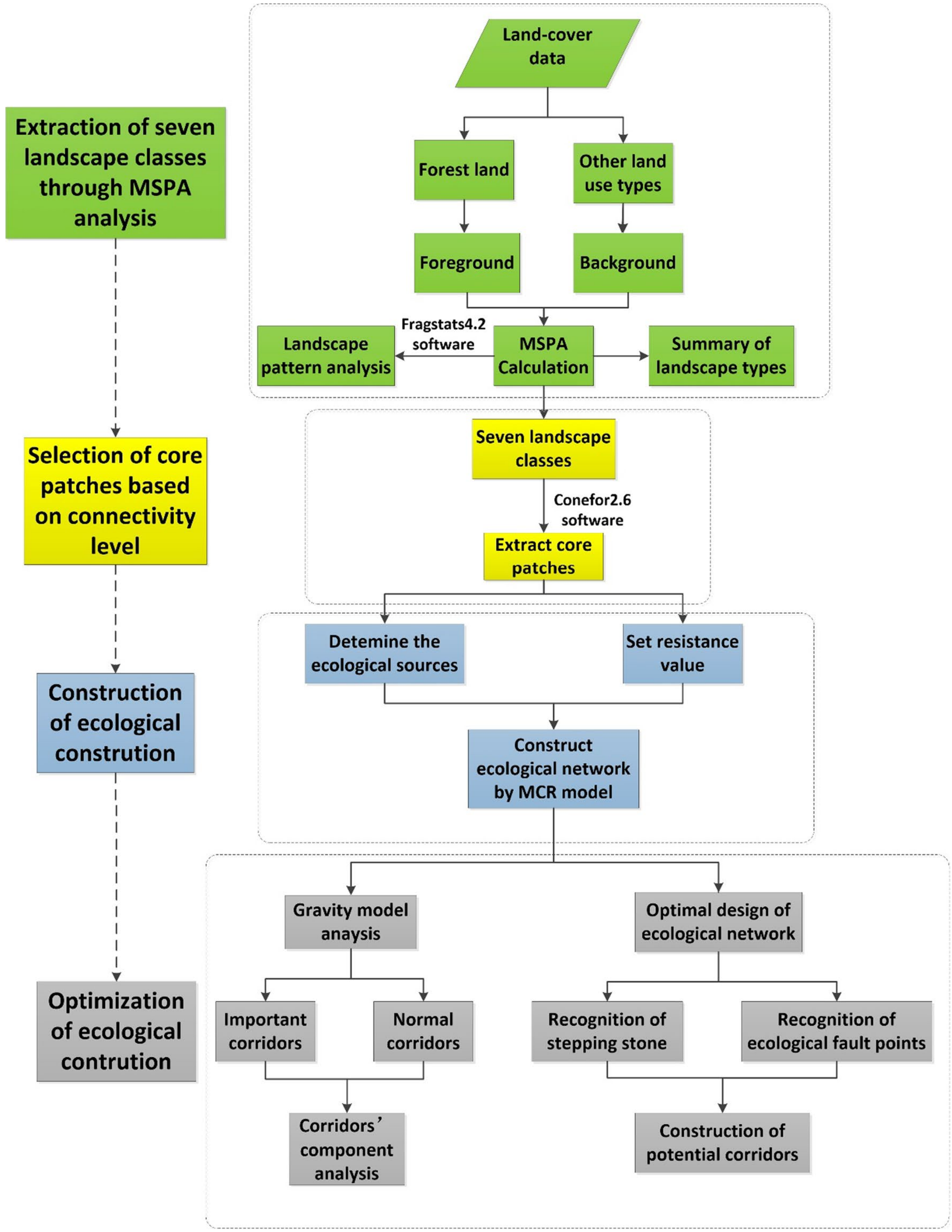

Fig. 2 Flow diagram describing the workflow for constructing and optimizing ecological networks in Shenzhen City. *MSPA* morphological spatial pattern analysis, *MCR* minimal cumulative resistance

of ecological resistance. The vegetation coverage of farmland and other land type was inferior to that of grassland, and they were assigned values of 3 and 5, respectively. The resistance coefficient of water body was set to 6. Built-up land in Shenzhen City is highly affected by human disturbance owing to little vegetation coverage. As such, its resistance coefficients were set to the highest value of 8 (Peng et al. 2018). Due to the characteristics of the animal species and geographical features of Shenzhen, most terrestrial wild animals are not sensitive to slope and elevation. Land-cover type and road distance reflected the disturbance caused by human activities to the natural environment. We set the weights of the four resistance factors of land-cover type, slope, road distance, and elevation to 0.34, 0.29, 0.21, and 0.06, respectively, based on past studies (Jiang et al. 2016; Yang et al. 2018). The assignments and weights are listed in Table 1. The raster calculator function of ArcGIS 10.2 was used to determine the ecological resistance of each point in the study area through a weighted calculation, and this was used to obtain the ecological resistance surface of the study area.

The minimum cumulative resistance (MCR) model was applied by using the distance analysis function in ArcGIS 10.2 to calculate the minimum cost path from each ecological source area to other ecological sources in turn. A total of 45 ecological corridors were constructed. The MCR model is calculated as follows (Knaapen et al. 1992):

$$MCR = f_{\min} \sum\nolimits_{j=m}^{i=m} \left(D_{ij} \times R_i \right), \tag{1}$$

where MCR is the resistance of a potential corridor between two habitat patches, f is an unknown positive function that represents the positive correlation between the minimum resistance at any point in the space and its distance to all sources and the characteristics of the landscape base surface, D_{ij} is the number of raster unit between two habitat patches, and R_i is the resistance of a raster type.

Table 1 Grading values and weights of resistance factors for the construction of an ecological resistance surface

Resistance factor	Classification index	Resistance value	Weight
Elevation (m)	< 200	1	0.06
	200–400	2	
	400–600	3	
	600–800	4	
	> 800	5	
Slope (°)	0–3	1	0.29
	3–10	2	
	10–20	3	
	20–30	4	
	> 30	5	
Road distance (m)	> 2000	1	0.21
	1500–2000	2	
	1000–1500	3	
	500–1000	4	
	< 500	5	
Land-cover type	Forest land	1	0.34
	Grassland	2	
	Farmland	3	
	Other land	5	
	Water area	6	
	Built-up land	8	

Evaluation and optimization of the ecological network

The ecological networks were evaluated based on a gravity model, which was constructed between pairs of the ten ecological sources extracted before. The formula of the gravity model is as follows (Kong and Yin 2008):

$$G_{ab} = k \times \frac{N_a N_b}{D_{ab}^2} = \frac{L_{\max}^2 \ln(S_a S_b)}{L_{ab}^2 P_a P_b}, \tag{2}$$

where G_{ab} is the interaction between patch A and patch B, N_a and N_b are the weights of the two patches, D_{ab} is the standardized value of potential corridor resistance between patch A and patch B, P_a and P_b are the resistance values of patch A and patch B, respectively, S_a and S_b are the areas of patch A and patch B, respectively, L_{ab} is the cumulative resistance value of the corridor between patch A and patch B, and $L_{\max}$ is the maximum resistance of all corridors in the study area.

According to the gravity model formula, the interaction intensity of each ecological corridor was calculated. Ecological corridors with an interaction intensity greater than 0.3 were identified as important corridors, whereas ecological corridors with an interaction intensity less than 0.3 were identified as general corridors (Yang et al. 2018).

The ecological network of the study area was optimized by selecting stepping stone patches, constructing potential corridors, and identifying ecological fault points. The minimum cumulative resistance model was applied to the stepping stone patches again to obtain the potential corridors. The optimized ecological network was evaluated and compared with the original ecological network using corridor network structure analysis by calculating the network closure index (α), network connectivity degree index (β), and the network connectivity rate index (γ) (Chen and Chen 2016; Yang et al. 2018). Higher values in these three indices mean better connectivity of the ecological network. The formulae for these are as follows:

$$\alpha = \frac{L-V+1}{2V - 5}, \tag{3}$$

$$\beta = \frac{L}{V}, \tag{4}$$

$$\gamma = \frac{L}{3(V-2)}, \tag{5}$$

where L represents the number of corridors, and V represents the number of nodes.

Table 2 Analysis of the landscape pattern index in Shenzhen City

Landscape pattern index	Value
PD	1.52
LPI	6.34
LSI	52.00
IJI	28.00
PCI	99.29
AI	93.92

PD patch density, *LPI* largest patch index, *LSI* landscape shape index, *IJI* interspersion and juxtaposition index, *PCI* patch cohesion index, *AI* aggregation index

Results

Landscape pattern analysis

The analysis of the spatial patterns of the landscape showed that the core area with potential ecological sources occupied 29.28% of the total area of Shenzhen City while the background accounted for 61.36% (Fig. 3). The remaining six landscape types occupied less than 10%. Moreover, the spatial distribution of the core area was fragmented, with a low degree of connectivity that was also reflected in the results of the landscape index analysis (Table 2).

Construction of the ecological network

Ten ecological sources were identified in Shenzhen (Fig. 4) according to the importance values of the patch (dPC) (Additional file 1: Table S1). The core patches with the best connectivity were mainly concentrated in the southeast of the study area, with significantly higher dPC values than other ecological sources. Ecological sources with numbers 1, 2, 3, 4, 9, and 10 were composed of rural forest, and the rest were mainly in urban greenbelt areas (Additional file 1: Table S1).

The ecological resistance surface of the study area was then built based on the resistance values of each point (Fig. 5). The results showed that the resistance values in the western part of the study area were significantly higher than those in the eastern part, and those in the eastern part of the city were mostly lower than 1. Several ecological patches in the west were obviously isolated.

The intensity of the interaction among the ten ecological sources was simulated by the gravity model. The results showed that ecological corridors with strong interaction (a gravity value greater than 0.3) were mainly concentrated in patch numbers 2, 3, 4, 7, and 10 in the eastern part of the study area, which could be classified

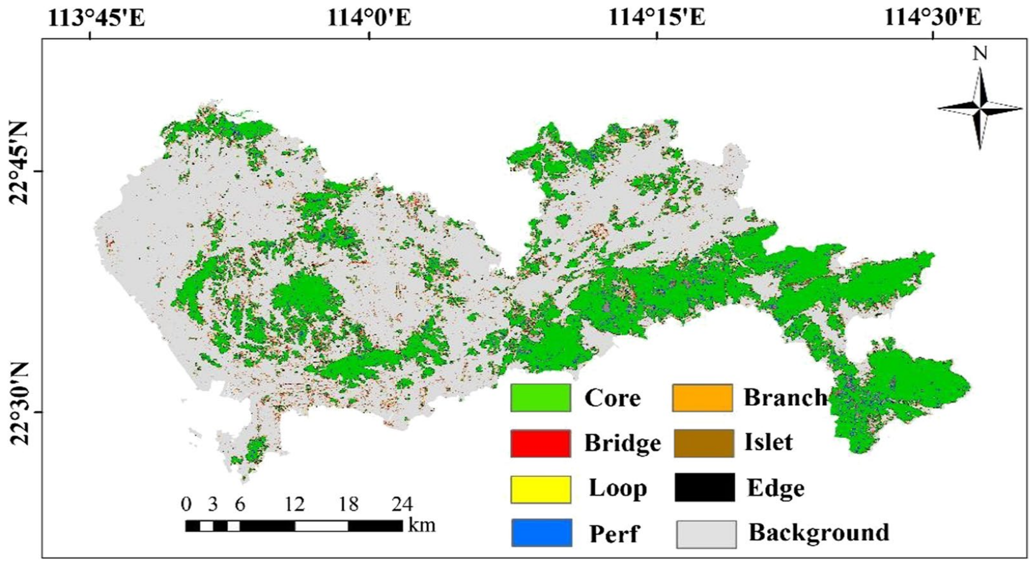

Fig. 3 Spatial distribution of landscape patterns (e.g., Core, Bridge, Loop, Perf, Branch, Islet, Edge, and Background) in Shenzhen City

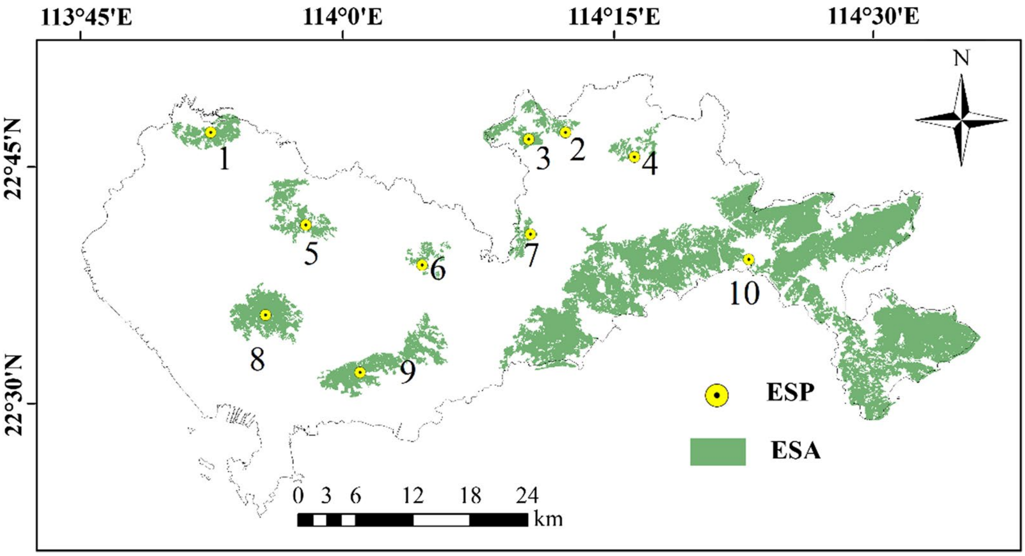

Fig. 4 Distribution of ecological sources in Shenzhen. Numbers from one to ten mark the locations of the ten ecological sources. *ESP* ecological source point, *ESA* ecological source area

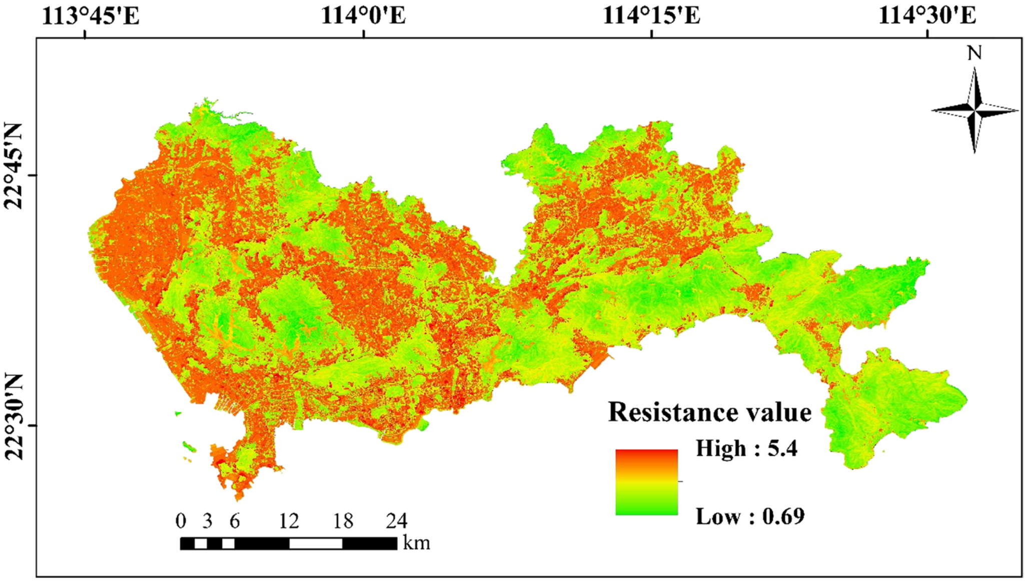

Fig. 5 Ecological resistance surface of the study area. The color from green to red denotes the resistance value ranging from low to high

as important corridors (Table 3, Fig. 6). Eleven important corridors were identified, and the number of general corridors was 34, with gravity values less than 0.3.

Optimization of the ecological network

Stepping stone patches, by serving as small patch habitats, have the potential to provide temporary habitats for animals. A total of 35 stepping stones were selected in this study. They can be useful for optimizing ecological corridor paths, improving the integrity of the network, and increasing its ecological benefits (Fig. 7). Another seven potential corridors were added to increase the connectivity of ecological sources after optimizing the ecological network. An ecological fault point is an area where the resistance on the path of an ecological corridor is particularly high. Seventeen ecological fault points were identified based on the resistance surface and the actual situation in the

Table 3 Calculated interaction matrix of each ecological source based on the gravity model. Ecological corridors with an interaction intensity greater than 0.3 were identified as important corridors

Ecological core number	1	2	3	4	5	6	7	8	9	10
1	0	0.0073	0.0059	0.0044	0.0585	0.0278	0.0117	0.0307	0.0161	0.0044
2		0	8.0311	2.8272	0.2033	0.4344	2.1003	3.3567	0.3145	0.6245
3			0	0.9697	0.1141	0.2516	1.3222	0.1521	0.1799	0.2837
4				0	0.0936	0.2077	0.6596	0.1229	0.1594	0.9185
5					0	0.0439	0.0117	0.0775	0.0205	0.0044
6						0	0.0395	0.0293	0.0234	0.0102
7							0	0.0132	0.0234	0.0263
8								0	0.0804	0.0059
9									0	0.0073
10										0

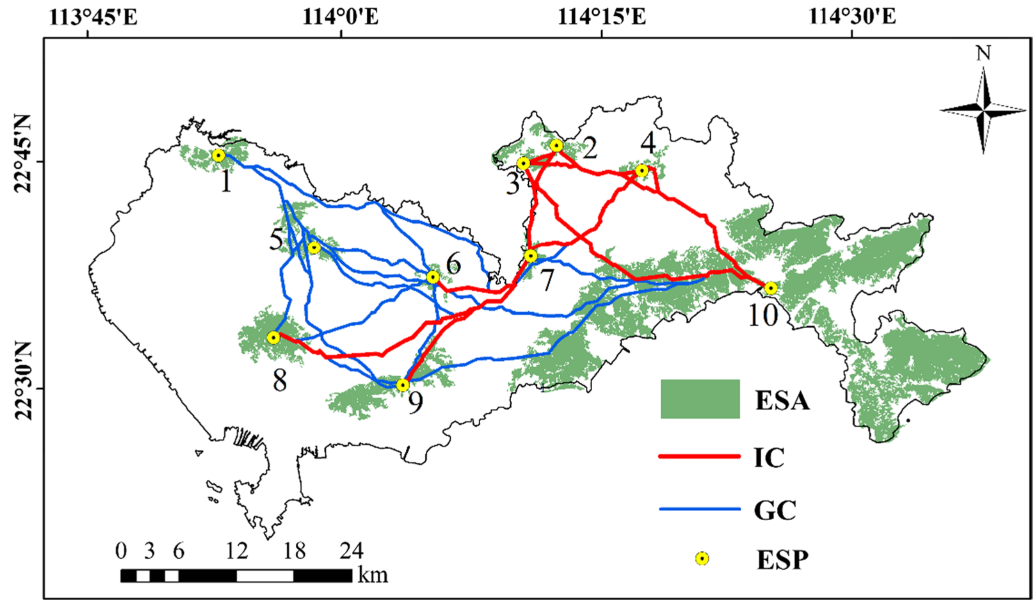

Fig. 6 Distribution of ecological corridors in the study area. Numbers from one to ten mark the locations of the ten ecological source points. *ESP* ecological source point, *IC* important corridor, *GC* general corridor, *ESA* ecological source area

study area (Fig. 7). The analysis of the corridor network structure showed that the indices of α, β, and γ all increased compared with the initial results (Additional file 1: Table S2), which indicated that the degree of connection of the ecological sources improved after optimization.

From the results for the landscape composition of ecological corridors, the area of forest continuously decreased, but the area of built-up land significantly increased with wider corridors in the study area (Table 4). For example, when the widths of the corridors were 60 and 200 m, forest and grassland occupied 74.14% and 71.69% of the total area, respectively. But when the corridor width increased to 1200 m, they occupied only 60.86% each. Changes in corridor width had no prominent effects on the area of cropland and water area.

Discussion

The optimized results obtained for the ecological network by coupling the MSPA and MCR approaches in Shenzhen City showed that important corridors with strong interaction (a gravity value greater than 0.3) were mainly concentrated in patches 2, 3, 4, 7, and 10 in the eastern and northern parts of the study area (Figs. 6 and

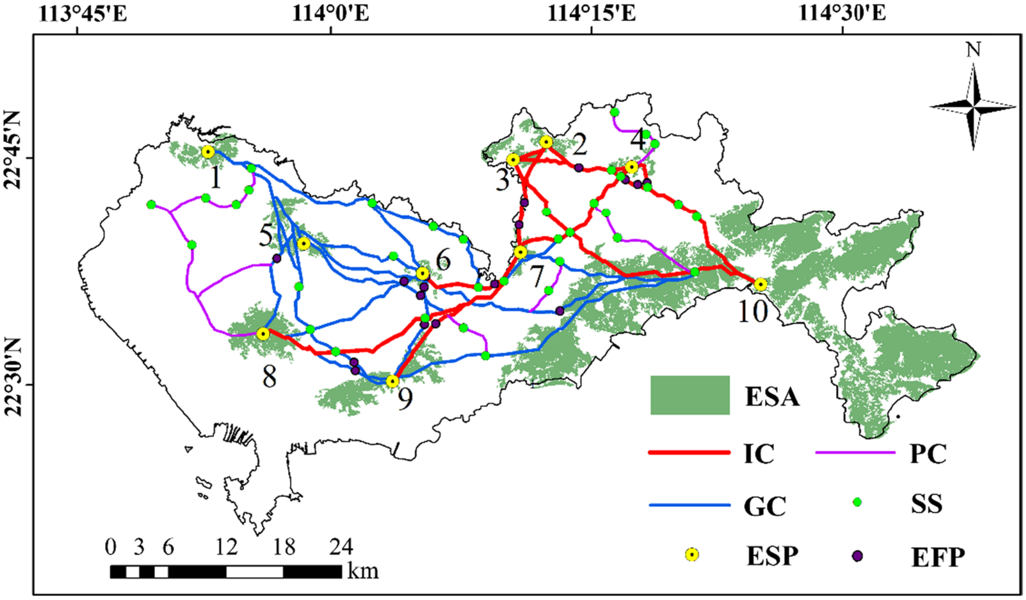

Fig. 7 Optimized ecological networks based on the stepping stones and ecological fault points in Shenzhen City. Numbers from one to ten mark the locations of the ten ecological source points. ESP, ecological source point; ESA, ecological source area; IC, important corridor; GC, general corridor; PC, potential corridor; SS, stepping stone; EFP, ecological fault point

7). This result was consistent with the findings of Deng et al. (2017), who found similar patterns of secondary ecological corridors classified according to the importance of ecological corridors in Shenzhen. Forests in the southeastern and northern parts of the city were well preserved (Fig. 7, Table 4), and can provide a large habitat for wild animals to constitute the ecological source in the east (Peng et al. 2015; Song et al. 2021). Forest lands in the west mostly comprise urban green spaces preserved during urban planning and are adjacent to dense road networks and residential areas, which means that the extracted ecological sources were relatively small. The ecological patches in the western part are highly isolated, with long distances between patches and high ecological resistance. Some corridors to be traversed involve urban roads and residential and commercial areas.

Overall, it was evident that the ecological network constructed in this study covered most of the scenic spots, nature reserves, forest parks, wetland parks, and country parks that need to be protected in urban land planning. Compared with the outline of the Pearl River Delta greenway network master plan for the Shenzhen section (Fig. 8), both the east–west corridor that was constructed and the potential corridor within the Baoan district in the west have a high degree of fit with the Pearl River Delta No. 2 Greenway (Housing and Urban–Rural Development Department of Guangdong Province in PRC, 2010). Pearl River Delta No. 5 Greenway coincides with some of the ecological breakpoints extracted in this study which require attention on when building corridors. The ecological network planned in this research resembles the existing urban greenway system, which is conducive to collaborative construction of a greenway–ecological network urban ecological system. These results can improve our understanding of the ecological patterns of urban ecosystems, and offer useful guidance for the construction of urban green infrastructure.

The setting of the ecological resistance surface determines the path direction of the ecological corridors (McRae et al. 2008; Yang et al. 2018). We used a comprehensive weighted index sum to determine the coefficient of resistance by comprehensively considering the influence of land-cover type, elevation, slope, and road network and combining the environmental characteristics of Shenzhen City. This method can better simulate the characteristics of flat terrain, low altitude, and dense road networks in Shenzhen. Built-up land and areas with water are regarded as insurmountable barriers for wild animals, with high resistance values, but the resistance values of forest land and cultivated land are lower. The urban road network is regarded as an important factor affecting wildlife movement, and the resistance value was therefore set according to the distance from the road network. The results of source extraction showed that the ecological sources of Shenzhen were concentrated in the southeastern part where large areas of ecological sources were found. The large ecological sources on the fringes

Table 4 Area and percentage of landscape composition with different ecological corridor widths in Shenzhen City

CW/m	Forest		Grassland		Cropland		Water area		Construction land		Others	
	Area (km^2)	Percentage (%)	Area (km^2)	Percentage (%)	Area (km^2)	Percentage (%)	Area (km^2)	Percentage (%)	Area (km^2)	Percentage (%)	Area (km^2)	Percentage (%)
60	1022.17	54.89	358.48	19.25	89.94	4.83	46.56	2.50	341.90	18.36	3.17	0.17
200	984.74	52.88	350.48	18.81	91.43	4.91	49.35	2.65	383.24	20.58	3.17	0.17
600	867.04	46.56	347.30	18.65	90.32	4.85	55.49	2.98	497.58	26.72	4.47	0.24
1200	788.22	42.33	345.18	18.54	87.84	4.72	50.5	2.71	584.54	31.39	5.93	0.32

CW corridor width

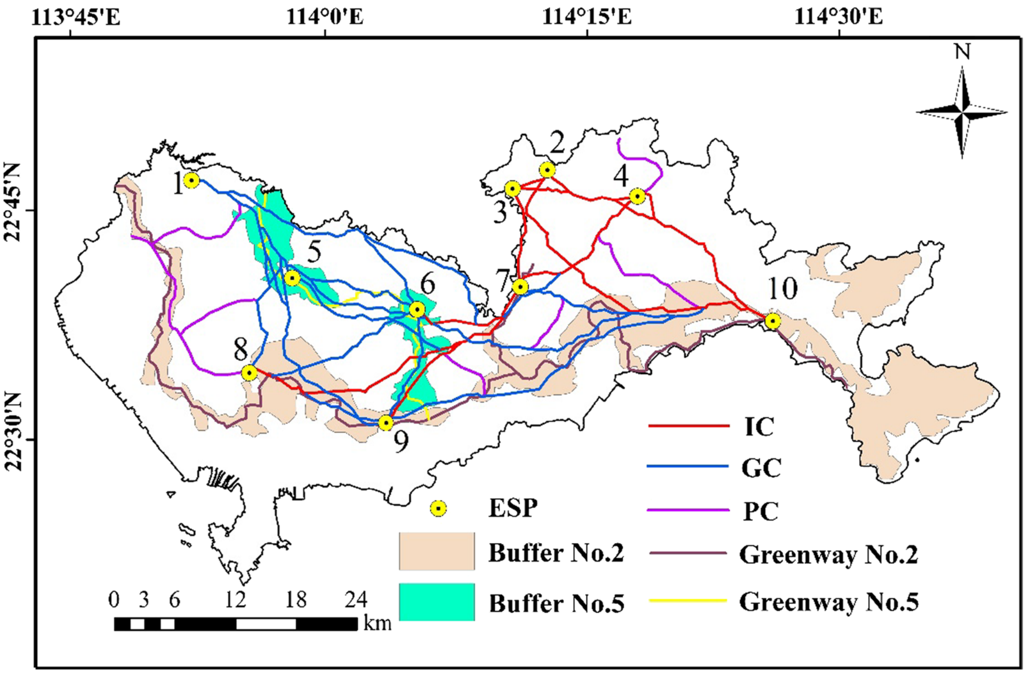

Fig. 8 Optimized ecological networks overlaid on the greenway network of the Pearl River Delta in Shenzhen City (revised from the Housing and Urban–Rural Development Department of Guangdong Province in PRC (2010)). Numbers from one to ten mark the locations of the ten ecological source points. ESP ecological source point; IC, important corridor; GC, general corridor; PC, potential corridor

of these areas are objects that need to be protected during urban expansion. The essence of constructing an ecological network in Shenzhen City is to use the small ecological source areas downtown to connect the large ecological source areas in the suburbs.

According to the landscape composition of ecological corridors detailed in Table 4, as the width of a corridor increases, the proportion of woodland in the corridor decreases continuously, and the proportion of built-up land increases. An increase in built-up area is not conducive to species diffusion and migration, and increases the difficulty of constructing ecological sources (Dondina et al. 2018; Ersoy et al. 2019). Based on previous studies, a 60-m corridor can meet the migration needs of birds and other small mammals and has a certain practical value because the area of built-up land is less than 20% (Zhu et al. 2005; Yang et al. 2018). For example, Liu et al. (2020) suggested building three-dimensional key corridors with widths of 61–100.6 m in Shenzhen City based on the priorities of migratory birds. A 200-m-wide ecological corridor would form an internal habitat and accommodate larger mammals; a 600-m corridor would better maintain the ecological diversity of species, but the construction difficulty and cost would greatly increase. A 1200-m ecological corridor would better simulate the living environment in the wild, which is an ideal condition for the protection of wild animals. However, when the corridor reaches a width of 1200 m, the proportion of built-up land inside that corridor exceeds 30%, making the corridor unsuitable for constructing ecological networks. Therefore, the short-term goal of the research area should be to build ecological corridors with a width of 60 to 200 m to meet the needs of small mammals and maintain biodiversity. Important corridors are not only the main framework of an ecological network, but also the most important passage for wildlife migration and movement, which need to be protected.

The ecological corridor planned in this study is in line with the "Four Belts and Six Corridors" ecological corridor system planned by the Shenzhen municipal government, and it coincides with the path of the urban greenway. Among these corridors, the continuous natural area between the central and northern urban areas and the corridor composed of reservoirs and mountains is well connected, but the ecological source area in the northwestern part of the study area is not well connected. Moreover, the connectivity of the whole ecological corridor between the east and west is poor, and the links between ecological sources are not short enough. Future ecological engineering projects should focus on restoring ecological breakpoints and increasing the connectivity of ecological corridors. It will also be necessary to use stepping stone patches as much as possible and improve the ecological network system to better connect ecological sources. At the same time, the ecological network should be coupled and properly embedded on a larger scale to form a complete ecological network system.

Conclusions

This study took the highly urbanized Shenzhen City as a case study, and integrated morphological spatial pattern analysis and the minimal cumulative resistance model to construct and optimize ecological networks for the city. Ten core areas with the maximum dPC values were extracted by the landscape index method as ecological source areas according to the MSPA method, after which corridors between these ecological sources were constructed based on the MCR model. The constructed ecological networks were optimized using 35 stepping stones and 17 ecological fault points. The optimized ecological networks include 11 important corridors, 34 general corridors, and seven potential corridors. The results of corridor landscape-type analysis showed that when the corridor width was between 60 and 200 m, the area of forest land was sufficiently large, and the corridor was ecologically suitable. This width is only suitable for the survival of small mammals and to maintain the most basic level of ecological diversity. These results can provide important guidance for biodiversity protection in the study area. Moreover, the combination of MSPA and the MCR model, which is a novel idea for landscape connectivity analysis, offers scientific support for the construction and optimization of ecological networks in similar regions of the world.

Abbreviations

MSPA: Morphological spatial pattern analysis; MCR: Minimal cumulative resistance; PD: Patch density; LPI: Largest patch index; LSI: Landscape shape index; IJI: Interspersion and juxtaposition index; PCI: Patch cohesion index; AI: Aggregation index; dPC: The probability of connectivity; IIC: Integral index of connectivity; PC: Probability connectivity; ESP: Ecological source point; ESA: Ecological source area; IC: Important corridor; GC: General corridor; PC: Potential corridor; SS: Stepping stones; EFP: Ecological fault points.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13717-021-00332-2.

Additional file 1: Table S1. The importance values of a patch (dPC) value, ecological type and specific landscape of each ecological source in Shenzhen City. **Table S2.** Comparisons of ecological network structure analysis between the optimized and initial ecological networks. *α* is the network closure index; *β* is network connectivity degree index; and γ is the network connectivity rate index.

Acknowledgements

We thank the editors and two anonymous reviewers for providing thoughtful and constructive comments on the earlier versions of this manuscript. We also thank International Science Editing for the language correction of this manuscript.

Authors' contributions

ZYJ and YYL designed this study. YYL, YZZ, BYW, and QLC coordinated the data collection. YYL, YZZ, ZYJ, and MYG performed data management and method analysis. ZYJ, YYL, YZZ, and CXG drafted the manuscript. ZYJ, CXG, and MYZ revised the manuscript. All authors read and approved the final manuscript.

Funding

This study was supported by the National Natural Science Foundation of China (Grant No. 41901027), the Natural Science Foundation of Guangdong Province, China (Grant No. 2021A1515012208), and the China Postdoctoral Science Foundation (Grant Nos. 2021T140222 and 2018M643110).

Availability of data and materials

The datasets used and analyzed in this study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Received: 22 March 2021 Accepted: 4 September 2021

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