



Integrating ecosystem services and landscape connectivity into the optimization of ecological security pattern: a case study of the Pearl River Delta, China

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Abstract

The ecological security pattern (ESP) focuses on key ecological elements in ecosystems by identifying, combining, and evaluating these elements. This study attempts to identify the ESP of the Pearl River Delta (PRD) and provide suggestions for optimization. Ecosystem services were calculated and applied to construct the ecological resistance surface; morphological spatial pattern analysis (MSPA) and landscape connectivity analysis were used to identify ecological sources; and minimum cumulative resistance (MCR) model was applied to extract ecological corridors and ecological nodes. The results show that during 1995 to 2015, the main landscape transformation occurred between forest, cropland, and urban land, and the location of the transformation was mainly in the central part of the study area. Regarding the ESP, the average resistance value increased from 0.30 to 0.33; the area of ecological sources decreased by 5.12%; the ratio of total cumulative resistance to the length of the corridors increased by 14.82%; and the number of ecological nodes increased from 71 to 99. For the ESP optimization, based on the correction of the resistance surface, 1348 km blue corridors and 61 blue nodes were extracted. Based on hot spot analysis, nine stepping stones were identified. This optimization compensates for the lack of ecological elements in the center of the study area, enhances weaker corridors, and improves the connectivity of the ESP, thus making the ESP more stable and complete. The ESP constructed and optimized in this paper holds great significance and serves as a valuable reference for ecological protection and environmental management.

Keywords Landscape transformation · Ecological security pattern · Ecosystem services · Ecological sources · Ecological corridors

Introduction

In the context of rapid urbanization, ecological landscapes are largely occupied by artificial landscapes and are accompanied by habitat degradation and landscape fragmentation

(He et al. 2014). The reduction and fragmentation of ecological landscapes, which are the main habitat for species, are problematic, and it has been suggested that they are the main reasons for the current biodiversity crisis (Berger-Tal and Saltz 2019; Li et al. 2014; Loro et al. 2015). The issue of finding a balance between the need for urban land for urbanization and the need for ecological land for biodiversity conservation is of global concern (Beninde et al. 2015). Furthermore, during recent decades, researchers have reached the consensus that conservation aimed at independent natural areas does not involve the ecological processes that occur between habitats (Cumming and Allen 2017), which indicates that a landscape pattern that is beneficial for ecological functioning and processing should be implemented (Zheng et al. 2019; Li et al. 2015).

Ecological security, which is a concept first proposed by the government of the USA in 1990, refers to the health and integrity of the earth's ecosystem and its effective

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conservation, protection, and restoration (Ezeonu and Ezeonu 2000). Many researchers have offered new definitions (Lu et al. 2018; Rogers 1997; Xiao et al. 2002), but they all emphasize the importance of maintaining the functions and processes of ecosystems. Yu (1995) proposed the concept of security patterns (SPs), which were subsequently referred to as ecological security patterns (ESPs). ESPs refer to potential spatial patterns composed of strategic portions and positions of the landscape that have critical significance in safeguarding and controlling certain ecological processes (Yu 1996). From the perspective of landscape ecology, the goal of ESP analysis is to explore what landscape pattern is more beneficial for maintaining ecological processes and functions. As an approach to studying ecological security, ESPs offer a relatively feasible and streamlined framework for extracting a pattern that has constituents with specific features and functions (Kong et al. 2010; Peng et al. 2019). Based on numerous studies, the approach to identifying ESPs is mature: constructing resistance surface, identifying ecological sources, and then identifying ecological corridors and nodes (Lu et al. 2016; Gao et al. 2017).

Ecological sources are patches that are important for biodiversity maintenance, which means that the ecological function, configuration, size, and spatial position of the patch are all factors that need to be evaluated. In previous studies, researchers identified larger patches in ecological landscapes as sources (Kong et al. 2010) or identified ecological sources based on morphology (Carlier and Moran 2019), landscape connectivity (Guo et al. 2018), or ecosystem services (Liquete et al. 2015). The ecological resistance surface is the basis of an ESP. The setting of the ecological resistance value plays a decisive role in identifying other important constituents, such as ecological corridors and ecological nodes. The methods for constructing resistance surface are diverse. The most direct method is to assign a resistance value for each landscape type, but it ignores the fact that the same landscape type may not have the same ecological resistance value for many reasons, such as landscape connectivity and human activity (Peng et al. 2018a). Thus, the resistance surface can be modified by nighttime lighting (Keeley et al. 2016) or impervious index data, which are the most widely used data for enhancing the internal differences in the same landscape type. As ecosystem services have become a research hotspot (Kindu et al. 2016), researchers have attempted to link the ecosystem service value to ecological resistance value (Wang et al. 2019; Peng et al. 2018b; Zheng et al. 2019). Ecological corridors are strip areas that connect ecological sources, ensuring the transfer of ecological flow and ecological processes (Pierik et al. 2016). The identification of ecological corridors is based on the ecological resistance surface. The most widely applied method for identifying ecological corridors is the minimum cumulative resistance (MCR) model. The MCR is used to quantify the

resistance to ecological flow transformation from source to destination (Adriaensen et al. 2003; Dong et al. 2015). Ecological nodes are the key points or fragile points along an ecological corridor that plays an important role in species migration and other functions. The points on ecological corridors with larger resistance values are considered easy to break, and these points can be identified by intersecting the ridge line based on the ecological resistance surface and the ecological corridors (Yu et al. 2017). In addition to the constituents mentioned above, stepping stones have been proposed as complementary to ESPs (Kramer-Schadt et al. 2011; Saura et al. 2014). When an ecological patch is not good enough to be identified as an ecological source or when a corridor is so long that it is easily disturbed, several stepping stones can play a transitory role for ecological flow.

The Pearl River Delta (PRD) urban agglomeration which located in southern China was taken as the study area. This area has experienced rapid economic development and urbanization since the reform and opening up and the economy of the PRD increased more than 15-fold in the 20-year period from 1995 to 2015 and is now one of the most developed urban agglomerations in the world. It has always been a research hotspot, and as the Chinese government proposed the Guangdong-Hong Kong-Macao Greater Bay Area development plan, attention focused on the PRD urban agglomeration has further increased. Further and tremendous development will inevitably increase the pressure on ecological conservation (Wei et al. 2017), and exploration of the impact of urbanization on regional ecosystems is becoming urgent. On the scale of urban agglomeration, what impact will rapid development bring to the landscape pattern? How can a complete landscape pattern be extracted from urban agglomerations as the basis of ecological security studies? To explore these questions, the landscape transformation of the PRD from 1995 to 2015 was analyzed, the ESP in 1995 and 2015 was constructed and evaluated, and the ESP in 2015 was optimized.

Materials and methods

Study area

The PRD urban agglomeration was chosen as the study area, which is in Guangdong Province, southern China (Fig. 1). It is one of the largest agglomerations in China and the most densely developed regions of the world. It covers approximately 54,000 km², including nine municipals: Guangzhou (GZ), Shenzhen (SZ), Foshan (FS), Dongguan (DG), Huizhou (HZ), Zhongshan (ZS), Zhuhai (ZH), Jiangmen (JM), and Zhaoqing (ZQ). The PRD region has a subtropical climate and the annual average temperature is 21.0–23.0 °C. The mean annual rainfall is in the range of 1600–2000 mm,

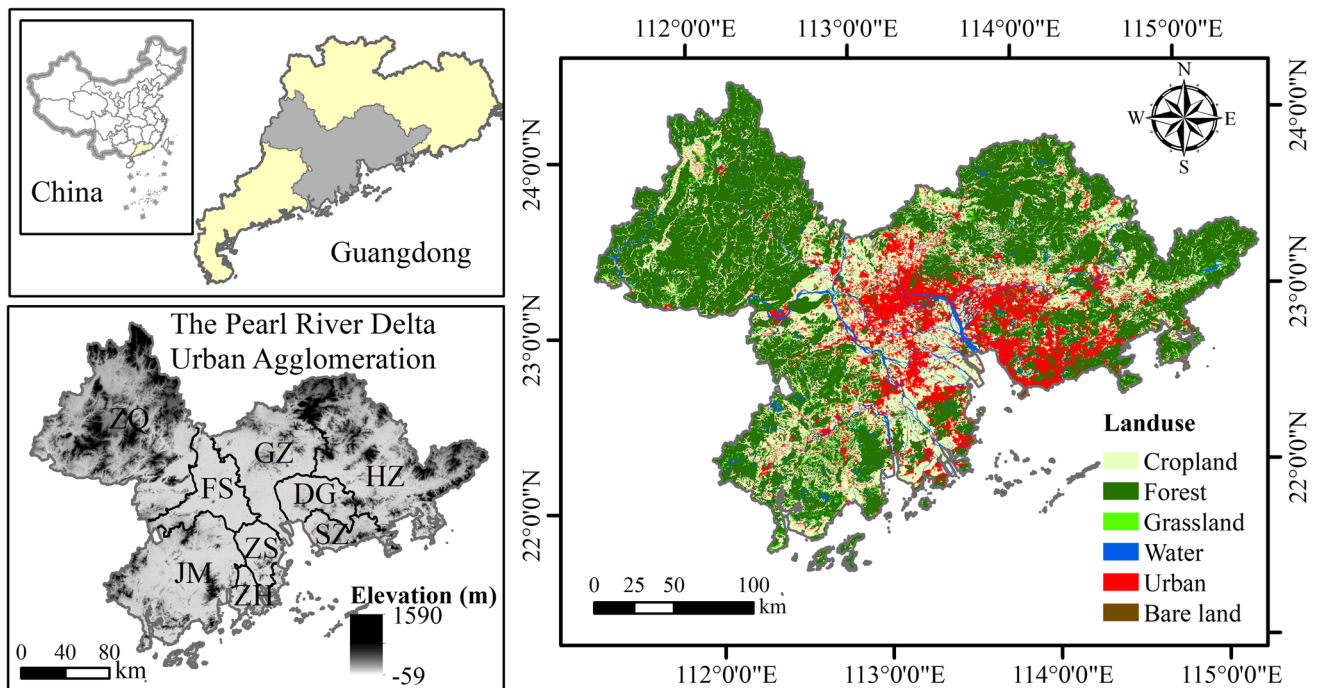


Fig. 1 Location, elevation, and land-use types of the PRD. GZ Guangzhou, SZ Shenzhen, FS Foshan, DG Dongguan, HZ Huizhou, ZS Zhongshan, ZH Zhuhai, JM Jiangmen, ZQ Zhaoqing

with 80% of annual precipitation occurring between April and September. The PRD region contains abundant water resources within a dense river network.

Following the implementation of the opening-up policy, economic development of the PRD region has been fast-paced, with the GDP increasing from 407 billion RMB in 1995 to 7571 billion RMB in 2017 (Guangdong Statistical Bureau 2018). The study area is one of the most densely populated areas in China, with a population density of 1072 persons/km² in 2015 (National Bureau of Statistics 2017). The highest population concentration is in the central part of the PRD. Rapid urbanization and a growing population have led to intensive transformations in the landscape, which have had extensive impacts on ecological security. Therefore, a study on the relationship between landscape pattern and landscape transformation in the PRD has become urgent.

Methodology

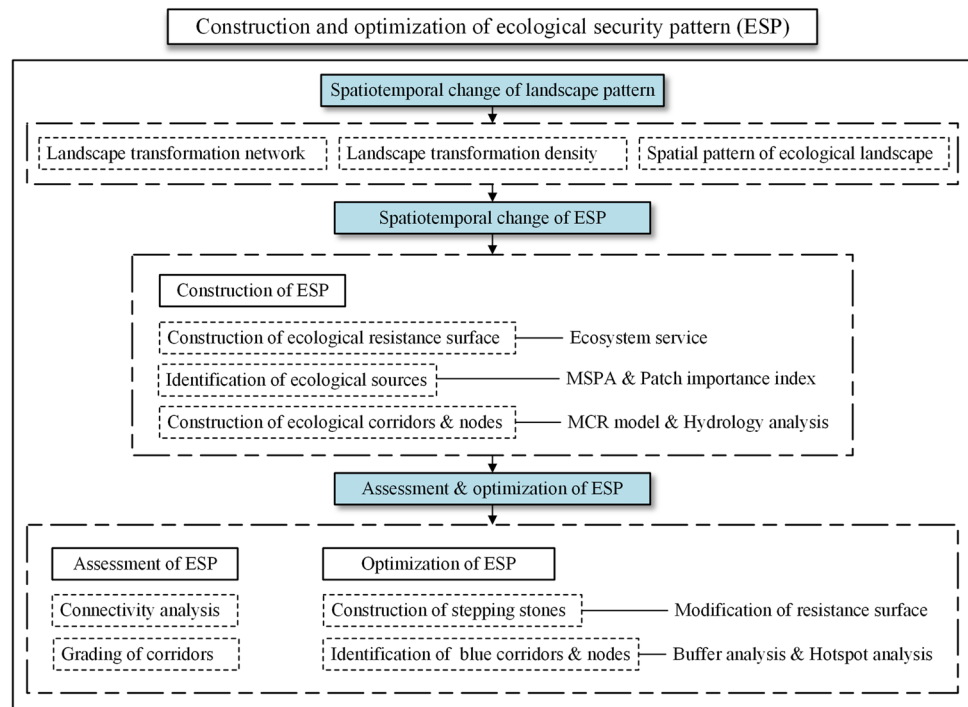
The methodology framework is shown in Fig. 2. The ESP constructed in this study is basically composed of ecological resistance surface, ecological sources, ecological corridors, and ecological nodes. Based on landscape pattern analysis and landscape transformation analysis, the ESPs in 1995 and 2015 were constructed and evaluated. To analyze the spatial characteristics of the ESPs more comprehensively, the ESP in 2015 was further evaluated and optimized. Detailed descriptions are provided in the following sections.

Landscape transformation analysis

The analysis of landscape transformation includes not only the quantity of changed landscape but also the spatial characteristics. The land-use data was provided by the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC; <http://www.resdc.cn>), then the raster map (1 km×1 km) was created. Landscape types were categorized based on land-use data, namely forest, grassland, water, cropland, urban land, and bare land. Based on the results of the transfer matrix of landscape from 1995 to 2015, a landscape transformation network can be carried out, which indicates the category and quantity of landscape transformation (Yu et al. 2017). Based on overlay analysis of the landscape maps, kernel density analysis in ArcGIS 10.5 was applied to illustrate the density of landscape transformation, which indicates the spatial characteristics of landscape changes.

Forest, grassland, and water are basic ecological elements and are essential for biodiversity conservation. Thus, forest, grassland, and water were considered as ecological landscape in this study. Fragstats 4.2 was used to calculate the landscape pattern metrics of ecological landscape from 1995 to 2015 (McGarigal and Marks 1995). In order to illustrate the spatial characteristics of landscape pattern, the following indexes were selected: mean patch area (AREA_MN), mean shape index (SHAPE_MN), and mean contiguity index (CONTIG_MN) were selected at patch level; patch

Fig. 2 Flowchart of methodological steps. MSPA morphological spatial pattern analysis, MCR minimum cumulative resistance



number (NP), splitting index (SPLIT), and division index (DIVISION) were selected at the landscape level. The formulas and descriptions of the landscape indexes are shown in Table S1.

Construction of the ESP

Construction of ecological resistance surface

Ecosystem services represent the capacity of an ecosystem to support ecological functions and processes (Costanza et al. 1997), while the ecological resistance value is generally described as the difficulty that species need to overcome when migrating between different habitat landscapes (de Groot et al. 2002; Huang et al. 2018). Linking them together is a meaningful endeavor. In ESP construction, the ecological resistance surface refers to a comprehensive resistance surface related to specific species. Therefore, the resistance value can be assigned only indirectly based on the factors that may affect species migration (Chetkiewicz et al. 2006). Assignment of the resistance value based on the landscape type or correction of the resistance value based on other factors are both effective methods. To date, little research has illuminated the relationship between ecosystem services and ecological resistance. There are many types of ecosystem services, among which habitat quality is the most closely related to biodiversity conservation (Sharp et al. 2014). With this approach, a resistance surface was constructed based on the inverse of the ecosystem service of habitat quality, which was calculated by Integrated Valuation of Ecosystem

Services and Tradeoffs (InVEST) model. Road data used in habitat quality calculation were provided by RESDC.

Identification of ecological sources

Ecological sources are regarded as the patches that fulfill the main ecological functions in an ecosystem, and they are composed of landscape types that are spatially connected or adjacent and have enormous ecological benefits. In broad terms, to be identified as an ecological source, a patch should meet the following conditions: (1) the landscape type of the patch has ecological integrity that is good enough for ecological functions and processes; (2) patches should be adjacent or connected spatially with good connectivity; and (3) the size of the patch needs to meet specific requirements.

Under the above conditions, a framework for identifying ecological sources was constructed. First, ecological landscapes were analyzed by morphological spatial pattern analysis (MSPA). MSPA based on GuidosToolbox 2.8 was used to analyze the spatial pattern of the landscape from the aspect of morphology (Vogt and Riitters 2017). MSPA describes the geometric arrangement and connectedness of the map elements and allocates each foreground pixel to one of the mutually exclusive thematic pattern classes defined in MSPA, which are core, islet, perforation, edge, bridge, loop, and branch (Table S2) (Soille and Vogt. 2009). In our study, forest, water land, and grassland were regarded as ecological landscape and MSPA was used to analyze the spatial pattern of the ecological landscape. In this study, the goal of MSPA

was to screen out “better” patches, namely, core patches, based on morphology as ecological source candidates.

When core patches were identified, the patch importance index (dPC) of core patches with an area larger than 1 km² was calculated by Conefor 2.6, indicating the importance of the patch for the connectivity of the landscape (Saura and Torné 2012). The calculation formulas are as follows:

$$PC = \frac{\sum_{i=1}^n \sum_{j=1}^n a_i \cdot a_j \cdot p_{ij}}{A_L^2} \tag{1}$$

$$dPC = \frac{PC - PC_{remove}}{PC} \times 100\% \tag{2}$$

where PC is the probability of connectivity, *n* is the total number of patches in the landscape, *a_i* and *a_j* represent the area of patch *i* and patch *j*, respectively, *A_L* is the total area of the landscape, and *p_{ij}* is the maximum diffusion probability between patches *i* and *j*. In this study, *A_L* is the total area of the study area. *PC_{remove}* is the landscape connectivity index value of the remaining patches after removing patch *i*.

Construction of ecological corridors and ecological nodes

Ecological corridors are practical landscape elements that act as corridors in the process of ecological flow. The minimum cumulative resistance (MCR) model and the Cost Connectivity module based on ArcGIS 10.5 were applied to extract ecological corridors based on the resistance surface (Li et al. 2020; Su et al. 2016).

$$MCR = f_{\min} \sum_{j=n}^{i=m} (D_{ij} \times R_i) \tag{3}$$

where MCR is the minimum cumulative resistance value, *D_{ij}* is the spatial distance from the source point *j* to the spatial unit *i*, *R_i* is the resistance coefficient of spatial unit *i*, and *f* is the positive correlation between the minimum cumulative resistance and ecological process, reflecting the distance relationship from any point in space to all sources.

The corridors obtained by the Cost Connectivity module are lines, which are without width. However, as corridors for species migration, ecological corridors must have a certain width. The width of ecological corridors varies by species, corridor structure, corridor connectivity, and substrate. The ecological corridors in this study were built for comprehensive ecological flow and biodiversity conservation support, rather than for specific species. Therefore, based on the research scale of this study and other relevant studies (Bueno et al. 1995; Forman 1983), the landscape components in the 1000 m buffer zone of the corridors were analyzed.

On the ecological corridors, there are points with relatively high resistance values, which are considered easier to break and require more attention. These kinds of points, namely ecological nodes, can be identified by intersecting ecological corridors and the ridge lines extracted from the ecological resistance surface.

Evaluation and optimization of the ESP

Connectivity analysis

Landscape connectivity is a core concept in ESP research; thus, it is important to evaluate the connectivity of the elements in an ESP. Based on graph theory, complex landscapes can be simplified into understandable spatial configurations, which provides a way to quantify either the structural or functional connectivity of habitats (Kong et al. 2010). Thus, a series of indices based on graph theory can be chosen to evaluate the connectivity of the elements in an ESP. The integral index of connectivity (IIC) and the probability of connectivity (PC), determined by Conefor 2.6 (Saura and Torné, 2012), were used to evaluate the connectivity of ecological sources. The formula of IIC is as follows:

$$IIC = \frac{\sum_{i=1}^n \sum_{j=1}^n \frac{a_i \cdot a_j}{1 + nl_{ij}}}{A_L^2} \tag{4}$$

where *n* is the total number of nodes in the landscape, *a_i* and *a_j* are the attributes of nodes *i* and *j*, respectively, *nl_{ij}* is the number of links in the shortest path (topological distance) between patches *i* and *j*, and *A_L* is the maximum landscape attribute. In this study, *A_L* is the total area of the study area.

Based on graph theory, ecological sources can be regarded as nodes and ecological corridors are regarded as lines. Ecological sources (nodes) are connected by ecological corridors (lines), and together, they form a network. From the perspective of network analysis, *α* and *γ* indices can be used to evaluate the circuitry and connectivity of a network, which also reflect the connectivity of an ESP (Forman and Godron 1986; Cook 2002). The formulas are as follows:

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

$$\gamma = \frac{L}{3(V - 2)} \tag{6}$$

where *α* is the degree of network circuitry, *γ* is the gamma index of connectivity, *L* is the number of linkages, and *V* is the number of nodes.

Grading of ecological corridors

As channels of ecological flow, ecological corridors with longer lengths and larger cumulative resistance values face a higher risk of breaking. Therefore, length and the cumulative resistance values were chosen as indicators to assess the risk of ecological corridors. Length and the cumulative resistance values were classified into five levels and formed the risk matrix, based on which the risk of ecological corridors was classified. Finally, the ecological corridors were divided into five levels based on their risk level. Level 1 corridors have the lowest risk, while level 5 corridors have the highest risk.

Modification of the ecological resistance surface

Water (rivers) plays a role as natural corridors in an ecosystem, and unlike forest and grassland, which are easily disturbed by human activities, rivers can maintain their function of carrying ecological flow in the presence of human interference. Additionally, in principle, the ecological flow carried by rivers is directional. However, the direction of ecological flow is ignored in this study. Considering the particularity of the water body and to reflect the important role of water in an ESP, the resistance of water was modified to 0. Based on the modified resistance surface, new ecological corridors could be extracted. The added corridors were identified because the water resistance value was reduced; thus, they were named as “blue corridors.” Similarly, the intersection points of the blue corridors and the ridge lines extracted from the modified resistance surface were named “blue nodes.”

Planning of stepping stones

As described before, ecological patches should meet several requirements in order to be identified as ecological sources. This means that planning new sources is very difficult in

highly urbanized areas. Furthermore, corridors distributed in highly urbanized areas are easy to break because of the dramatic impact of human activity. The stepping stone concept was proposed. Stepping stones are patches that do not meet the requirements of ecological sources; however, they can act as “transfer stations” in the transfer of ecological flow between ecological sources. In this study, the geographical center of core patches was extracted and the area was taken as the weight for hot spot analysis. The hotspots falling within the 2000 m buffer zone of level 4 corridors, level 5 corridors, and blue corridors are identified as stepping stones.

Results

Landscape transformation of the PRD

Landscape transformation network

In the landscape transformation network shown in Fig. 3, the vertices represent different landscape types and the lines represent the transformation types and quantity. There are 30 kinds of transformation relationships within the study area and the landscape transformation mainly occurred between forest, urban land, and cropland, which is presented as a constant triangle in Fig. 3.

From 1995 to 2005, the total area of landscape transformation was 3119 km². The top three transformations were cropland to urban land, forest to urban land, and urban land to forest, accounting for 46.93%, 17.86%, and 15.40%, respectively, of the total transformation area.

The total landscape transformation area from 2005 to 2015 was 2865 km², and the transformation type was similar to that from 1995 to 2005. The top three transformations were cropland to urban land, forest to urban land, and forest to grassland, accounting for 53.22%, 18.29%, and 4.19% of the total transformation area, respectively. During the

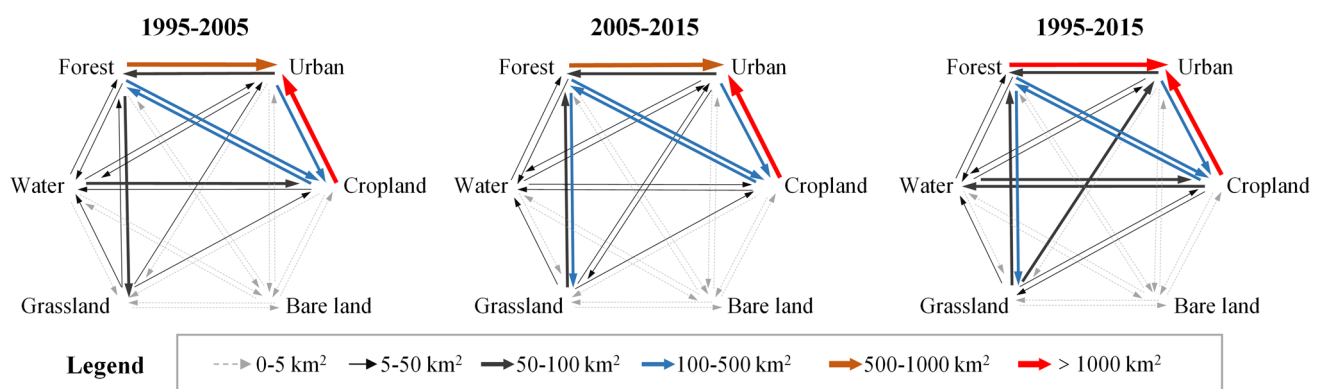


Fig. 3 Landscape transformation network of the PRD

20 years from 1995 to 2015, as a result of urbanization, the area of urban land increased from 4263 to 7729 km², mainly due to the transformation of cropland and forest.

Landscape transformation density

By overlapping the raster map of the landscape of different periods, the grids that changed in landscape type could be extracted. Based on kernel density analysis, the density of the central points of those changed grids can be determined, indicating the landscape transformation density (Fig. 4), and landscape transformation intensity. The results of landscape transformation density present similar spatial characteristics during 1995 to 2005 and 2005 to 2015. The areas with intense landscape transformation were mainly distributed in the central part of the study area (DG, SZ, FS, and ZS), which is consistent with the spatial distribution characteristics of urban land.

Spatial pattern of ecological landscape pattern

In this study, forest, grassland, and water are regarded as ecological landscape. The ecological landscape was mainly distributed in the outer ring area within the study area (Fig. 5a). As a result of urbanization, the ecological landscape decreased because of the occupation of artificial landscapes (Fig. 5b). From 1995 to 2015, the ecological landscape area decreased by 1125 km² (3.38%). With respect to the results of the landscape indices, AREA_MN, SHAPE_MN, and CONTIG_MN decreased and NP, SPLIT, and DIVISION increased (Fig. 5c), indicating a fragmentation trend of the ecological landscape.

Spatiotemporal change in the ESP

Given the results above, the PRD experienced similar landscape transformations from 1995 to 2005 and from 2005

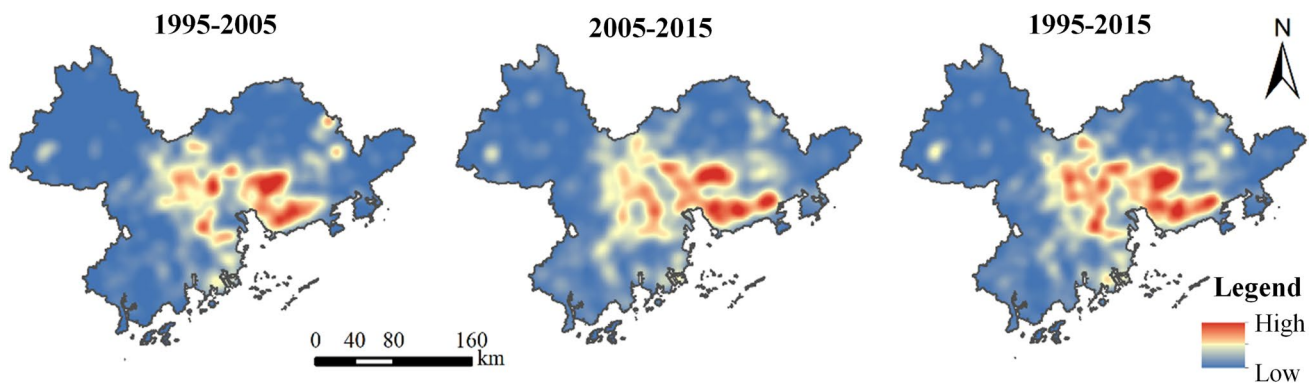


Fig. 4 Landscape transformation density analysis of the PRD

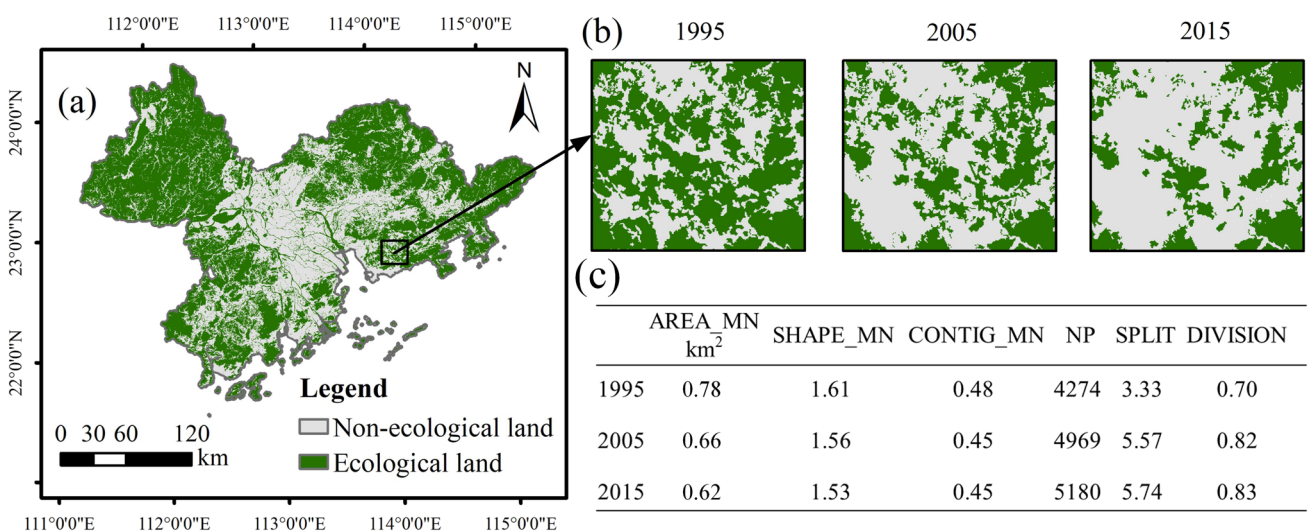


Fig. 5 Change of ecological landscape in the PRD. **a** Ecological landscape distribution in 2015, **b** change of degradation of ecological landscape, and **c** landscape metrics of ecological landscape

to 2015. Thus, we chose the 1995 to 2015 period in the following content to illustrate the spatiotemporal change of the ESP, which will more directly and succinctly present the impact of landscape change on the ESP.

The key components of the ESP are discussed below in four sections: ecological sources, ecological resistance surface, ecological corridors, and ecological nodes. The establishment of a large-scale ESP is based on the precise recognition and classification of the key components of the ESP.

Spatiotemporal change in ecological sources

Based on MSPA, core patches were extracted, the dPC index of the core patches with an area larger than 1 km^2 was calculated, and the patches with $dPC > 0.1$ were taken as ecological sources (Fig. 6a). The ecological sources were mainly distributed in the peripheral region of the research area.

Forty-eight ecological sources with a total area of $12,054 \text{ km}^2$ in 1995 were identified, and 51 ecological sources with an area of $11,462 \text{ km}^2$ in 2015 were identified. From 1995 to 2015, ecological sources were reduced by 5.12%. Some ecological sources decreased (Fig. 6b), and some disappeared, (Fig. 6c) but the number of ecological sources increased because of the landscape fragmentation.

Spatiotemporal change in the ecological resistance surface

The resistance value was defined as the inverse of habitat quality, which was calculated to be in the range of 0–1 using the InVEST model (Fig. S1). In general, the average ecological resistance value of the study area was 0.30 in 1995 and 0.33 in 2015. In the central part of the study area, the resistance value was much higher (Fig. 7).

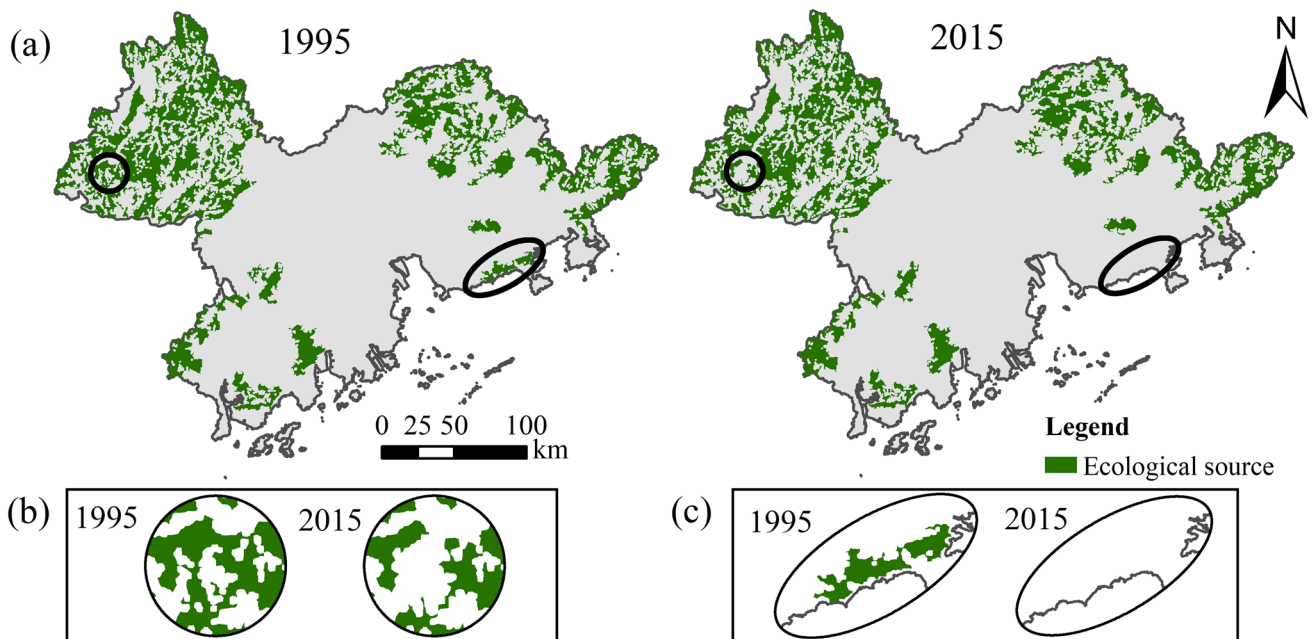
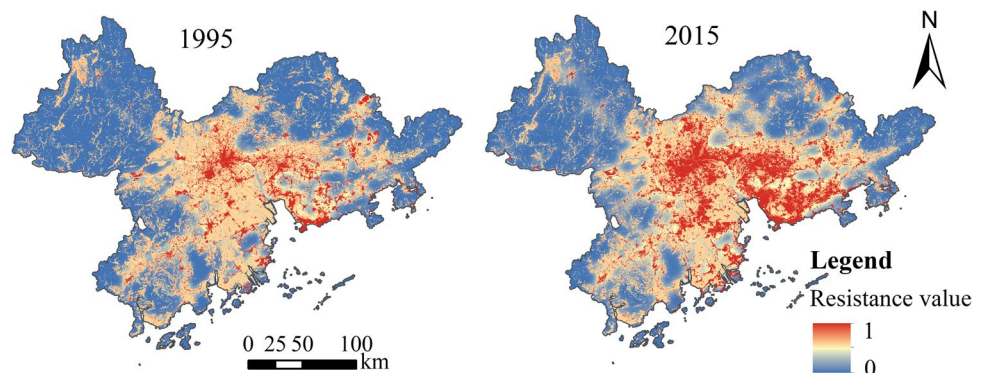


Fig. 6 Spatial pattern of ecological sources. **a** Distribution of ecological sources. **b** and **c** Change of ecological sources

Fig. 7 Ecological resistance surface of the study area



Spatiotemporal change in ecological corridors and ecological nodes

Based on the ecological resistance surface and ecological sources, ecological corridors can be extracted through the cost connectivity module of ArcGIS (Fig. 8). Ecological corridors are mainly distributed in the peripheral region of the study area, and the high resistance in the central region hinders ecological flow. In 1995, the total length of the ecological corridors was 3366 km, with a total cumulative resistance of 96,809; in 2015, the total length of the ecological corridors was 3617 km, with a total cumulative resistance of 125,928. From 1995 to 2015, the ratio of total cumulative resistance to the length of the corridors increased by 14.82%.

The landscape composition within the 1000 m buffer zone of the ecological corridors was analyzed and is shown in Table 1. The main component of the corridors is forest, which accounted for 88.63% of the total area of the buffer zone in 1995 and 86.12% in 2015. From the perspective of the change in corridor components, urban land, cropland, grassland, and water increased, while forest decreased.

By intersecting ecological corridors and the “ridgeline” extracted from the ecological resistance surface, ecological nodes were determined. There were 71 ecological nodes in 1995 and 99 in 2015 (Fig. 8).

Assessment and optimization of the ESP

Evaluation and optimization of the ecological corridors

Two factors, i.e., length and cumulative resistance, were chosen to characterize the risk of corridors. Based on the risk matrix (Fig. 9a), the risk of ecological corridors was divided into five levels and the ecological corridors were divided into five categories according to their risk levels. Level 1 corridors represent the corridors with the lowest risk, while level 5 corridors represent the corridors with the highest risk (Fig. 9b). The percentages of corridors from level 1 to level 5 in the total length of corridors are 11.83%,

Table 1 Landscape type composition of ecological corridors

Landscape	1995/km ² (%)	2015/km ² (%)
Cropland	386.29 (6.19)	458.47 (7.02)
Forest	5512.58 (88.63)	5616.77 (86.12)
Grassland	137.67 (2.17)	155.23 (2.38)
Water	132.00 (2.11)	187.81 (2.88)
Urban	56.30 (0.90)	104.30 (1.60)
Bare land	0.22 (0.00)	0.17 (0.00)

24.49%, 49.25%, 7.35%, and 7.09%, and these results indicate a skewed distribution.

Based on the modified resistance surface, blue corridors and blue nodes were extracted. A total of 1348.55 km of blue corridors was identified, and 61 blue nodes on the blue corridors were identified (Fig. 9c). The blue corridors and blue nodes were mainly distributed in the central part of the study area, filling the void in the ecological elements in the center of the study area.

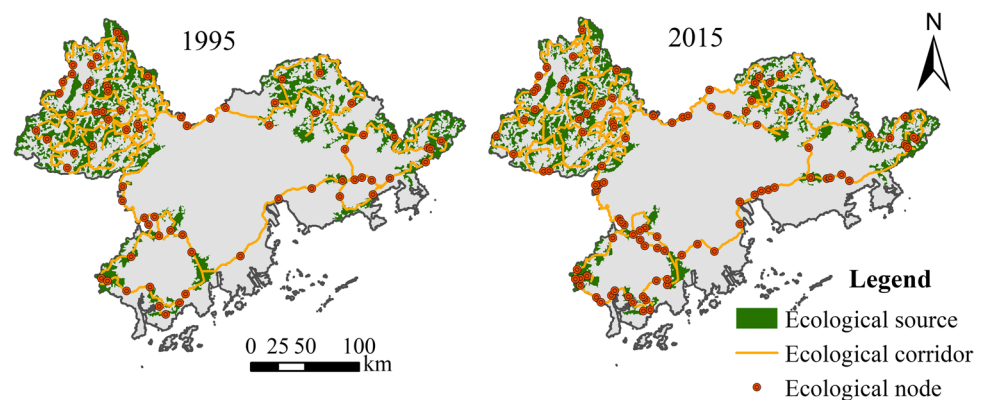
Planning of stepping stones

Hot spot analysis on the core patches that were not identified as ecological sources was conducted. In total, 17 hotspots were identified at a 90% confidence level (Fig. 10a). Based on buffer analysis, 9 hotspots fell within the 2000 m buffer zone of level 4 ecological corridors, level 5 ecological corridors, and blue corridors (Fig. 10b). These 9 hotspots were identified as stepping stones. The stepping stones, along with ecological sources, ecological corridors, and ecological nodes, compose the optimized ESP of the PRD (Fig. 10c).

Connectivity analysis

To evaluate the improvement of the ESP after optimization, connectivity analysis was conducted. The improvement in the connectivity of ecological sources was characterized by the PC and IIC indices; the improvement of the network formed

Fig. 8 Map of the ecological security pattern



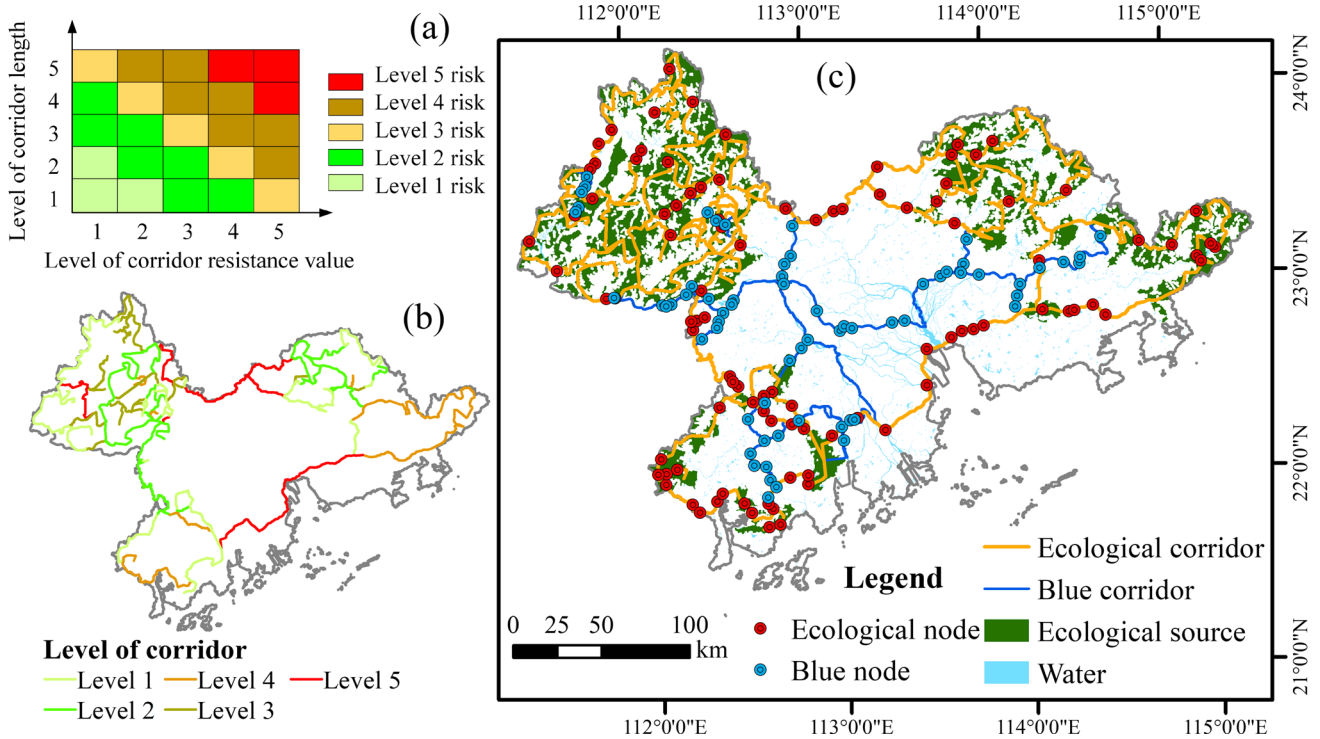


Fig. 9 Classification and optimization of the ecological corridors in 2015. **a** Risk matrix applied for ecological corridors classification, **b** classification of ecological corridors, and **c** pattern of optimized ecological corridors and nodes

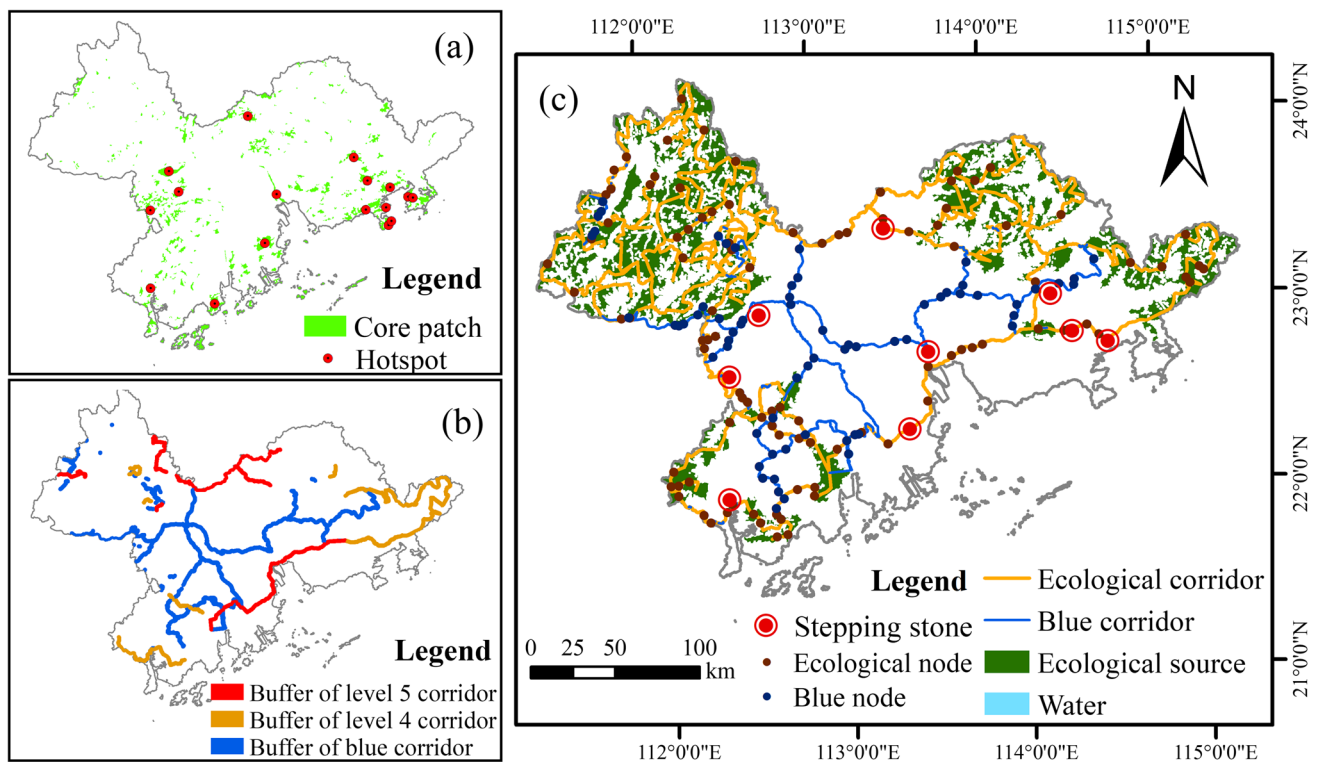


Fig. 10 The planning of stepping stones and the optimized ESP of the PRD. **a** Hot spot analysis (90% confidence), **b** buffer analysis of ecological corridors, and **c** the optimized ESP

by ecological sources and ecological corridors was characterized by the α and γ indices. Table 2 shows that PC and IIC increased, indicating that the connectivity of ecological sources improved after the planning of stepping stones. Likewise, the α and γ indices also increased. Graph theory redefines a complex landscape as a network formed by nodes (ecological sources) and linkages (ecological corridors). The α and γ indices were developed to evaluate the degrees of circuitry and connectivity of a network. The planning of blue corridors and stepping stones was put on both the number of nodes and linkages in the network, leading to the increase in the α and γ indices. As a result, the increase in α and γ indices reveals the improvement in the circuitry and connectivity of the optimized ESP.

Discussion

Meaning of ESPs for urban landscape management

Ecological sources and ecological corridors are regarded as basic elements of an ESP. Ecological sources are regarded as the main habitats for species, and ecological corridors are regarded as the main paths for ecological flow. Based on the comparison of the 1995 and 2015 ESPs, the area of ecological sources decreased by 5.12% (592 km²), and the ratio of the cumulative ecological resistance value to the length of the ecological corridors increased by 14.82%. However, the urban land of the study area, which is the fastest developing urban agglomeration in China, has increased by 81.33% (3456 km²). Urbanization mainly occurred in the central part of the study area, and ecological sources and ecological corridors were mainly distributed in the peripheral region within the study area. As a result of the inconsistent spatial distribution of urbanization and ecological sources, there seems to be a much smaller change in the ecological elements compared with the intense urbanization. Thus, it is easy to draw biased conclusions if we focus on only individual habitats and ignore the interaction between them. The ESP provides an overall insight into landscape management, and this perspective is also reflected in the development of environmental management strategies in China. In response to ecological degradation, the Chinese government has established various ecological reserves since 1956, including natural reserves, national parks, and forest parks, and the protected area covers 18% of the total area of China (IUCN 2019). Although the establishment of ecological reserves is certainly positive, many studies

have shown that protected areas do not achieve the expected conservation benefits (Liu et al. 2001; Xu and Melick 2007; Wu et al. 2011). There are still many problems in the management of reserves, including their scattered distribution, insufficient connectivity, and incomplete coverage (Yang et al. 2019). Therefore, there is a growing call for an effective protection pattern to work with ecological reserves. In 2010, the State Council of China issued the “National Plan for Major Function-oriented Zones,” which classified land into four categories: optimized, key, restricted, and forbidden development zones (State Council of China 2010). In 2011, China proposed the Ecological Conservation Redline strategy, which sought to create an ecological protection pattern at a national scale. (Gao et al. 2020). In conclusion, the management strategy that focuses on individual habitats or species should be replaced by a more systematic management approach that links key ecological elements into one system and integrates them into a comprehensive protection strategy.

ESP elements within municipalities

In landscape ecology, scale has always been a key issue. Many scholars have tried to construct ESPs at different scales, such as the county scale (Yu et al. 2017), city scale (Peng et al. 2018a), urban agglomeration scale (Wang et al. 2019), and basin scale (Shi et al. 2020). It is of considerable significance to understand regional ecological status by constructing ESPs, but at the same time, ecological processes at smaller scales are easily overlooked. The ESPs constructed in this study was based on the urban agglomeration scale. The statistics of the ecological elements within the nine municipalities of the study area are shown in Table 3. Hierarchical clustering analysis was applied to analyze the statistics of the ecological elements (Fig. 11a), and the nine municipalities were divided into three groups according to these statistics (Fig. 11b). ZQ is included in group 1, which has the most ecological elements. In ZQ, the area of ecological sources accounts for 50.93% of the total area of ecological sources; the length of the ecological corridors accounts for 47.64% of the total length of ecological corridors; and the number of ecological nodes accounts for 31.33% of the total number of ecological nodes; and the area of ZQ accounts for 27.65% of the total study area. GZ, DG, FS, SZ, ZH, and ZS are included in group 3. The area of ecological sources of these 6 cities accounts for 7.71% of the total area of ecological sources; the length of the ecological corridors accounts for 15.83% of the total length of ecological corridors; and the number of ecological nodes accounts for 21.22% of the total number of ecological nodes; and the area of the 6 cities accounts for 34.33% of the total study area. Regarding SZ, ZH, and ZS, there are barely any ecological elements in the ESP constructed at the urban agglomeration scale. Of course, we cannot simply conclude that there are

Table 2 Connectivity analysis of the ecological security pattern

	PC	IIC	α	γ
ESP	0.020	0.018	0.289	0.531
Optimized ESP	0.022	0.020	0.522	0.684

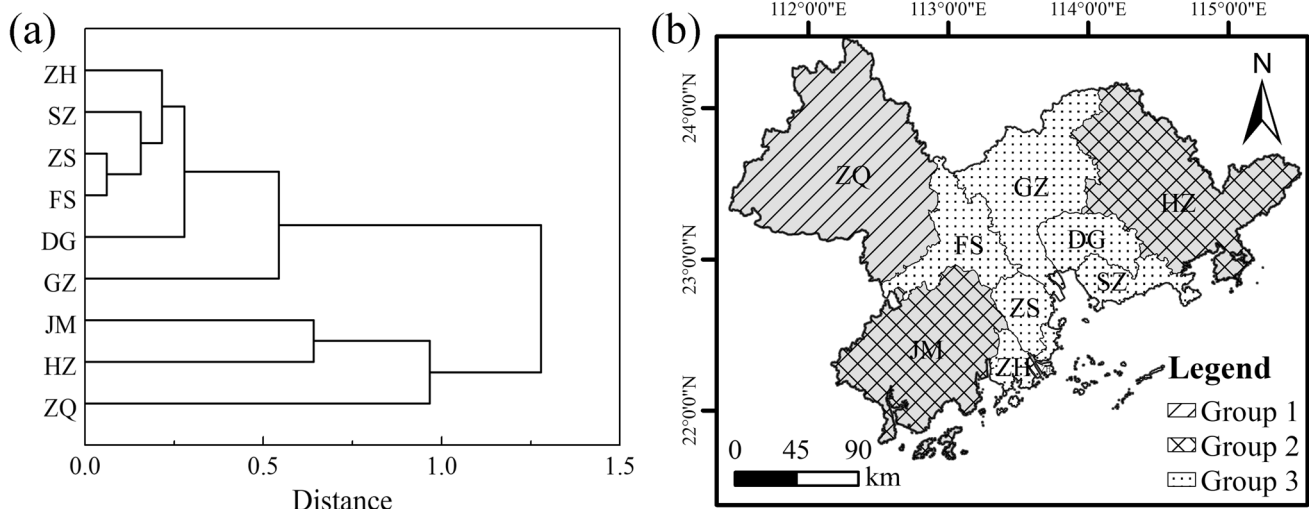


Fig. 11 The grouping of municipalities. **a** Hierarchical clustering analysis based on statistics of ecological elements and **b** spatial pattern of municipalities grouping. GZ Guangzhou, SZ Shenzhen, FS

Foshan, DG Dongguan, HZ Huizhou, ZS Zhongshan, ZH Zhuhai, JM Jiangmen, ZQ Zhaoqing

no habitats or few ecological processes in these places. The ESPs constructed in this study makes us lose sight of ecological processes at smaller scales. With a complete ESP construction framework, ESPs can be constructed at different scales. However, in landscape management, there is still a lack of research on how to combine ESPs at different scales. Furthermore, in this study, the study area is still bounded by administrative districts while ecological processes are not limited by administrative regions. In future research, multi-scale ESP construction and how to combine ESPs in practical landscape management will be worth studying.

Optimization of ESPs

The optimization of ESPs is also an important part of research on ESPs. At present, ESP optimization is mainly based on the optimization of ecological sources and

ecological corridors, since these two components are the most basic and the most important components of an ESP (Li et al. 2020; Yu et al. 2017). In this study, the ESPs was optimized from two perspectives: the construction of blue corridors and the identification of stepping stones. In previous studies, some scholars assigned the resistance value of water as 0, while others assigned the resistance value of water as a higher value (Gurrutxaga et al. 2010; Yu et al. 2017), which does not stress the particularity of water. From the perspective of ecosystem services, water is very important, while from the perspective of species migration for some species (e.g., land animals), water acts as an obstacle to migration. In the construction of the ESP in this study, water was regarded as a normal ecological landscape when the ESP was constructed, and in optimization, the resistance value of water was set to zero and blue corridors were specifically developed. The blue corridors

Table 3 Statistics of the ecological elements within the municipalities of the study area

Municipal	Average resistance value	Area of ecological sources / km ²	Length of ecological corridors/km	Number of ecological nodes
ZQ	0.14	5833	1722	31
HZ	0.24	3278	775	15
JM	0.31	1467	546	32
GZ	0.44	779	380	13
DG	0.73	80	80	5
FS	0.58	25	50	1
ZS	0.61	0	60	2
SZ	0.68	0	2	0
ZH	0.50	0	1	0

not only reflect the importance of water in the ESP but also transport ecological flows in highly urbanized areas (the central area of the study area), where there is an absence of other ecological corridors. However, the ecological flows carried by water (rivers) tend to be directional. Thus, the importance and particularity of water in ESPs should be highlighted in further research.

With habitat loss and fragmentation becoming two of the major threats to biodiversity conservation, stepping stones have attracted much attention as an effective strategy (Kramer-Schadt et al. 2011; Saura et al. 2014). It is undoubtedly difficult to find ecological sources or to construct new sources in highly urbanized regions. In addition, ecological corridors often need to pass through highly urbanized regions. A stepping stone is composed of the existing ecological landscape, which can be either a separate ecological patch or several adjacent ecological patches connected. As a supplement to the ESP, stepping stones act as both alternative ecological sources and “stopovers” for ecological flow when it moves along ecological corridors. Vulnerable corridors such as the level 5 or blue corridors in this study are either too long or have a high ecological resistance value since they need to pass through highly urbanized areas.

Conclusion

As one of the fastest growing urban agglomerations in the world, the PRD urban agglomeration has experienced rapid economic development, explosive population growth, and intensive landscape transformation. Under a background of high urbanization, how can ESPs with complete structures and functions be extracted? What changes does rapid urbanization bring to ESPs? To make existing ESPs more effective and stable, how can optimization be performed? To explore these questions, based on an analysis of the characteristics of landscape transformation, the ESPs of the study area from 1995 to 2015 was constructed and then optimized. A complete framework for ESP construction was carried out: ecological sources were identified by MSPA and landscape metrics; ecological resistance surface was constructed based on ecosystem services and ecological corridors were identified by the MCR model. From 1995 to 2015, the urban landscape of the study area increased by 81.33%. Landscape transformation mainly occurred in the middle of the study area, which is consistent with the spatial distribution of urban land. In contrast, the ecological landscape is mainly distributed in the peripheral region, where landscape transformation is not intensive. Changes in the landscape led to changes in the ESP. Urbanization brought a 10% increase

in the average ecological resistance value. The area of ecological sources, which were selected from the ecological landscape, decreased by only 5.12%. At the same time, the ratio of the cumulative ecological resistance value to the length of ecological corridors increased by 14.82%, because ecological corridors must cross highly urbanized areas and areas with intensive landscape transformation to connect ecological sources. In the optimization of the ESP, blue corridors and stepping stones were constructed, the lack of ecological elements in the center of the study area was compensated for, and the stability of high-risk corridors is increased, which improves the stability and effectiveness of the ESPs. Connectivity analysis based on graph theory and network analysis also indicates that the construction of blue corridors and the planning of stepping stones has improved multiple aspects of the connectivity of the elements within the ESPs.

Analysis of the spatiotemporal changes in an ESP based on landscape transformation provides a global perspective for research on the impact of urbanization on regional ecological functions and processes. Together with other environmental management strategies, ESPs can play a significant role in environmental management. The complete framework for ESP construction and optimization built in this paper can be applied in other regions. However, key issues such as the connections between ecosystem services and ESP construction, the combination of multiscale ESPs, and the particularity of water in an ESP need to be further explored.

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Data availability The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

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