RESEARCH ARTICLE

Research on recognition and protection of ecological security patterns based on circuit theory: a case study of Jinan City

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Abstract

Accelerated urbanization and population growth have resulted in the loss of ecological land and biodiversity, accompanied by the degradation of ecosystem services. Identifying and improving existing ecological security patterns are of great significance for maintaining the sustainable development of cities. In this study, Jinan, the capital of China's Shandong Province, was used as a case study area. Based on three ecosystem services, namely, soil conservation, water conservation and carbon fixation, ecological sources were determined. Furthermore, a resistance surface was constructed based on biodiversity. On these bases, the circuit theory concept of random walks was applied to simulate ecosystem processes in a heterogeneous landscape and identify ecological corridors, pinch points and barriers. A total of 25 ecological sources, 48 ecological corridors and 19 pinch points were identified, and restoration areas were delimited to three levels. These elements together constituted the ecological security patterns. Specifically, the ecological sources were mainly distributed in southern Jinan and were covered mostly with forest land. The ecological corridors were located mainly in the eastern and southwestern plains below the southern mountainous areas and were covered mostly with cropland. Furthermore, the eastern corridors were much longer than the southwestern corridors. Pinch points were distributed mostly along rivers or around large-scale construction land. Barriers were distributed mainly in Zhangqiu District and northern Licheng District. Based on these findings, hierarchical restoration areas were delimited. Differentiated development contradictions in restoration areas were discussed, and corresponding ecological protection measures were proposed. An ecological security optimization pattern of "one center, two wings, and two belts" was finally proposed to provide planning strategies for decision-makers.

Keywords Ecological security · Circuit theory · Ecological security patterns · Ecological restoration areas · Ecological services · Jinan, China

Introduction

The current era is one of eco-environmental deterioration (Jones et al. 2018; Sevik et al. 2019; Shujah-ur-Rahman et al. 2019; Turkyilmaz et al. 2019). Since the twentieth century, global industrialization and urbanization have led to dramatic changes in land-use patterns and extensive socioeconomic development but also severe problems such as loss of habitat, fragmentation of ecological networks and reductions in ecosystem service capacity (Cetin et al. 2019; Costanza et al. 2014; Pietsch 2017). Habitat loss and fragmentation are considered the greatest threats to biodiversity and the main causes of species extinctions (Fahrig 2003; Pimm et al. 2014; Rodrigues et al. 2004; Wan et al. 2019). Maintaining ecological integrity and environmental quality is essential in ensuring the protection of species, habitats and various ecological processes (Chouchenarojas 2000; Jones et al. 2018).

Sustainable development of cities cannot be separated from stable support and protection of the ecological environment, and improvement of the structure and function of the global ecosystem requires effort from all countries (Cetin 2019; Cetin et al. 2018). In response to the deteriorating ecological environment, countries around the world have implemented

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technological schemes or planning strategies for protecting the ecological environment, such as the "urban growth boundary (UGB)" (Cho et al. 2008), "environmental network (EN)" (Esbah et al. 2009) and "green infrastructure (GI)" (Benedict and Mcmahon 2002) measures. The relevant "ecological security pattern (ESP)" effort initiated more recently in China has gradually become an important means of planning and management for coordinating economic development and ecological protection. The ESP strategy is currently listed as one of the three strategies for land and space development and protection in China (Jie 2016). Similar to the EN and GI concepts, the ESP strategy consists of an ecological planning network composed of points, lines and planes based on landscape ecology (Badiu et al. 2016; Peng et al. 2019).

After more than 20 years of improvement in theory and methods, "source identification-corridor extraction" has become the basic paradigm of ESP research (Ma et al. 2019). The most direct and simplest method is to select green spaces, water bodies, protected areas, mountain areas, and scenic sites as ecological sources (Junxiang et al. 2011; Ma et al. 2004; Vergnes et al. 2013; Zhao and Xu 2015). Another method is to establish an evaluation system for identifying the importance of patches, where ecological sensitivity, ecological functions, landscape connectivity, and ecological risk are usually considered (Liang et al. 2018; Peng et al. 2018a; Yang et al. 2017). The latter method has been widely used because it is comparative and quantitative. Among these indicators, ecological functions based on ecosystem services in the regional ecological background are the most important to assess (Peng et al. 2018c). Areas with superior ecological functions can provide better ecological goods and services to benefit species directly or indirectly (Costanza et al. 1998) and thus are prioritized as ecological sources. These areas can also be regarded as bottom-line green spaces in sustainable urban development.

The research focus of extracting corridors is the construction of a resistance surface and the simulation of species migration processes. Researchers commonly construct resistance surfaces based on expert experience to assign different land-use types (Balbi et al. 2019; Guo et al. 2019; Ya-Ping et al. 2016), while some modify the resistance on the basis of night-time light intensity (Zhang et al. 2017), impervious surfaces (Peng et al. 2018b), or comprehensive topographic indicators (Pierik et al. 2016). Simulation of species migration processes is usually based on species' foresight regarding the optimal landscape through which they migrated and mostly depends on the minimum cumulative resistance (MCR) and morphological spatial pattern analysis (MSPA) models (Carlier and Moran 2019; Yu et al. 2018). Random walk theory may be more in line than these methods with the behavioral characteristics of species (Song and Qin 2016), and corresponding fitting methods usually employ ant colony algorithm and circuit model (Peng et al. 2019). In particular, circuit model has been widely used in species conservation research because

electric currents can sufficiently simulate ecological flow, thus allowing the identification of connective and obstructive ecological elements (Brodie et al. 2016; Grafius et al. 2017; Melles et al. 2015; Pierik et al. 2016).

After a long period of high-intensity construction, Jinan has become a second-tier developed city in China. This development has been accompanied by substantial impacts on the ecological environment. In the current stage of rapid economic growth, Jinan is a typical city facing the conflict between regional development and ecological protection. Therefore, we selected Jinan as a case study for in-depth exploration, with the aim of resolving this conflict by constructing ESPs. We identified ecological sources by assessing regionally significant ecosystem services and then utilized a circuit model to identify and build important spatial elements for sustainable regional development. We hope that our study can provide a theoretical reference for regional planning.

Study area and data sources

Jinan (in 2019, Laiwu was merged into a district of Jinan, but the data obtained in this paper span up to 2016; thus, the Jinan city mentioned in this paper does not include the newly merged Laiwu) is located in the central and western part of Shandong Province and is the capital of Shandong Province (36° 1′~37° 33′ N, 116° 12′~117° 45′ E) (Fig. 1). Additionally, Jinan covers an area of 7998 km^2 and accounts for approximately 5% of the total area of Shandong Province. Plains and mountains account for 62% and 38% of Jinan's total area, respectively. Mount Tai is to the south, and the Yellow River runs through the city from southwest to northeast. The hypsography of Jinan is high in the south and low in the north, with an elevation of 57.8 m. Jinan is located in the midlatitude zone and has a warm temperate monsoon climate with an annual average precipitation of 685 mm.

By the end of 2016, the number of permanent residents in Jinan had reached 7.23 million, and the proportion of the urban population in Jinan was 75%, which was nearly 29 percentage points higher than the national average of China. Urban impervious surfaces have gradually encroached upon green spaces in the surrounding countryside (Wang et al. 2014). From 2010 to 2016, cropland and forest land decreased by 4765 hm^2 and 2184 hm^2, respectively. Specifically, the reduced cropland areas were concentrated in Licheng District and Zhangqiu District, and the reduced forest land areas were concentrated in Zhangqiu District and Changqing District. The area of water bodies decreased by 69 hm^2, mainly in Zhangqiu District and Shanghe District. Moreover, the existing land-use types with ecological functions in Jinan are scattered and have not yet formed a connected ecosystem because of a poor layout and network system. The importance of ecological protection during the process of economic
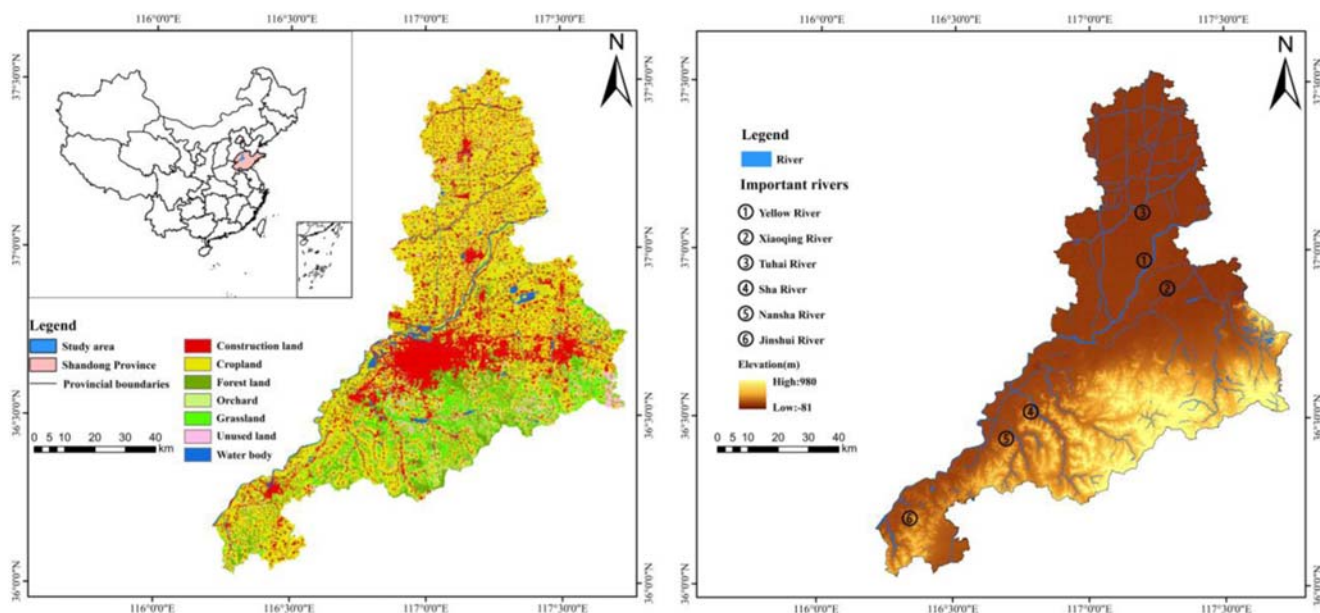
Fig. 1 Location and land-use cover of Jinan

development in Jinan has been recognized. Furthermore, within the context of gradually strengthening the "construction of ecological civilization", China's requirements for regional ecological protection are becoming increasingly stringent, especially in economically developed regions. Therefore, ecological construction in Jinan is an urgent topic requiring research.

The data sources used in this study were as follows: (1) the 2016 land-use vector database was provided by the planning department of Jinan; (2) vector data for monthly average precipitation in 1981–2010 interpolated by the kriging method were obtained from the National Meteorological Information Center website (http://data.cma.cn/) at a spatial resolution of 500 m; and (3) digital elevation model (DEM) data were obtained from the Geospatial Data Cloud website at a spatial resolution of 30 m (http://www.gscloud.cn/). We reclassified all data using the nearest-neighbor method to ensure that the spatial resolution was 30 m × 30 m.

Methodology

Construction of ESPs involves identifying or restoring key ecological elements that are important for maintaining and controlling ecological processes in specific areas, such as pinch points, ecological sources, corridors, and even the whole network. We constructed the ESPs of Jinan in three steps. First, ecological sources were identified based on key ecosystem services. Second, we constructed a resistance surface based on habitat quality derived by the integrated valuation of ecosystem services and tradeoffs (InVEST) model. Finally, we extracted ecological corridors, pinch points, and

barriers based on circuit theory to delimit restoration areas. The methodological framework is shown in Fig. 2, and each process is described in detail thereafter.

Identification of ecological sources

Ecological sources are important patches that provide key ecosystem services or perform important radiation functions. By evaluating the spatial differentiation of ecosystem functions, important ecological patches can be identified. Large mountainous areas with high vegetation coverage are located in southern Jinan, and denser river networks are scattered in the north. Moreover, soil erosion in Jinan is severe due to its undulating topography. Therefore, based on the ecological background characteristics of Jinan, typical ecosystem services, namely, soil conservation, water conservation, and carbon fixation, were selected for evaluation. We divided the ecosystem services into five grades by the natural breaks algorithm, and then patches with ecosystem service grades greater than three were extracted and selected as ecological sources. These areas are important habitats that provide specific, significant ecological services. Some small patches distributed fragmentarily with weak radiation functions were removed due to their weak influence on ESPs. These patches were merged with other patches that had small areas but concentrated distributions.

Soil conservation assessment

The soil conservation service was evaluated by the revised universal soil loss equation (RUSLE) and used to estimate potential and actual soil erosion. The difference between the
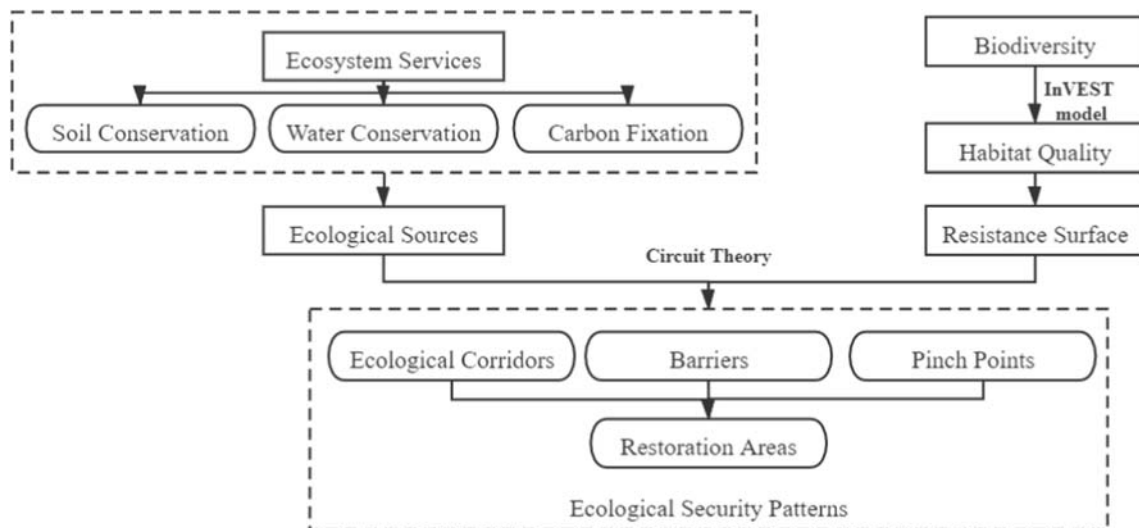
Fig. 2 The methodological framework of this study

two erosion values was used as the value of soil conservation, obtained using the following equation:

$$A = R \times K \times LS - R \times K \times LS \times C \times P \qquad (1)$$

where A is the soil conservation capacity; R is the rainfall erosivity factor; K is the soil erodibility factor based on different kinds of soils; LS is the terrain factor based on the DEM; C is the vegetation cover management factor; and P is the erosion conservation factor (Du et al. 2016; Rozos et al. 2013; Xiao et al. 2015).

We quantified K as 0.24 according to the relevant calculation (Ting et al. 2014), where R and LS were calculated by the formulas suggested by Wischmeier and Smith (1978):

$$R = \sum_{i=1}^{12} 1.735 \times 10^{1.5\left(log_{P_i^2} - logP_a\right)} \qquad (2)$$

where P_i is monthly average precipitation and P_a is annual average precipitation, and

$$LS = \left(\frac{l}{22}\right)^{0.3} \times \left(\frac{\theta}{5.16}\right)^{1.3} \qquad (3)$$

where l is slope length and θ is slope angle, both of which can be extracted based on the DEM.

On the basis of parameter settings in previous research (Lewis et al. 2005; Ting et al. 2014; Xiao et al. 2015), combined with the characteristics of the study area, the parameters of different land-use types were assigned as shown in Table 1.

Water conservation assessment

The water conservation service was evaluated according to water source guarantee and flood storage. We calculated the basic value for water conservation capacity based on the table of coefficients for ecosystem service value in China provided by Xie et al. (2017) and then revised it according to the importance of the river and flood safety buffer distance. The formula was as follows:

$$Wat = L \times M \times I \qquad (4)$$

where Wat is the water conservation capacity; L is the land-use type; M is the water conservation service value; and I is the importance correction coefficient (Chen and Zha 2016; Huang et al. 2019; Xie et al. 2017). The specific parameter settings are shown in Table 2.

Carbon fixation assessment

The carbon fixation service was evaluated with the carbon fixation module of the InVEST model. According to the distribution of land-use types and the average carbon densities of different land-use types, a spatial distribution map of carbon

Table 1 Parameter assignment for soil conservation assessment of different land-use types

Land-use types		C	P
Cropland	Irrigated cropland	0.2	0.45
	Rainfed cropland	0.31	0.4
	Paddy field	0.12	0.15
Forest land	Woodland	0.01	1
	Shrubbery land	0.02	1
	Sparsely forested woodland	0.03	1
Grassland		0.15	1
Orchard		0.15	0.15
Construction land		0	0
Unused land		0	1
Water body		0	0

Table 2 The evaluation system for the importance correction coefficient (I)

Water body size	Buffer range	Importance hierarchy	Correction coefficient
> 1000 hm^2	200 m	1	1
	400 m	2	0.8
	600 m	3	0.6
100–1000 hm^2	200 m	2	0.8
	400 m	3	0.6
	600 m	4	0.4
< 100 hm^2	200 m	3	0.6
	400 m	4	0.4
Others	/	5	0.2

fixation was generated for the study area, and more details regarding the calculation and value setting can be found in the instructions of the InVEST model (Sharp et al. 2018). The formula was as follows:

$$C = C_{above} + C_{soil} + C_{dead} + C_{below} \quad (4)$$

where C is total carbon fixation; C_{above} is carbon fixation aboveground; C_{soil} is carbon fixation in the soil; C_{dead} is carbon fixation of dead organic matter; and C_{below} is carbon fixation belowground. Specific parameter settings are shown in Table 3 (land-use types not listed in the table were assigned a value of 0).

Construction of a resistance surface

A resistance surface expresses the background value of ecological processes occurring between different patches. This value reflects the cost of species migration and energy flow in heterogeneous landscapes. The value of a resistance surface is related to land cover, location, distance, and human impacts. However, in most studies, resistance values are assigned empirically based on different land-use types without considering different utilization status values of the same land-use type (Yang et al. 2017). Therefore, a more scientific habitat quality assessment is required. In this study, habitat quality was evaluated by the InVEST model with four influences: distance from threat patches, sensitivity, habitat conservation, and mutual threat of habitats. More detailed information on model theory and parameter setting can be found in the InVEST user's guide and in related studies (Sharp et al. 2018). Then, we calculated the reciprocal of habitat quality as the resistance value because better habitat quality means lower resistance. The resistance value ranges from 1 to 10, indicating impoverished to enriched habitat conditions, respectively. The specific parameter settings are shown in Tables 4 and 5 (for land classification information, please refer to Land Use Classification in China (GB/T 21010–2017)).

Extraction of ecological corridors, pinch points, and barriers

Ecological corridors are a kind of ecological landscape with a line or strip configuration and integrated ecological, cultural, social, and other functions (Jian et al. 2017). Such corridors represent important paths of material, energy, and information exchange in ecosystems. Therefore, ecological corridors are important for ecological processes and maintaining biodiversity. Construction of ecological corridors can improve ecological connectivity and maintain ecosystem function integrity. Pinch points and barriers exist near ecological corridors. Pinch points are areas with frequent ecological processes and symbolize key nodes for ESPs, which cannot be removed or destroyed (Mcrae et al. 2012). Barriers will significantly hinder ecological processes, and identifying and improving barriers

Table 3 Parameter assignment for carbon fixation assessment of different land-use types

Land-use types		C_{above}	C_{below}	C_{soil}	C_{dead}
Cropland	Rainfed cropland	0.3	0.2	0.8	0.1
	Paddy field	0.2	0.1	1	0
	Irrigated cropland	0.3	0.2	1	0
Forest land	Woodland	9	6	11	3
	Shrubbery land	0.8	0.8	2.5	0.3
	Sparsely forested woodland	7.5	4.5	8.5	2
Grassland		0.5	0.2	1	0
Orchard	Fruit plantation	12.5	0.5	11.5	0.1
	Other orchards	1	0.3	9	0.1
Railway		0	0	3.5	0
Highway		0	0	3.5	0
Rural road		0	0	3.5	0
Canal and ditch		0	0	2.5	0
Inland mudflat		1	0.5	2	0
Barren land		0.1	0.1	1	0
Land for scenic site facilities		1	0.7	7.6	0.3

Table 4 The maximum distance over which each threat affects habitat quality and its weight

Maximum distance	Weight	Threat	Decay
1.5 km	0.6	Cropland	Exponential
6 km	0.8	Urban land	Exponential
8 km	0.8	Industrial and warehouse land	Exponential
2 km	0.7	Rural residential land	Exponential
2.5 km	0.6	Railway and highway	Linear
1 km	0.5	Rural road	Linear

are of great significance for landscape connectivity, especially in highly urbanized cities (Lechner et al. 2015; Pierik et al. 2016).

This study used the geographic information system (GIS) tool Linkage Mapper to extract ecological corridors, pinch points, and barriers based on circuit theory. Circuit theory regards the landscape as a conductive surface and simulates the ecological processes of species in the landscape by the random walk of electrons (McRae 2006). Each grid on the conductive surface is given a finite value reflecting the energy consumption or difficulty of moving across that cell, and each ecological source consisting of many grids is represented as a node with zero resistance (Song and Qin 2016). When current is injected from one ecological source and flowed out from another, the current values in each intervening grid represent the probability that a random walker would pass through the grid if it started from the source and moved to the destination (McRae et al. 2008). All pairs of sources are connected to a current of 1 A, and grids with different resistances in the path will pass through different currents (Peng et al. 2018b). Higher current densities between source patches

indicate that successful dispersers are more likely to pass through the area, and high-current density locations are called "pinch points". Ecological corridors are extracted according to the cumulative resistance threshold, and the areas beyond, the resistance threshold are removed. Ecological corridors represent least-cost paths (LCPs) for species flow (Dickson et al. 2013). Barrier recognition is based on the assumption that if a certain area is restored and the resistance across it is therefore reduced, then the LCP of the best route connecting the patches through the restoration area will also be reduced (Mcrae et al. 2012). On the basis of the LCP, the pixel value of the moving search window is assumed to be reduced by one unit, and the LCP is reduced to LCP_1 after barrier removal. Therefore, the simple metric of connectivity recovery is as follows:

$$\Delta LCP = LCP - LCP_1 \qquad (5)$$

Dividing the ΔLCP by the search diameter provides the restoration coefficient, which represents the recovery benefits per unit distance.

Table 5 Habitat types and sensitivity of habitat types to each threat

Habitat types		Habitat value	Cropland	Urban land	Industrial and warehouse land	Rural residential land	Railway and highway	Rural road
Cropland	Rainfed cropland	0.6	0.3	0.5	0.3	0.4	0.5	0.6
	Paddy field	0.4	0.3	0.5	0.3	0.4	0.5	0.6
	Irrigated cropland	0.4	0.3	0.5	0.3	0.4	0.5	0.6
Forest land	Woodland	1	0.8	0.9	0.6	0.85	0.9	0.7
	Shrubbery land	1	0.4	0.6	0.65	0.5	0.8	0.6
	Sparsely forested woodland	0.9	0.9	1	0.7	0.9	1	1
Grassland		0.8	0.75	0.7	0.5	0.6	0.5	0.4
Orchard		0.6	0.3	0.5	0.5	0.4	0.5	0.65
River		1	0.7	0.9	0.5	0.8	0.85	0.75
Lake		1	0.7	0.9	0.5	0.8	0.85	0.75
Pond		1	0.7	0.9	0.6	0.8	0.85	0.75
Reservoir		0.9	0.7	0.9	0.6	0.8	0.85	0.75
Inland mudflat		0.6	0.7	0.9	0.6	0.8	0.85	0.75

Results

Spatial patterns of ecosystem service grades and ecological sources

The values of ecosystem services were divided into five grades ranging from 1 to 5. The spatial distributions of the three ecosystem services showed heterogeneity. Among the three ecosystem services in Jinan, the capacity for carbon fixation was highest. Significant ecological service areas (grade > 3) in terms of carbon fixation covered 1349 km^2, 16.87% of the total area. The corresponding regions were mainly distributed in the southern mountainous areas with abundant rainfall, high vegetation coverage, and a lack of human activity. This pattern was due to the undulating topography and serious soil and water losses in Jinan. Significant ecological service areas in terms of soil conservation covered only 34 km^2, 0.34% of the total area. Significant ecological service areas in terms of water conservation encompassed 523 km^2, 6.54% of the total area. The corresponding regions were mainly distributed near the Yellow River, Xiaoqing River, and Tuhai River and in patches surrounding these rivers (Fig. 3).

In general, large areas of ecological sources were distributed in the southern mountainous areas, while others were scattered in the plains outside the city center. Twenty-five ecological sources covered 1733 km^2, and ecological sources accounted for 21.67% of the total area. Among the ecological sources, forest land was the dominant land-use type, accounting for 30.74% of the ecological source patches, followed by

cropland (26.21%), grassland (26.21%), garden land (11.48%), and water bodies (8.09%). The proportions of ecological sources differed among administrative regions in Jinan, with most ecological sources (31.80%) distributed in Licheng District. Changqing District contained 22.72% of the total ecological sources. The ecological sources distributed in Huaiyin District were the least abundant, accounting for only 0.25% of the total ecological sources (Fig. 4).

Spatial distribution of the resistance surface

In general, the ecological resistance in the south was significantly lower than that in the north. The resistance value was calculated to be in the range of 0–10, and the average ecological resistance of Jinan was 3.93. The resistance value of Lixia District was the highest of all the administrative regions, with a value up to 7.62, followed by that in Huaiyin District (6.75). Changqing District had the lowest resistance, with a value of 3.04 (Fig. 4).

Spatial distribution of ecological corridors

As shown in Fig. 5, cumulative resistance was increased from 1000 to 9000 in increments of 2000 to determine the range of ecological corridors. The corresponding area proportions of ecological corridors covered 5.22%, 12.84%, 21.02%, 28.14%, and 32.94% of the total study area, respectively (Fig. 5). Although the total area of the ecological corridors increased, their spatial layout remained unchanged. The pinch points became more prominent, but the location and number
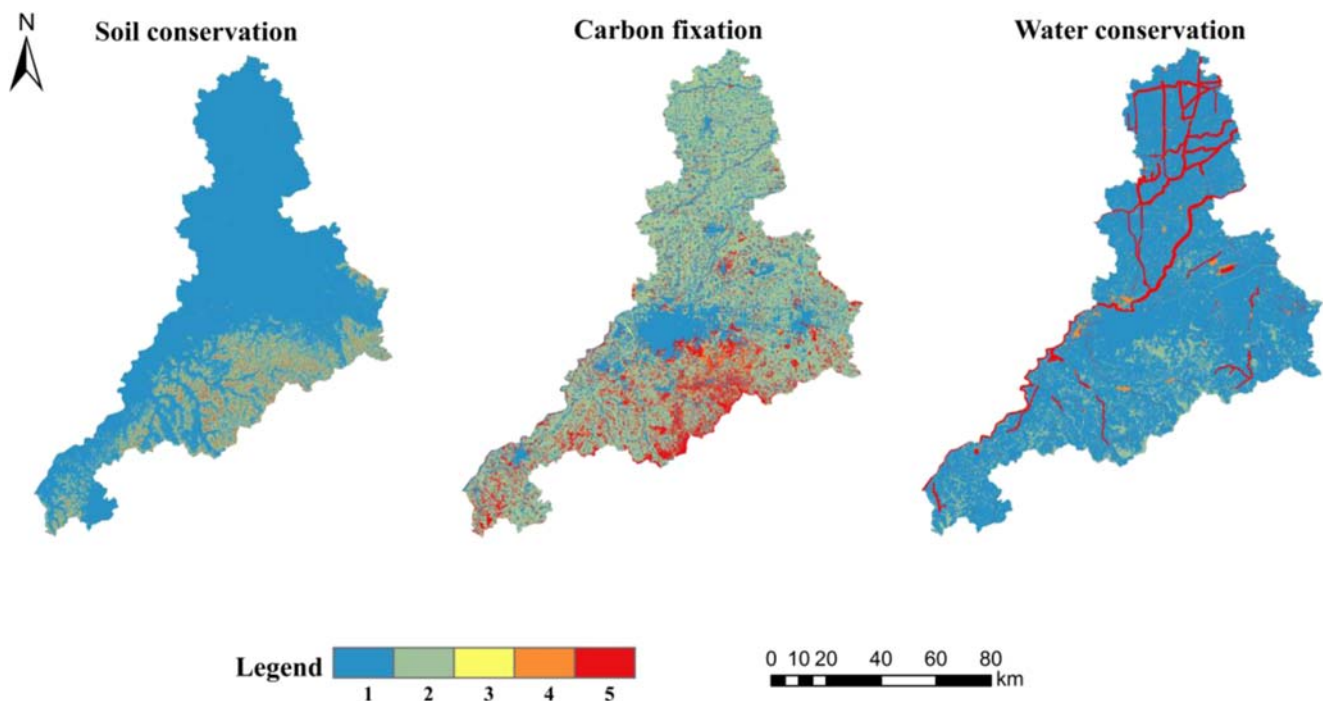

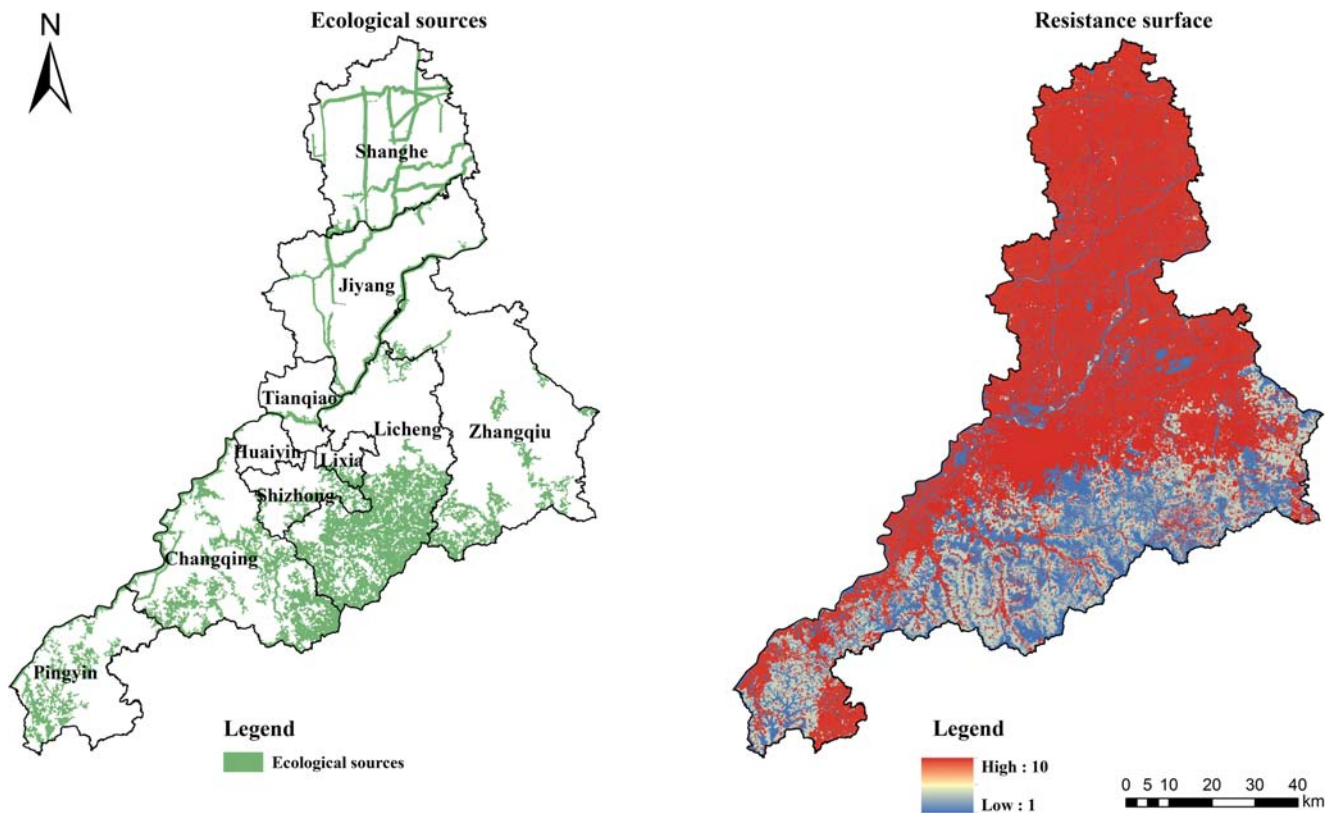**Fig. 3** Spatial distribution map of ecosystem service grades in Jinan

Fig. 4 Spatial distribution maps of ecological sources and the resistance surface in Jinan

of these points remained unchanged. Widening corridors will disperse current transmissions, indicating more possibilities for biological communication, but doing so will also lead to higher maintenance or reconstruction costs.

Considering the dual needs of economic development and ecological protection, we assumed that investment in the protection of ecological corridors could cover approximately 20% of the entire study area. Then, the threshold of 5000 was chosen to determine the range of the ecological corridors. A total of 48 corridors were identified in the study area, and these corridors increased the connectivity between the southern mountainous area and the north-south landscape. The corridors covered 1681 km^2 and were mainly composed of cropland. The eastern corridors were cobweb shaped, and the corridors in the southwest showed a lumpy, aggregated distribution. In particular, the length of the corridors in eastern Jinan city was greater than 10 km, and the length of the corridors in the southwestern region was less than 5 km. The average cumulative current density in the southwest was lower than that in the east.

Spatial distributions of pinch points, barriers, and restoration areas

By grading the cumulative current on the basis of natural breaks, 19 pinch points were identified, as shown in Fig. 6. Overall, these points were mainly concentrated in eastern Jinan, with a

total of 12 pinch points. The remaining 7 pinch points were located in southwestern Jinan. Among the administrative regions of Jinan, Zhangqiu District had the most pinch points, with a total of 8, followed by Changqing District (5), Licheng District (4), Pingyin District (1), and Huaiyin District (1). Pinch points were not identified in the remaining districts (Fig. 6).

By overlaying identified corridors with barriers, we found that 66.45% of the total area of barriers coincided with corridors, indicating that most barriers need to be improved. Barriers were divided into two parts by natural breaks based on the importance of connectivity recovery: high-level restoration areas and medium-level restoration areas. The coefficient of high-level restoration areas was between 0.99 and 2.95, and the coefficient of medium-level restoration areas was between 0 and 0.99. The corresponding areas covered 310 km^2 and 1136 km^2, respectively. As shown in Fig. 7, the high-level restoration areas covered mainly construction land (43.73%) and cropland (43.13%). The medium-level restoration areas covered mainly cropland (48.12%), followed by construction land (23.87%). The high-level restoration areas and medium-level restoration areas were distributed mainly in Zhangqiu District and northern Licheng District (Fig. 7).

After clipping the barriers, the remaining peripheries of corridors were low-level restoration areas, as shown in Fig. 6. The low-level restoration areas covered 564 km^2. The most common land-use types in the low-level restoration areas were
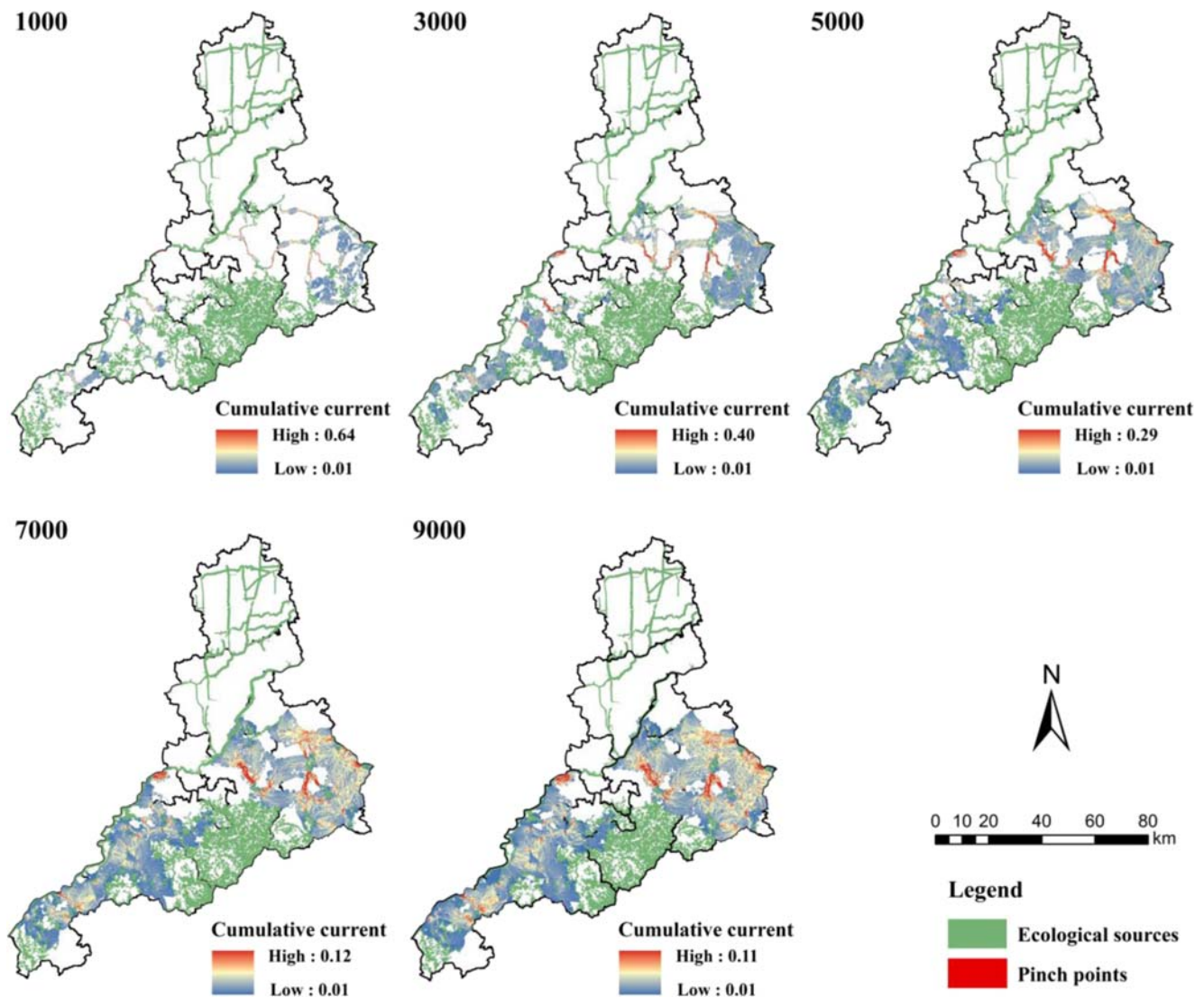
Fig. 5 Spatial distributions of ecological corridors for thresholds from 1000 to 9000

cropland (56.33%), followed by grassland (15.16%), forest land (10.53%), construction land (8.03%), and water bodies (4.11%). The low-level restoration areas were distributed mainly in Changqing District and Pingyin County (Fig. 7).

Construction of ecological security patterns

Viewed as a whole, the ESPs in Jinan consisted of ecological sources dominated mostly by forest land and water bodies connected by radial ecological corridors located in the plain below the mountains, including 25 ecological sources, 48 ecological corridors, 19 pinch points, barriers, and restoration areas. Four main parts of the ESPs could be distinguished, as follows: a northern ecologically natural area, a southern ecologically stable area, a western ecologically sensitive area, and an eastern ecologically fragile area.

The northern ecologically harmonious area was located mainly in Shanghe County and Jiyang County. No ecological corridors, pinch points or barriers were identified in this area. The river network was densely distributed in northern Jinan and constituted the connected ecological sources.

The southern ecologically stable area was located mainly in the Mount Tai area, south of Licheng District, and Changqing District. In this area, the ecological corridors were rare and very short. Forests were widely distributed in the southern part of the study area, providing carbon fixation and water conservation services for urban development. The few barriers identified in Shizhong District may be due to threats from urban expansion that hinders ecological processes in the east-west direction.

The western ecologically sensitive area was located mainly in Changqing District and Pingyin County. The average current density in this area was higher than that
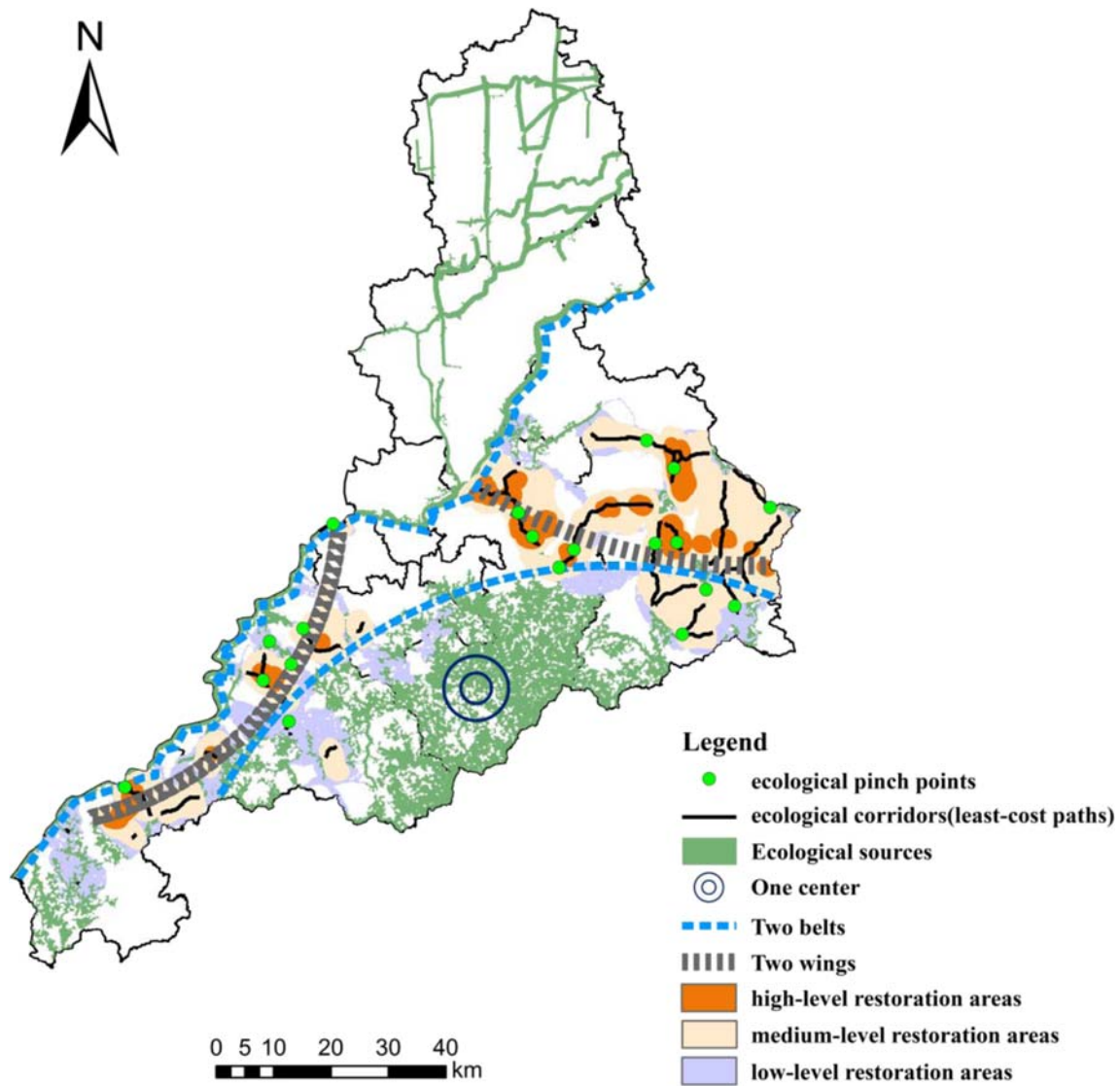
Fig. 6 Spatial distribution map of ecological security patterns

in the southern mountainous area. In addition, the ecological corridors in this area were short but numerous. The barriers in this area were located mainly near the Sha River, Nansha River, and Jinshui River. Two pinch points were located near the Yellow River. Five pinch points were located in the area between the Nansha River and Shahe River, near the breakpoints of two adjacent ecological source patches. Several pinch points were located in the center of the barriers, and future ecological restoration projects should be prioritized in these areas. Other pinch points and ecological corridors were located near the Yellow River. Therefore, the ecological security of these basins must be ensured in the process of urban development.

The eastern ecologically fragile area was located mainly in Zhangqiu District and northern Licheng District. The average current density in this region was higher than that in the western ecologically sensitive area. The ecological corridors in this area were long and numerous, forming a dense network connecting the surrounding small ecological sources. Barriers in the study area were concentrated in the east-central section of Jinan. Furthermore, the cumulative current in this region was much higher than that in the western ecologically sensitive area. A total of twelve ecological pinch points were identified in this region, all of which were close to ecological corridors. Eight ecological pinch points were located on the periphery of large-scale construction land, five of which were near the river. Four ecological pinch points were detected on the periphery of large-scale ecological sources. The steel, construction, and biological industries are prominent in this area. Rapid regional development has led to the degradation of local ecosystems. Ecological restoration projects should be concentrated in Zhangqiu District, where most restoration areas are located.
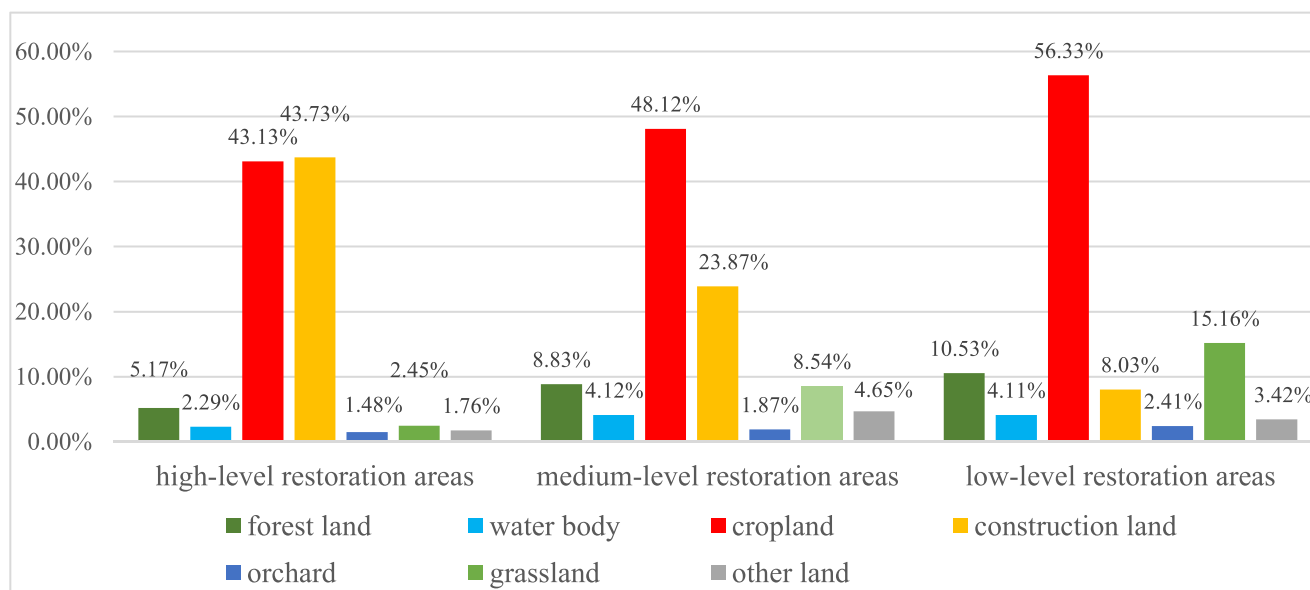
Fig. 7 The proportions of land-use types in restoration areas of different levels

Discussion

Differentiated development contradictions in restoration areas

The improvement of restoration areas has gradually become an important task in the context of urban planning for maintaining and improving ecological corridors (Peng et al. 2019). The ultimate goal of previous studies was usually to identify the spatial distribution of corridors; however, no definite restoration areas were given. In some identified restoration areas, uniform-width buffers were established around ecological sources according to subjective experience (Guo et al. 2019; Jian et al. 2017). This method has poor economic benefits in urbanized areas, as it does not incorporate land use and is difficult to implement. In this study, a hierarchical restoration area system was constructed on the basis of circuit theory.

In particular, improvement of restoration areas at different levels requires different costs. Generally, more advanced restoration areas correspond to higher costs. However, more advanced restoration areas also result in better landscape connectivity. High-level restoration areas are distributed around construction centers and cover mainly construction land, making them the main areas with contradictions between economic development and ecological protection. Such areas are the most prominent barriers to landscape connectivity, and removing or reducing barriers will lead to greater connectivity of the whole ecosystem. However, these areas also form the economic support or political centers in various administrative regions of Jinan, and performing ecological engineering-based construction such locations is difficult. Therefore, implementing ecological engineering, such as establishing green belts on both sides of the road, is usually suitable and

has low impact on preexisting buildings. Medium-level restoration areas are the largest of the three restoration areas. Compared with high-level restoration areas, the proportion of ecological land in such areas is larger, and the demand for construction land is lower. Medium-level restoration areas are important areas for the connection of ecological sources. Ecological construction should be concentrated at pinch points, and the allocation of ecological elements in such areas should be optimized. Furthermore, ecological construction should be diversified. In particular, based on the spatial distribution of pinch points, water bodies seem to be threatened by the expansion of construction land. In fact, the pollution and shrinking of rivers in Jinan have been serious in recent years. To solve these problems, a treatment project was carried out on malodorous rivers and reservoir connections in Jinan. Low-level restoration areas resemble irregular buffers around ecological sources. The proportions of forest land and grassland are high. The peripheral area of ecological corridors is used to provide services for the stability of ecological sources. In general, how to deal with the utilization of cropland in different locations seems to be very important for the ecological protection of Jinan city. In fact, the phenomenon of "land grabbing" between ecological construction and cropland protection has become increasingly prominent. Therefore, the importance of food conservation and ecological protection must be weighed in different locations.

Optimization strategy for ecological security patterns

To ensure ecological security and sustainable urban development, an optimization model of "one center, two wings, and two belts" (Fig. 6) was proposed based on the construction of ESPs in this paper. "One center" indicates that the southern

mountainous area (a large tract of ecological sources) should be given priority in ecological security protection and designated as the ecological center of gravity in Jinan, as it performs important ecological radiation functions. "Two wings" refers to the eastern and western sides of the southern mountainous area with parts of the plain, which are composed mainly of forest land and connected by cropland and water bodies. Many restoration areas are distributed in this region, representing priority areas for future ecological restoration actions. "Two belts" refers to the ecological isolation zones along the Yellow River and around the southern mountainous area; the former is composed mainly of wetland and forest land, while the latter is composed mainly of forest land and rainfed cropland. The optimization model provides an overall ecological strategy for urban planners.

The study area serves as an important industrial base. The recent increase in output was accompanied by the development of a large number of plots into industrial land, which led to ecological land loss and environmental pollution. To alleviate the contradiction between urban development and ecological protection, approximately 60 enterprises in the old eastern industrial zone were discontinued and relocated before May 2019, which reduced the number of polluting enterprises and provided more land. Furthermore, Jinan's 13th Five-Year Plan for eco-environmental protection proposed ecological engineering construction related to the "two belts". However, the ecological isolation zone is currently too small to play its intended role, and there is an overemphasis on landscape appearance and too little focus on ecological community stability. Therefore, the width and specific ecological engineering in this zone need to be improved.

Some ESP issues require further study. For example, the distribution of corridors with different resistance thresholds was analyzed in this study, revealing the same spatial distribution and different width ranges. Choosing a resistance threshold for the ecological layout requires more scientific information. This choice will affect the spatial distribution of the restoration area. Moreover, detailed improvement measures in the restoration area are worth further consideration. In this study, the layout of the ecological spatial elements was analyzed mainly at a macro scale. Nevertheless, ESPs should incorporate several topics, and landscape ecological processes at several scales should be fully analyzed. It is very likely that when we analyze the ESPs at a provincial or national scale, the layout of elements in Jinan will change. Then, the question of how to integrate different scales of ESPs arises. Different scales and different regions need to be further studied to solve these problems.

Conclusion

In this study, using GIS technology and spatial analysis models, important patches of ecological sources in Jinan were identified based on ecosystem services. Furthermore, the spatial distributions of ecological corridors, pinch points, barriers, and restoration areas were identified based on circuit theory, which provided a scientific method for identifying ecological elements and constructing ESPs. These elements constitute the ESPs of Jinan. The optimization pattern of "one center, two wings, and two belts" was proposed based on the construction of ESPs, providing spatial guidelines for ecological conservation in urban planning.

Compliance with ethical standards

Competing interests The authors declare that they have no competing interests.

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