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Ecological network construction and gradient zoning optimization strategy in urban-rural fringe: A case study of Licheng District, Jinan City, China

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A R T I C L E I N F O

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A B S T R A C T

Ecological network construction and optimization is an effective way to balance the contradiction between regional development and ecological protection in the process of urbanization. The urban–rural fringe is both a frontier zone in the direction of urban expansion and an important space for improving the urban ecological environment. However, there are few studies on how to construct and optimize the ecological networks in urban–rural fringe. In this paper, the morphological spatial pattern analysis (MSPA) and the minimum cumulative resistance model (MCR) were firstly employed to initially construct the ecological network and reveal the characteristics and problems of ecological security pattern in the study area. Then, a new ecological network optimization strategy with a multi-scenario coupling of urban–rural gradient spatial zoning was proposed to meet the maximization of integrated benefits of future urban development and ecological protection. The study results show that: (1) Urbanization caused a high fragmentation of ecological patches, and exerted a strong spatial hindrance to ecological processes. (2) The spatial distribution of the initially constructed ecological network was extremely uneven, and ecological communication in the north–south direction was severely difficult. The optimized ecological network was significantly improved in this respect, and the priority construction of important corridors will also help to strengthen ecological communication in the direction of urban–rural gradient. (3) The proposed optimization strategy improved the connectivity and accessibility of the ecological network in Licheng District, and enhanced its structure, which will promote the overall ecological process cycle and better balanced the urban development and ecological protection. (4) Policy makers should strengthen the construction and implementation of ecological green corridors and forest belts in urban–rural fringe to achieve a balance between urban development and ecological protection. This study can provide scientific references for biodiversity conservation, green infrastructure planning, and sustainable development in the process of urbanization.

1. Introduction

Rapid urbanization, while achieving rapid economic growth (Han et al., 2021), has also led to dramatic changes in land use/land cover (Gao et al., 2021; Li et al., 2019b) and has gradually changed the urban and rural landscape patterns (Modica et al., 2021). The continuous encroachment of urbanization on ecological patches will lead to a reduction in landscape connectivity, hinder ecological processes such as species migration and energy circulation. This will eventually produce a series of ecological problems such as ecosystem degradation (Li et al., 2019a), urban heat island (Ma et al., 2016), and biodiversity reduction (Zhang et al., 2017), which directly affects the urban ecological security (Peng et al., 2019) and sustainable development (Xu et al., 2022). Ecological network can couple landscape types with different ecological functions, to protect ecosystem biodiversity and the stability of ecological processes by improving regional landscape connectivity (Ma et al., 2022). In regional planning and sustainable development, the distribution of ecological networks and their protection or restoration

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are important in guiding land use processes, such as the layout and planning of residential and industrial areas, and the integration of urban planning and ecological networks is the basis for the conservation of biodiversity and good living conditions for human beings (Hou et al., 2023). Therefore, reasonable construction and optimization of ecological network is essential to improve eco-environmental quality, protect biodiversity, and safeguard sustainable development (Zhang et al., 2019).

Ecological network construction is an effective way to balance regional socioeconomic development and ecological protection (Zhang et al., 2022). After years of theoretical and methodological research, it has gradually developed into a research paradigm of "ecological source extraction – ecological resistance surface construction - ecological corridor simulation" (Gao et al., 2022; Wei et al., 2022). Ecological sources are habitat patches of species that are important for maintaining the integrity, connectivity, and stability of ecosystem (Jin et al., 2022). However, in the past decades, human activities (Qiu et al., 2022) and climate change (Yu et al., 2021) have led to the fragmentation, degradation, and even disappearance of a large number of ecological sources, which has resulted in their uneven distribution. Therefore, in practical application, it is often necessary to supplement ecological sources by means of ecological protection and restoration in the regions lacking ecological sources to improve the balance of the spatial distribution of ecological sources (Nie et al., 2021). For example, Cui et al., (2022) increased the size of ecological patches by establishing buffer zones in areas lacking ecological sources to provide ecological services for humans while providing ecological sources for species' habitats. Huang et al. (2021) considered the coordination of economic development and ecological protection, and kept the production and living land unchanged while expanding the existing ecological patches area and improving the ecological quality. Additionally, ecological corridors, as channels for ecological processes such as species migration and energy flow, often suffer from a lack of spatial connectivity or a decrease in spatial connectivity efficiency due to the unbalanced distribution of ecological sources. Therefore, some scholars suggested selecting patches with certain ecological functions as stepping stones linking ecological corridors (Luo et al., 2020) to provide rest and transit places for species migration. This would improve the migration efficiency and survival rate of species (Dong et al., 2015), and ensure the structural stability of ecological network (Wang et al., 2022a). In addition, some scholars have also suggested optimizing the internal structure of ecological corridors by constructing ecological patches of optimal distance and area as intersections of ecological corridors (ecological nodes), thereby enhancing the connectivity of ecological networks (Fu et al., 2022). However, regions are generally spatially heterogeneous in terms of the natural background conditions, land use structure, or economic development level. At present, less attention has been paid to this spatial heterogeneity in existing ecological network optimization studies, which will affect the feasibility of its application to guide urban ecological protection, restoration, construction, and planning.

The urban–rural fringe is located between the urban and rural, which is a transition zone generated by the interaction between the urban and rural. Here, the mutual nesting and influence between the urban and rural gradually deepen, and the boundaries become increasingly blurred (Peng et al., 2016). At the same time, the urban–rural fringe is the frontier of gradient expansion of urban to rural, and the encroachment of construction land on ecological land is the most dramatic (Ke et al., 2021). However, the destruction and the creation coexist, and the urban–rural fringe is also in a special position in the urban ecological pattern, with strong ecological functions and large leeway. It is an important zone to improve the urban ecological environment, connecting the ecological space of the urban–rural gradients, and promoting the cycle of ecological process (De Montis et al., 2016). However, there are few studies on the ecological status and the construction and optimization of ecological network in the urban–rural fringe. Therefore, the overall ecological protection and sustainable development of cities are greatly impacted by the construction and optimization of ecological networks in the urban–rural fringe.

To address the aforementioned problems, this study took the Licheng District of Jinan City, China as the study area, and attempted to explore "site-specific" ecological optimization idea and method that takes into account the comprehensive benefits of urban development and ecological protection for the urban–rural fringe. The main research objectives are: (1) to analyze and reveal the characteristics and problems of ecological security pattern in the study area by constructing an ecological network; (2) to propose a comprehensive optimization strategy of coupling multiple scenarios of urban–rural gradient zoning to optimize the ecological network in the study area. The study results will provide scientific references for the protection, construction, and planning of ecological space in the urban–rural fringe in the context of rapid urbanization development, which is of great significance for urban sustainable development.

2. Study area and data sources

2.1. Study area

The lower reaches of the Yellow River Basin in China are characterized by intense human activities, sensitive and fragile ecological environment, and especially severe water scarcity. As a mega-city in the lower reaches Yellow River Basin, Jinan City is experiencing rapid urbanization, population growth, and Gross Domestic Product (GDP) growth (Yu et al., 2022). The study area is Licheng District, located in the southeast of Jinan City (116°55′24″-117°22′15″ E and 36°19′51″-36°53′45″ N, Fig. 1), with a total area of 1306.31km^2.

In 2003, Jinan City established the urban development strategy of "eastward expansion, westward advancement, southward controlling, northward spanning, and central dredging". Which, Licheng District plays the pivotal role of linking the east and the west, connecting the north and the south, and is an important "growth pole" for Jinan's modernization construction to extend from urban to rural, as well as the "main battlefield" for realizing high-speed economic development to high-quality economic development (Zhang et al., 2012).

The development plan of Licheng District from 2016 to 2020 is set to implement the ecological protection of the Yellow River Basin and the southern mountainous, as well as to realize the major strategy of high-quality development in the east and north. Under the guidance of this strategic plan, the urban area of Licheng District expanded rapidly along the urban–rural gradients, and the corresponding population and GDP increased significantly, resulting in an increasingly prominent conflict between economic development and ecological protection.

2.2. Data sources

(1) Gaofen-2 remote sensing image data

This study is aimed at small-scale areas, so Gaofen-2 high-resolution images (resolution of 2 m) were used to obtain the distribution status of ecological land in Licheng District under the background of rapid urbanization as refined as possible. The Gaofen-2 images were Panchromatic Multispectral Cameras (PMS) products in 2019 and downloaded from the China Center for Resources Satellite Data and Application (https://www.cresda.com). After preprocessing the image data, the object-oriented classification method based on the random forest model in eCognition 9.0 software was used to classify the image into seven types of land use/land cover: farmland, construction land, unutilized land, forest land, grassland, orchard, and water (Fig. 1). The classification results were verified by the samples obtained from the national geo-information survey data of Jinan City, and the overall accuracy reached 85%, which met the requirements of this study.

(2) DEM data

Digital Elevation Model (DEM) data were mainly used to construct topographic resistance surfaces and to analyze the hindering effects of

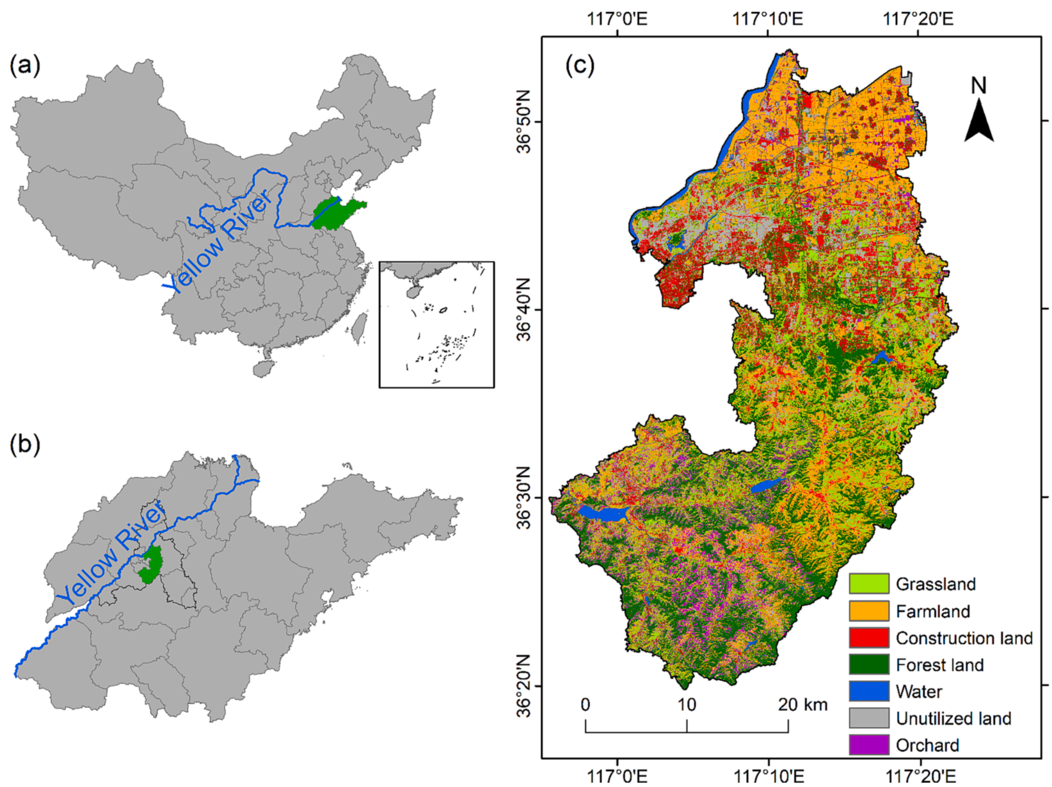

Fig. 1. Overview of the study area: (a) Location of the Shandong Province in China; (b) Location of the study area in Shandong Province; (c) Land use/land cover of the study area.

natural topographic factors such as elevation and slope on ecological processes. The DEM data were ASTER GDEM V2 released in 2015, from the Geospatial Data Cloud (https://www.gscloud.cn), with a spatial resolution of 30 m. The slope was then calculated using the slope tool in ArcGIS 10.7 software.

(3) VIIRS NTL image data

The Visible Infrared Imaging Radiometer Suite (VIIRS) Nighttime Light Data (NTL) image data was mainly used to construct the resistance surface of human activities and to analyze its hindering effect on ecological processes. The data was the Annual VIIRS nighttime lights V2 product in 2019 from Earth Observation Group (https://eogdata.mines.edu) with a spatial resolution of 500 m. The product was processed for moonlight, clouds, and most fires. Compared with ordinary remote sensing images, nighttime light images more directly reflect human activities (Chen et al., 2021), and have been proven to be significantly correlated with human socio-economic activities, which can reflect the difference in socio-economic development between urban–rural gradient and the intensity of human activities (Levin et al., 2020).

3. Methods

The technical framework of this study consisted of four steps, as shown in Fig. 2. Firstly, the spatial zoning of urban–rural gradient was carried out according to the difference in land use structure. Then, the ecological network of the study area was constructed. Third, based on the urban–rural gradients spatial zoning of the study area, a multi-scenario coupled ecological network optimization strategy was proposed. Finally, the ecological network structure before and after

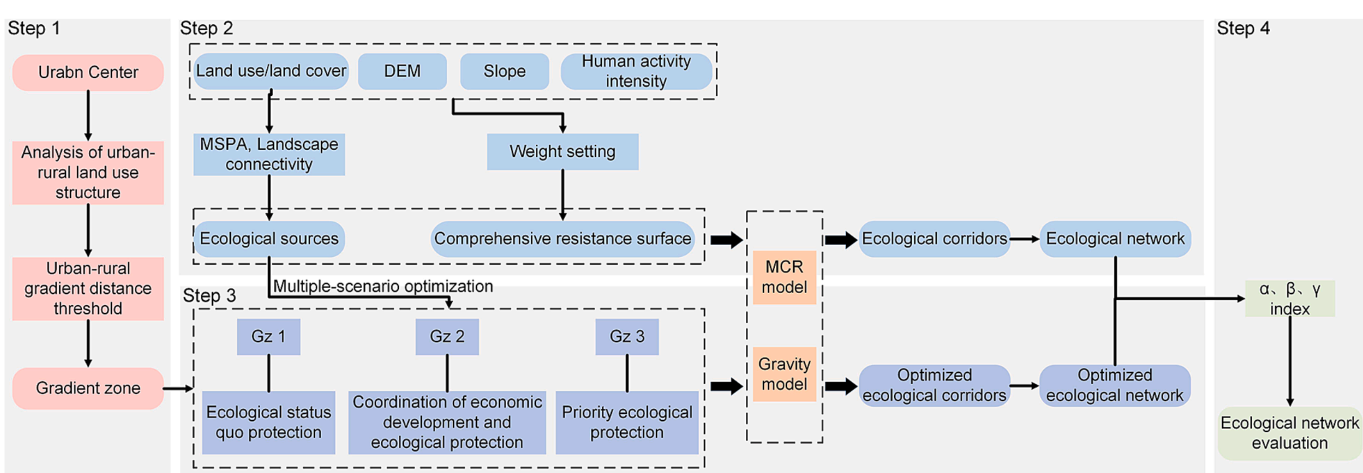

Fig. 2. The technical framework for constructing and optimizing ecological network.

optimization was compared using the graph theory-based network structure index.

3.1. Urban-rural gradients spatial zoning

The building density, economic activity, and landscape between urban and rural are transitional changes (Ye et al., 2018). To be able to reveal the differences in land use structure between urban and rural, an urban–rural gradient analysis (Hou et al., 2015) was used here to spatially zone the study area. One of the gradient patterns is concentric rings scattered from the urban center to the rural (Kroll et al., 2012). The other gradient pattern is the transect extending from the urban center to the rural (Zhou and Wang, 2011). In this study, to facilitate spatial statistical analysis, we used the concentric rings analysis (i.e., buffer zone method) to spatially describe the changes in land use structure in the direction of urban–rural gradients in Jinan City.

First, the urban center of Jinan City was determined based on the 2019 nighttime light images combined with the 2011–2020 land use planning map of Jinan Central City (Jinan People's Government, https://www.jinan.gov.cn). Then, the proportion of land use/land cover from the urban center to the rural was counted at an interval of 0.5 km (Fig. 3). The analysis revealed that the urban–rural gradients can be divided into four sections. Of these, the second and third sections were located in the range between 7 and 27 km. The widths of each of the two sections accounted for about half of this range, i.e., 10 km. Meanwhile, we referred to the buffer zone distance established by the existing studies (Ye et al., 2018). Finally, 10 km was taken as the buffer zone distance of the urban–rural gradients spatial zoning in this study (Fig. 4a), and obtained the result shown in Fig. 4b.

The gradient zone 1 (Gz 1) was located in the urban edge zone, with an area of 65.00 km^2, which was more densely populated and still had a high level of urbanization. The land use structure of gradient zone 2 (Gz 2) and gradient zone 3 (Gz 3) were generally similar, with the largest area of ecological land, followed by farmland, construction land, and unutilized land, and thus both belonging to the urban–rural fringe in terms of attributes. However, Gz 2 is more adjacent to the urban edge and spatially belongs to the suburban contiguous area, while Gz 3 is more adjacent to the rural and spatially belongs to the rural contiguous area, and their land use/land cover percentages slightly differ. Therefore, they were divided into two gradient zones based on the buffer zone distance threshold (10 km), with areas of 488.67 km^2 and 567.16 km^2, respectively. The gradient zone 4 (Gz 4) was the natural rural area, which is far away from the urban center and located in the southern mountainous area. The ecological land in this zone occupied an absolutely large proportion and was in good ecological status, with an area of 185.49 km^2.

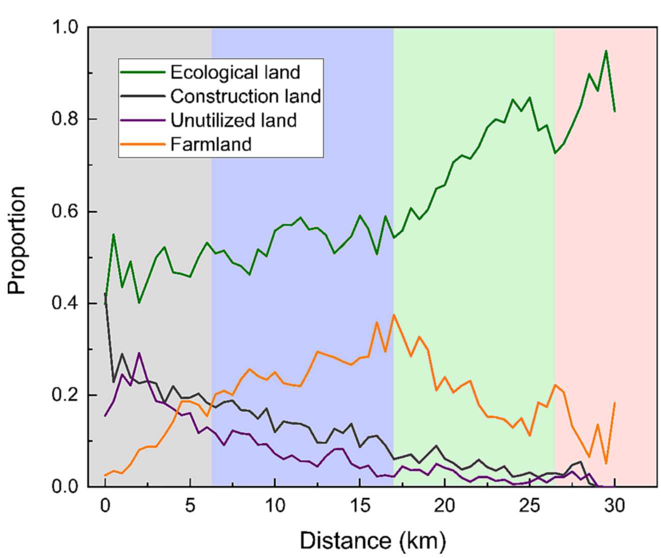

Fig. 3. Proportion of each land use/land cover on each gradient. Where the gray panel represents the first section, the purple panel represents the second section, the green panel represents the third section, and the red panel represents the fourth section.

3.2. Ecological network construction

3.2.1. Ecological source extraction

The extraction of ecological sources was performed using the Morphological Spatial Pattern Analysis (MSPA) and the landscape connectivity. Compared to other methods, this approach emphasizes structural connectivity and relies only on land use/land cover data, avoiding subjectivity in the selection of ecological sources and increasing the scientific validity of ecological source and corridor extraction. MSPA is based on the concept of mathematical morphology (Soille and Vogt, 2009), which uses pixels as the unit of computation to identify areas that have an essential impact on the overall connectivity of the ecological network (Cui et al., 2020). The MSPA is calculated by the Guidos Toolbox 2.8 software (https://forest.jrc.ec.europa.eu/en/), and the edge width can be chosen according to pixel (Carlier and Moran, 2019). After the MSPA calculation, seven morphological categories of core, islet, perforation, edge, loop, bridge, and branch can be obtained (Table 1). Among them, only core and bridge contribute to ecological connectivity and are important for ecological processes (Lu et al., 2022), which is one of the necessary conditions for determining ecological sources.

Landscape connectivity indicates the role of landscape type in facilitating or hindering species dispersal processes in ecological patches (Hu et al., 2022). We used the Conefor 2.6 software (https://www.conefor.org) to calculate the probability of connectivity (PC) and the delta of PC (dPC) of the cores to rank their importance and thus further extract ecological sources from cores.

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

$$dPC(100\%) = \frac{PC - PC'}{PC} \times 100\% \quad (2)$$

where n is the total number of patches in the landscape, a_i and a_j represent the area of patches i and j, respectively, A_L is the area of the total landscape in the study area, P_{ij} represents the maximum product of the probabilities of all path between patches i and j, PC denotes the possible connectivity of a patch in the landscape, and PC' denotes the possible connectivity index of the remaining patches after removing a certain patch.

3.2.2. Ecological resistance surface construction

The resistance surface reflects the resistance to ecological processes, such as the degree of difficulty for species to traverse different patches (Peng et al., 2018). In this study, forest land and grassland, as ideal habitats for most species and are less disturbed by human activities, so they were assigned lower resistance values. Water are essential habitats for the survival of species, but have a hindering effect on the migration of some species. Construction land, such as buildings and roads, has a very strong hindering effect on species migration. Besides, topography is also a crucial factor affecting species migration. Lower elevation and relatively flat terrain are more conducive to species dispersal. In addition, urbanization leads to the increase in human activity intensity and range, which also has a strong hindering effect on species migration. In this study, the brightness values of nighttime light images were used to characterize the intensity of human activities. According to the existing studies (An et al., 2021; Ye et al., 2020), the resistance values and

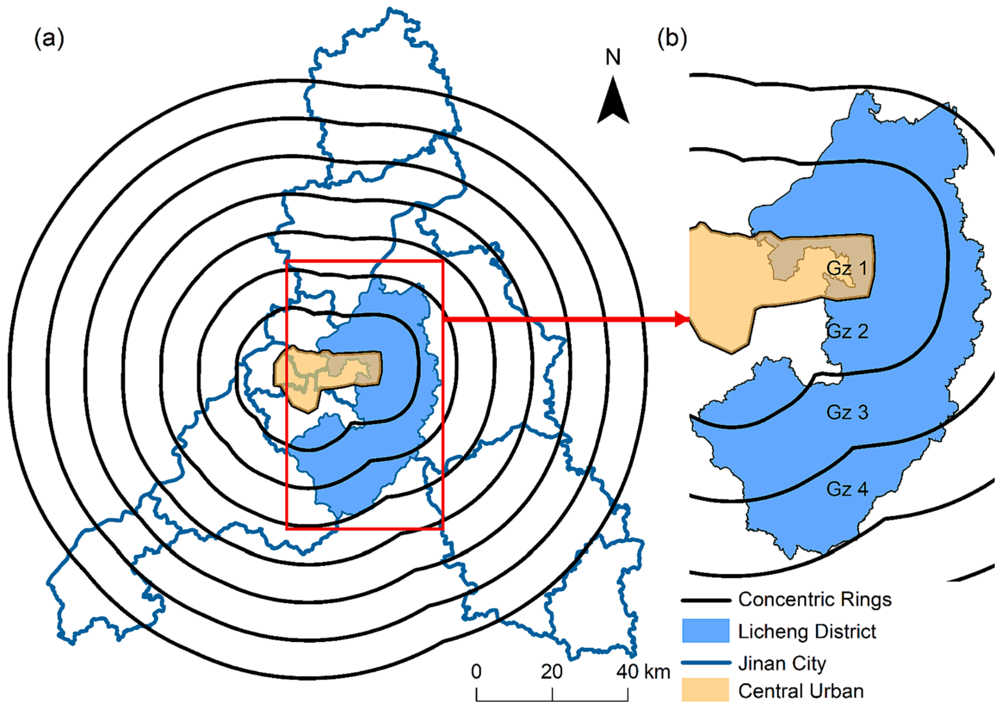

Fig. 4. Urban-rural gradients zoning. (a) Urban-rural gradients zoning of Jinan City. (b) Urban-rural gradients zoning of Licheng district.

Table 1
Pattern classes of MSPA and their ecological meanings.

Pattern class	Ecological meaning
Core	Larger habitat patches in foreground can provide habitats for species, which are important for biodiversity conservation and are ecological sources in the ecological network.
Islet	Small patches are weakly connected, with less potential for material transfer and energy exchange.
Perforation	The edge of the internal patch (edge effect), is the transition zone between the core and the non-green landscape patches.
Edge	The transition zone between the core and the main non-green landscape patches.
Loop	Corridors connecting the same core, shortcuts for species migration within the same core.
Bridge	Narrow and long area that connecting the core and provide corridors for species diffusion and energy exchange between adjacent core.
Branch	Only one side is connected to the perforation, edge, loop, or bridge.

weights corresponding to the four resistance factors of elevation, slope, land use/land cover, and human activity intensity were set as shown in Table 2. On this basis, the comprehensive ecological resistance surface was obtained by weighted summation.

3.2.3. Ecological corridor simulation

Minimum cumulative resistance model (MCR) can reflect the possibility and trend of material energy and species movement in landscape patches (Huang et al., 2020). It generates potential ecological corridors by calculating the path of minimum cumulative resistance of species migration between the source and the target (Wang et al., 2021). Therefore, the MCR model was used in this study to simulate potential corridors for animal community migration.

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

where D_{ij} denotes the distance from patch i to patch j and R_i denotes the resistance coefficient of patch i to ecological processes. n is the number of sources, and m denotes the number of resistance surface grids.

Table 2
Ecological resistance factors and its resistance values and weight settings (Li et al., 2022).

Resistance factor	Classification	Resistance value	Weights
Elevation	<200 m	15	0.25
	200 m–400 m	30	
	400 m–600 m	55	
	600–800 m	80	
	>800 m	100	
Slope	<5°	5	0.22
	5°–15°	20	
	15°–25°	40	
	25°–35°	60	
	35°–45°	80	
	>45°	100	
Land use/land cover	Forest land	5	0.17
	Grassland	15	
	Orchard	30	
	Water	50	
	Unutilized land	60	
	Farmland	80	
	Construction land	100	
Human activity intensity	<5	5	0.36
	5–20	15	
	20–40	30	
	40–80	60	
	>80	100	

The gravity model is used to quantitatively evaluate the interaction force between ecological sources. The greater the force, the higher the relative importance of the corridors, so the priority of the ecological corridor can be effectively determined (Hu et al., 2022). The calculation formula is as follows:

$$G_{ij} = \frac{N_i \times N_j}{D_{ij}^2} = \frac{\left[\frac{1}{P_i} \times \ln(S_i)\right]\left[\frac{1}{P_j} \times \ln(S_j)\right]}{\left(\frac{L_{ij}}{L_{max}}\right)^2} = \frac{L_{max}^2 \times \ln(S_i) \times \ln(S_j)}{L_{ij}^2 \times P_i \times P_j} \quad (4)$$

where G_{ij} is the strength of the interaction between patch i and j, N_i and

N_j represent the corresponding weight values of source i and j, respectively; D_{ij} is the normalized resistance value between patch i and j; P_i and P_j are the cumulative resistance values of patch i and j respectively; S_i and S_j are the area of patch i and j respectively; L_{ij} is the cumulative resistance value of corridors between patches i and j; L_{max} is the maximum cumulative resistance value of all the corridors in the study area.

3.3. Ecological network optimization strategy

Urbanization tends to cause the uneven spatial distribution of regional ecological network components, which hinders the overall ecological process cycle of the region. Optimization of the spatial pattern of ecological networks is often required to promote ecological safety and sustainable development. However, there are significant differences in the land use/land cover structure and demand in different spatial regions of the urban–rural gradient. Therefore, this study proposed an ecological network optimization strategy that “site-specific recommendation” and considers the comprehensive benefits of urban development and ecological protection (Fig. 5).

Gz 1 is the edge of the urban center, where the population density is relatively high, and the spatial distribution of production and living land is dense and occupies a relatively high proportion. The overall demand for construction land in this area is strong in the process of urbanization, so it is difficult to adjust the land use structure. The protection of existing ecological land (such as parks, etc.) should be strengthened within this zoning area to enhance the ecological quality, service functions, and stability, and improve its potential to become an ecological source or stepping stone.

In Gz 2, the interaction between urban and rural is relatively high, and production and living land still occupy a certain proportion. The scheme of coordinating economic development and ecological protection can be adopted in this zone. First, the ecological buffer zones were established by selecting the core with a certain area in the areas lacking ecological sources, and preserving the ecological safety distance to enhance the size of ecological core areas. Then, the ecological service function and stability of the core are improved by promoting the transformation of other lands in the buffer zone into ecological lands keeping the production and living lands in the buffer area unchanged. The setting of the ecological buffer zone should consider the optimal distance threshold. Therefore, it is determined by analyzing the proportion of construction land, farmland, unutilized land, and ecological land in the buffer zone. With the expansion of the buffer zone, when the proportion of each land use/land cover within it no longer changes, this buffer zone has the lowest land adjustment cost and significantly improved ecological function, and it can be used as the best buffer zone.

In Gz 3, the interaction between urban and rural is relatively weak, and the proportion of production and living lands is relatively low. Therefore, the same means of ecological improvement and optimization in Gz 2 can be adopted, but ecological protection should be given priority. In the process of implementation, other lands can be transformed into ecological lands, and their ecological quality and functions should be ensured not to be destroyed by urban development and rural construction, so that they can become ecological sources with certain stability and scale.

3.4. Ecological network evaluation

Firstly, spatial statistical methods were applied to analyze the changes in ecological source area and ecological corridor length within each gradient before and after optimization. Secondly, to compare the effects of ecological network on ecological processes before and after optimization, the network structure evaluation index based on graph theory was adopted here. Among them, α index is the ratio of the actual number of loops in the network to the maximum possible number of loops, which is used to describe the degree of loop occurrence. β index is the ratio between the number of corridors and the number of nodes, which reflects the relationship between corridors and nodes, and is used to measure the degree of network accessibility. γ index is the ratio of the number of corridors in the network to the maximum possible number of nodes, which is used to describe the degree of all connected nodes in the network. A larger value indicates better network connectivity (Miao et al., 2019).

$$\alpha = \frac{L - v + 1}{2v - 5} \quad (5)$$

$$\beta = \frac{L}{v} \quad (6)$$

$$\gamma = \frac{L}{L_{max}} = \frac{L}{3(v - 2)} \quad (7)$$

where L is the number of corridors in the ecological network, L_{max} is the maximum possible number of connected corridors, and v is the number of intersecting nodes of corridors.

4. Results

4.1. Results of ecological network construction in Licheng District

4.1.1. Distribution pattern of ecological sources

In Fig. 6a, the total area of the core of Licheng District was

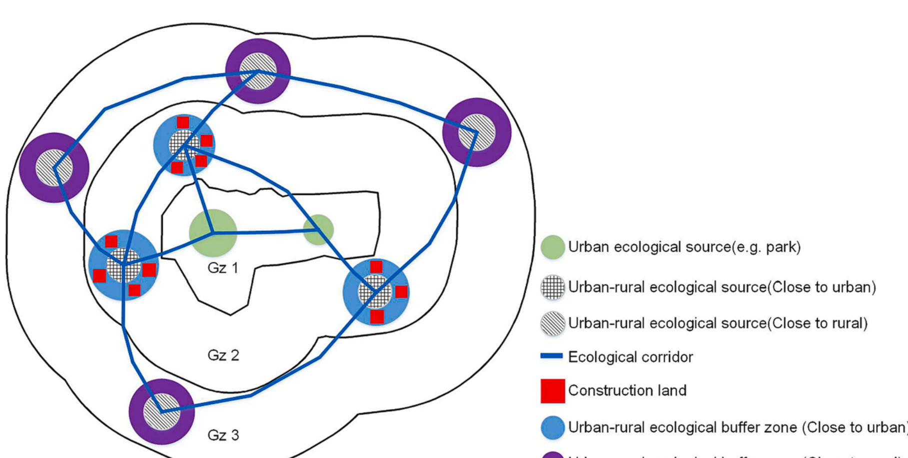

Fig. 5. Schematic diagram of the zonal multi-scenario integrated optimization strategy for ecological networks.

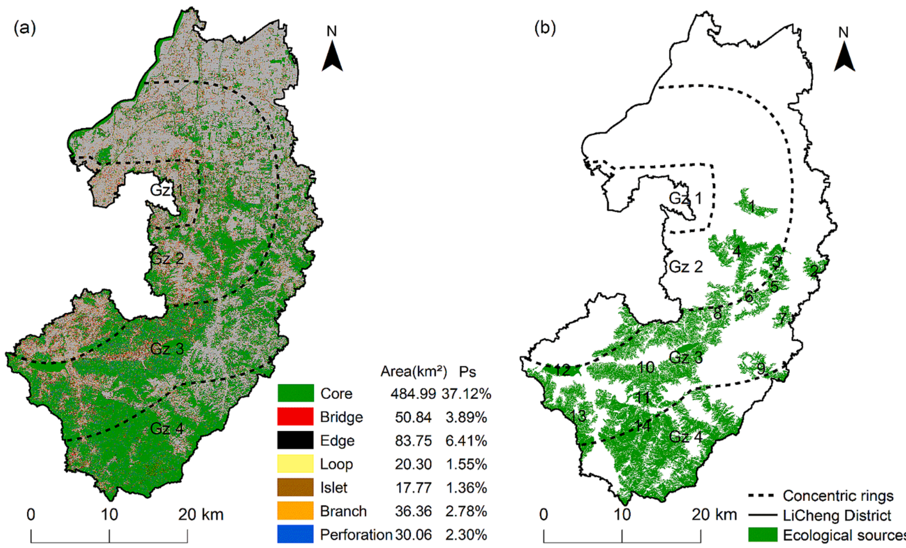

Fig. 6. Distribution of MSPA landscape types and ecological sources. (a) is the result of MSPA, Ps indicates their proportion in the study area. (b) is the distribution of ecological sources.

484.99 km^2, accounting for 37.12% of the total area. However, the spatial distribution of ecological core patches within each zone of the urban–rural gradients varied greatly. In comparison to the rural gradient zone, the urban edge gradient zone saw far more ecological core patch fragmentation, and the fraction of core patches was significantly smaller (Fig. 7). Additionally, the proportion of the core patches (< 0.5 km^2) is very high (99.97%), accounting for about two-thirds of the core area, which further reflects the high degree of landscape fragmentation caused by urbanization. The loop is crucial for promoting species migration and energy exchange within the same patch, but it only accounted for 1.55% of the total area, which indicated the poor species migration within core patches in the Licheng District.

With a patch connectivity threshold of 5 km and a connectivity probability of 0.5 (Xiao et al., 2020), connectivity analysis was conducted for core patches larger than 1 km^2. The 14 patches with dPC greater than 2 were finally extracted as ecological sources (Fig. 6b), with a total area of 270.08 km^2. According to the spatial distribution of ecological sources, these were mainly distributed in the center and south of the Licheng District, with a highly uneven spatial distribution and a serious north–south fault that significantly affected the connectivity of ecological processes in the north–south direction. Therefore, it is necessary to strengthen the construction and protection of the northern ecological sources to ensure the balance of the north–south ecosystem in the Licheng District.

4.1.2. Distribution pattern of ecological resistance surface

The spatial distribution of each factor resistance and comprehensive resistance are shown in Fig. 8. Where the high resistance areas of elevation and slope were mainly distributed in the central and southern mountainous. The resistance of high-intensity human activities to ecological processes was mainly distributed in the northern densely populated areas. In addition, because farmland was mainly distributed

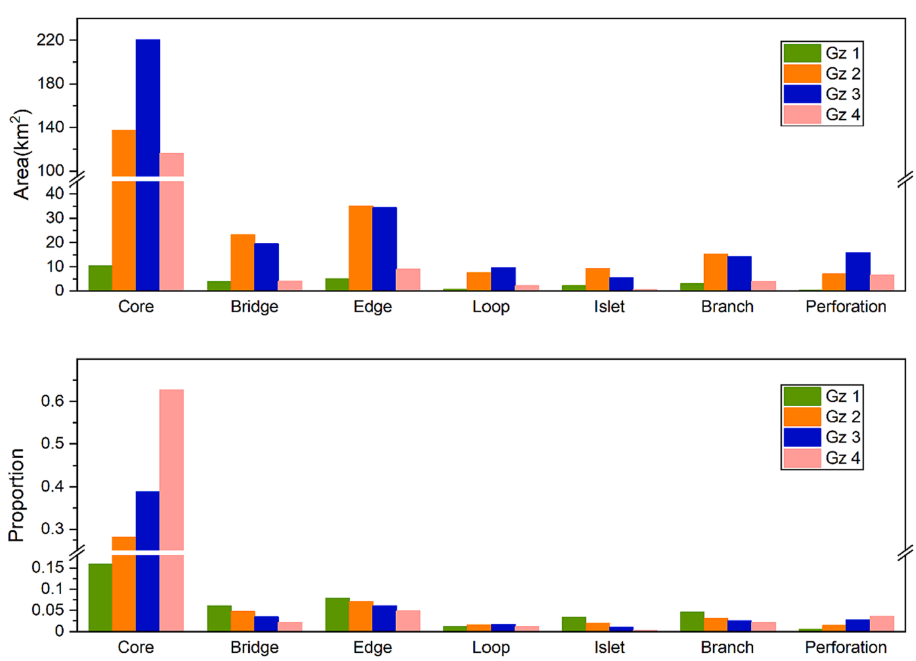

Fig. 7. Area and proportion statistics of MSPA landscape types in each gradient zone.

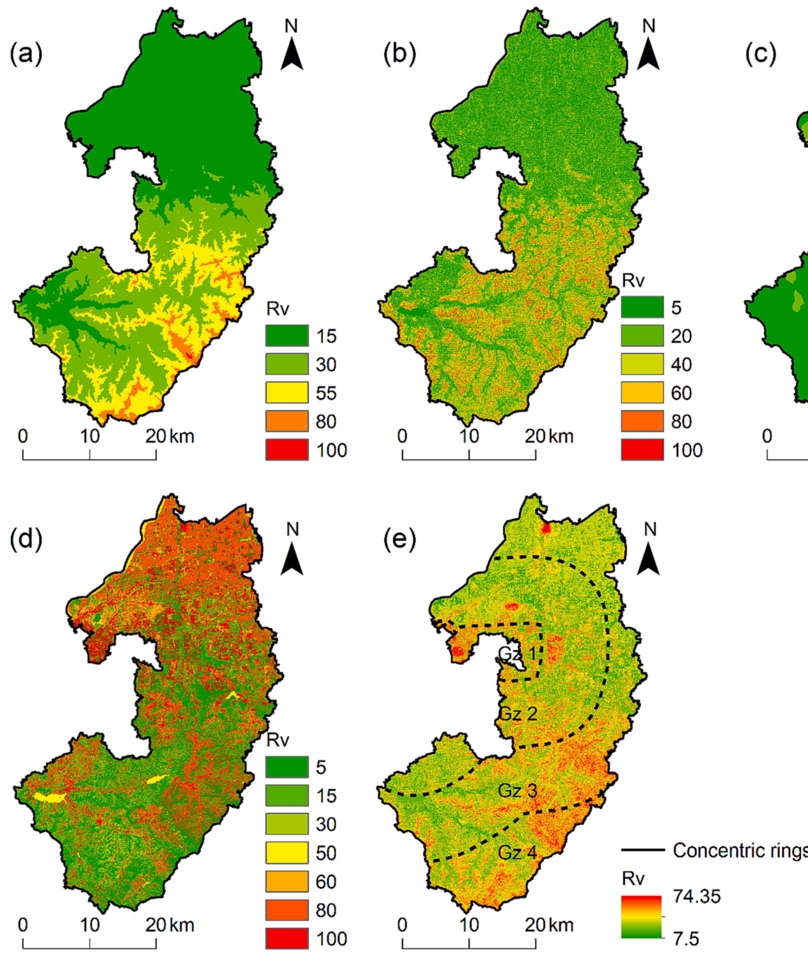

Fig. 8. Spatial distribution of ecological resistance surfaces. (a) is resistance surface of the elevation. (b) is resistance surface of the slope. (c) is resistance surface of the human activity intensity. (d) is resistance surface of the land use/land cover. (e) is the comprehensive resistance surface. Rv indicates the resistance value.

in the north, which was the main area of urban expansion, the resistance of land use/land cover to ecological processes in the north was relatively high. At the same time, since there were many villages and towns in the central and southern mountains, and their construction and development also formed a high resistance to ecological processes. According to the results of the spatial distribution of the comprehensive ecological resistance surface, part of the high-resistance area was located near the northern urban edge (between Gz 1 and Gz 2). This was the main area of urban expansion with dense land for production and living. There was also a high resistance area in the north of Gz 3, where Jinan Yaoqiang International Airport is located, with a high degree of construction. In addition, there was another part located in the southeast of Licheng District, where the high elevation, steep slopes, and the development of villages and towns make the ecological resistance higher. Overall, high ecological resistance areas in Licheng District were distributed in all gradient zones, but the overall distribution had obvious regional heterogeneity. Of which, urbanization and topography were the dominant factors hindering ecological processes.

4.1.3. Distribution pattern of ecological corridors

Based on the extraction of ecological sources and the construction of ecological resistance surfaces, 56 potential corridors were identified using the MCR model, with a total length of 218.46 km (Fig. 9). In addition, the intersections of ecological corridors (ecological nodes) are key points in the ecological network and provide important resting places for species migration (Tang et al., 2021). Therefore, this study further identified 40 ecological nodes, which were concentrated in the east-central part of Licheng District. We used the gravity model to calculate the interactions among ecological sources (Fig. 10), and classified 14 ecological corridors with interaction forces greater than 13 (the corridors in the top 25 % of importance) as important corridors and the rest as general corridors. In Fig. 9, it can be seen that ecological corridors were mainly distributed in Gz 2, Gz 3, and Gz 4, and are connected by important corridors. This plays a crucial role in the connection of ecological processes between the urban–rural fringe and natural rural areas. However, we can also find that the ecological corridors are concentrated in the middle and south of Licheng District. The uneven distribution of ecological sources caused the lack of connection of ecological processes between the north and the south.

4.2. Results of ecological network optimization

According to the original ecological network of Licheng District, the ecological security problem was mainly reflected in the lack of ecological sources in the north the poor ecological communication between urban and rural gradients. Considering the future urban expansion and the demand for ecological protection, this study used the proposed ecological network optimization strategy based on gradient zoning to optimize the element composition and spatial distribution of the ecological network in the urban–rural fringe. Firstly, the Yellow River, a key ecological protection area in Licheng District, and the core patches with certain ecological service potential (area larger than $0.2 km^2$) within the Gz 1, Gz 2 and Gz 3, were taken as the key ecological spaces for protection and construction to compensate for the lack of ecological sources in the north. Then, a sequence-scale buffer zone analysis was performed for the newly incorporated core patches in the north of the

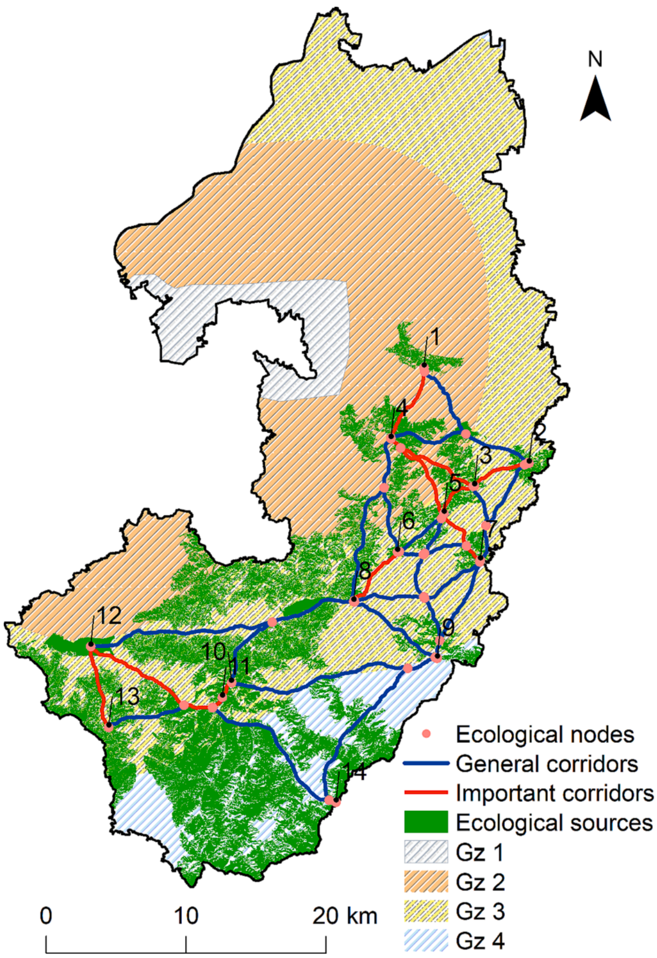

Fig. 9. Spatial pattern of ecological network in Licheng District.

urban–rural fringe (Gz 2 and Gz 3) (Fig. 11). When the buffer zone distance reaches 700 m, the proportion of each land use/land cover basically did not change. Therefore, considering the cost of ecological protection for land use/land cover adjustment, 700 m was taken as the scale range of ecological construction and protection in the urban–rural fringe. Then, the supplementary core patches were planned and optimized according to the coordination scenario of urban development and ecological protection and the priority scenario of ecological protection. Finally, the ecological corridor was simulated according to the results of ecological source optimization, and the optimized ecological network was constructed.

The optimized ecological network consisted of 23 ecological sources and 99 potential corridors (Fig. 12). Among them, 9 ecological sources with an area of 79.51 km^2 were added to the north, which filled the gap of lacking large ecological sources. The total length of the optimized ecological corridors reached 442.06 km, and 27 ecological corridors with interaction forces greater than 35 (the corridors in the top 25 % of importance) were classified as important corridors (Fig. 13). The urban edge zone (Gz 1) and the urban–rural fringe (Gz 2 and Gz 3) had seen significant increases in the area of ecological sources and the length of ecological corridors (Fig. 14). Their ecological spatial layout was optimized, which reduced the cost-weighted distance in each zone. From the perspective of overall spatial distribution, the elements of the optimized ecological network were more balanced. Wherein, most of the important corridors were concentrated in the north, forming cross-regional connections between Gz 1, Gz 2, and Gz 3. This indicates that the adoption of this scheme to strengthen the construction of the northern ecological corridors will be conducive to the circulation of ecological processes between urban and rural, and may help to solve the problem of segregation of urban–rural gradient ecological process (Liang et al., 2022). Additionally, the evaluation of the ecological network structure (Table 3) showed that the optimization strategy proposed in this study improved the ecological network's connectivity and accessibility with a more complete structure.

5. Discussion

5.1. Spatial pattern and optimization of ecological network in Licheng District

Although Licheng District has more than 50% of the ecological space, it is faced with serious ecological security problems. On the one hand, the central and southern regions had the majority of ecological sources with stable ecological quality and robust ecological service functions, whereas the north lacked ecological sources due to the high degree of ecological land fragmentation. To a certain extent, this exacerbated the uneven distribution of biological habitats and led to a decline in biodiversity. On the other hand, the relatively dense distribution of production and living spaces and the high intensity of human activities in the north of Licheng District, resulted in high ecological resistance. Due to the coupling effect of high ecological resistance and fragmented ecological space, there was no ecological corridor for species migration in the north of Licheng District. As a result, the ecological network in Licheng District presented a spatial imbalance of ecological elements and a north–south disconnection pattern of ecological processes.

Similar to many urban development plans and ecological security strategies (He and Chen, 2022; Hou et al., 2022), Jinan City established the urban spatial development strategy of "eastward expansion, westward advancement, southward controlling, northward spanning and central dredging" according to its natural conditions in 2003. In the process of urbanization, it is necessary not only to protect the Yellow River from development, but also to control the overdevelopment of the southern mountainous. As a result, "eastward expansion" and "westward advancement" were the dominated behind Jinan City's urban development, with the northern half of Licheng District at the forefront. This indicates that the spatial development strategy at the urban scale is the main factor affecting the exchange of ecological processes between the north and the south of Licheng District. This also shows that sustainable urbanization requires both a reasonable spatial development strategy at the urban scale and a feasible ecological protection strategy at the regional scale.

Therefore, from the regional scale, the proposed zonal optimization strategy was used to optimize the ecological network of Licheng District for the urban–rural fringe with strong ecological cyclotron function. After optimization, the balance of spatial distribution of ecological sources and corridors in Licheng District has been significantly improved, and the ecological circulations between the north and the south and between the zones of the urban–rural gradient are obviously enhanced. In the context of rapid urbanization, this will support the overall cycle of ecological processes, which helps realize the aim of sustainable terrestrial ecosystems (Sustainable Development Goals 15) (Manolis and Manoli, 2021). Additionally, this strategy will provide more residents green space with ecological services like air purification, leisure, and entertainment by optimizing the spatial distribution of ecological sources and enhancing ecological quality. This will improve the unfairness of the green infrastructure and help to realize the objective of sustainable cities and communities (Sustainable Development Goals 11) (Eisenmenger et al., 2020).

5.2. Proposals for ecological network implementation

The ecological security problem in Licheng District is mainly manifested by the uneven distribution of ecological sources from north to south and the poor ecological communication between urban and rural

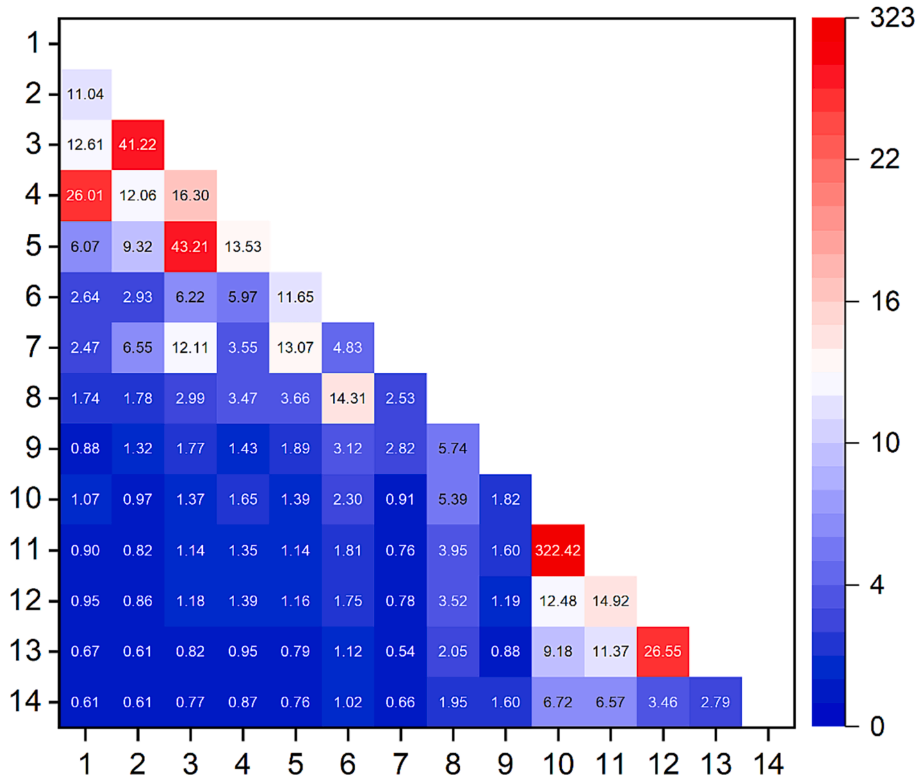

Fig. 10. Interaction matrix of ecological sources based on gravity model. The redder color indicates a stronger interaction, and the bluer color indicates a weaker interaction.

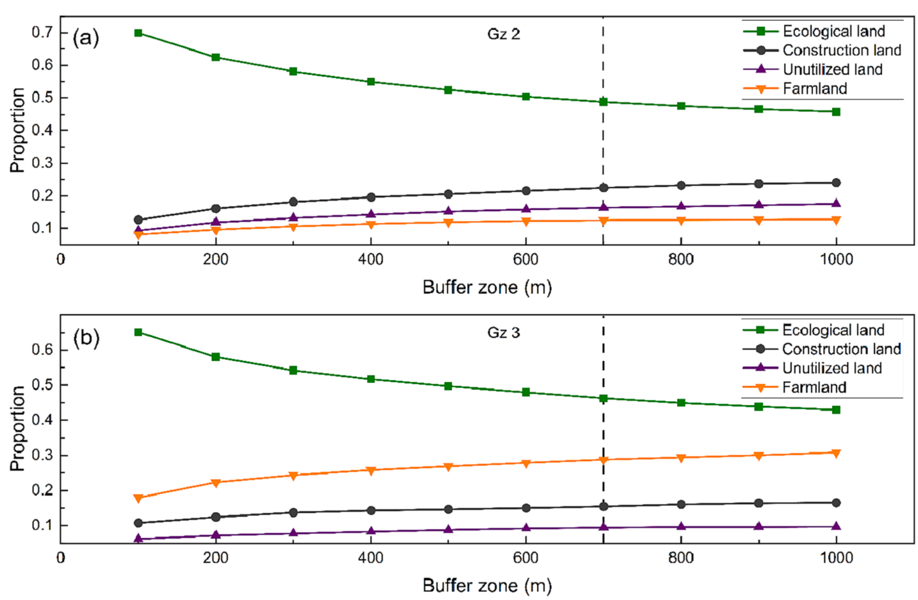

Fig. 11. The proportions of ecological land, construction land, farmland and unutilized land in buffer zones of different scales in the urban–rural fringe. (a) indicates the scale analysis within the Gz 2 (suburban contiguous zone). (b) indicates the scale analysis within the Gz 3 (rural contiguous zone).

gradients. Therefore, the government of Licheng District should seek a balance between urban development and ecological protection through the way of land space layout optimization and ecological construction. On the one hand, the government needs to strengthen the construction of green infrastructure (Bai and Weng, 2023). Firstly, the Yellow River in the northern part of Licheng District has remarkable scale and important ecological service functions, so it can be constructed as an ecological landscape zone along the Yellow River. Secondly, the protection and construction of limited green areas within Gz 1 in the northern part of Licheng District should be strengthened to maintain its ecological quality and service functions. Thirdly, the planning and construction of ecological reserves should be carried out in Gz 2 and Gz 3 relying on the limited ecological land to provide transit services for the ecological cycle between the north and the south and between the urban and rural gradients. On the other hand, the government should strengthen the construction of lower-cost ecological green corridors (Xu et al., 2019). For example, forest belts can be constructed in the northern part of the Licheng District, relying on the road network and rivers. This will

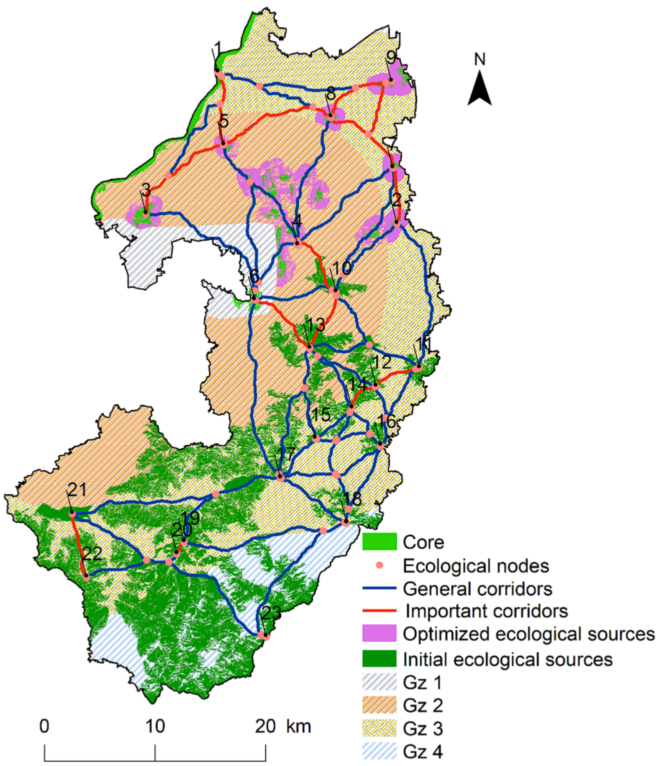

Fig. 12. Spatial pattern of optimized ecological network.

provide connecting corridors to solve the ecological segregation between the north and the south and between urban and rural gradients.

5.3. Advantages of the proposed optimization strategy

The ecological network optimization strategy proposed in this study has two advantages in balancing the contradiction between urban development and ecological protection. On the one hand, it considers the spatial differences of urban–rural gradient land use/land cover structure from the regional scale, and carries out spatial zoning of the study area through gradient analysis. This can provide ideas for the lack of consideration of regional spatial differences in ecological network construction and optimization studies at the watershed, basin scale (Huang et al., 2022), urban scale (Wang et al., 2020), or urban agglomeration scale (Guo et al., 2019). On the other hand, although this strategy also adopts methods such as increasing adjacent ecological patches (Chen et al., 2020) and establishing ecological buffer zones (Ding et al., 2022) to improve the service function of weak ecological patches in the region, it designs site-specific optimization schemes for different zones of the urban–rural gradient. Through the targeted coupling of different scenarios in different zones, the feasibility of regional ecological network optimization will be enhanced, and the comprehensive benefits of regional development and ecology can be maintained to the maximum extent. In particular, the adjustment of farmland involved in the implementation of ecological optimization can be supplemented by land reclamation and consolidation in rural areas according to the policy of "requisition-compensation balance" (COUNCIL, 2017). The adjustment of construction land in the rural involved can be achieved through reasonable landscape planning. Furthermore, the refined ecological network optimization schemes at the regional scale can also be helpful for ecological corridor deployment and urban–rural transformation (Valeri et al., 2021).

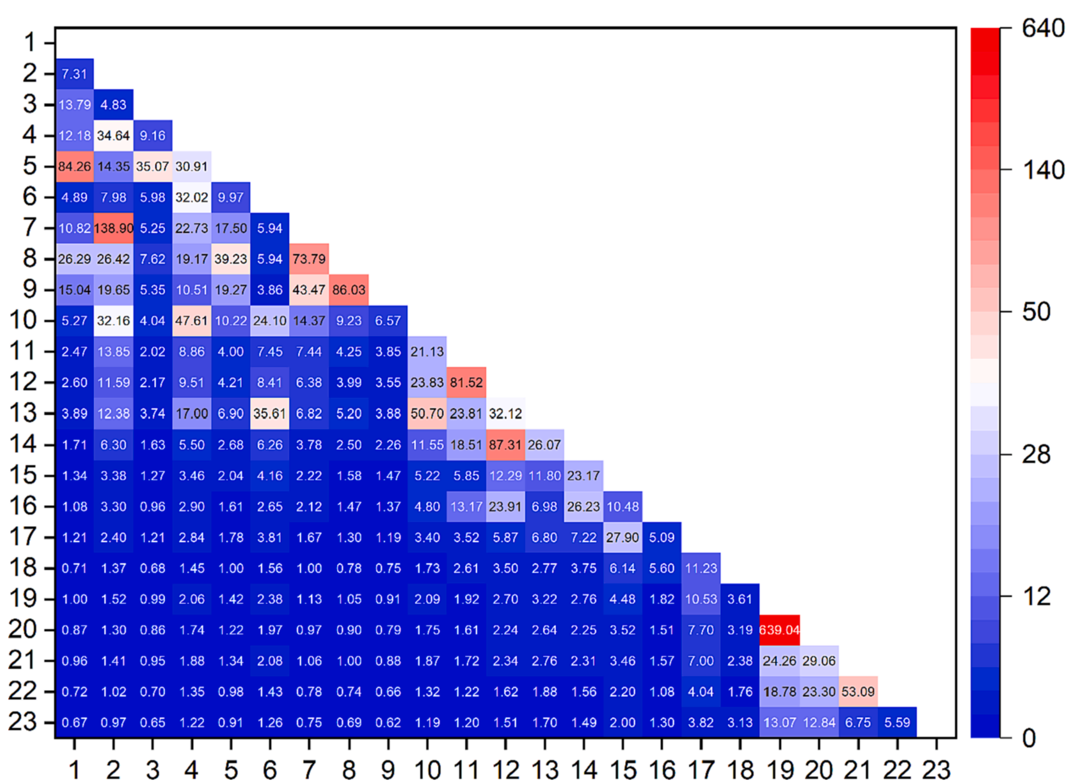

Fig. 13. Interaction matrix between optimized ecological sources based on gravity model.

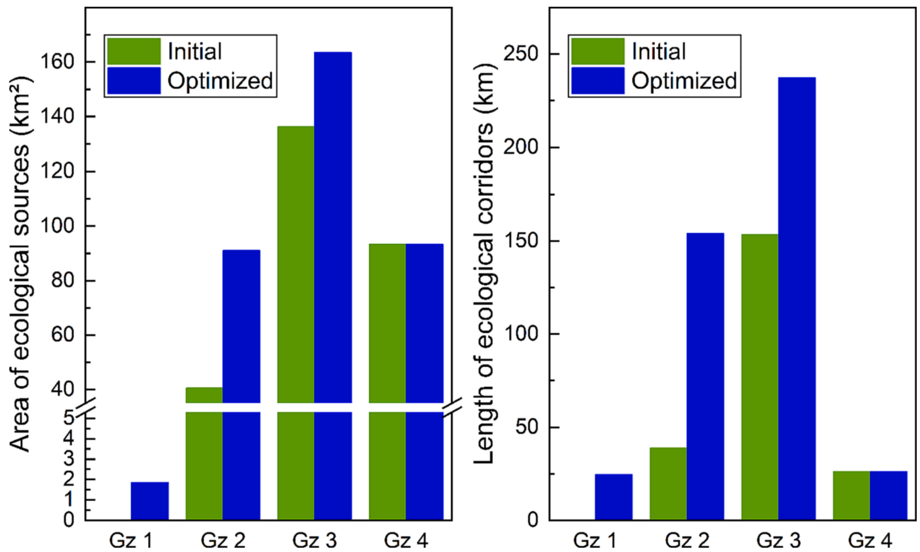

Fig. 14. Comparison of source area and corridor length before and after optimization.

Table 3
Evaluation of ecological network structure before and after optimization.

Indicator	Initial ecological network	Optimized ecological network	Change Value
L	56	99	+ 43
v	40	69	+ 29
α	0.2267	0.2331	+ 0.0064
β	1.400	1.4348	+ 0.0348
γ	0.4912	0.4925	+ 0.0013

5.4. Limitations and future work

In the process of ecological source extraction, we only considered attributes such as the size and connectivity of the sources. During the construction of ecological resistance surfaces, this study also lacked the consideration of resistance factors such as ecological risk and transportation networks. Compared with the existing study (Zhang et al., 2021), ecological sources and resistance factors were not considered for specific species or ecological processes. This would enable the construction of ecological networks that meet the migratory needs of animal communities, but lack some specificity. In addition, urban development patterns vary globally, and there are significant differences in land demand and land use policies in each country. Therefore, the integrated scenarios involved in our proposed optimization strategy may not be fully applicable to the development and ecological conservation needs of different cities around the globe. This may require site-specific reference to this study's approach in the specific implementation. Also, the ecological network optimization strategy proposed in this study only targets ecological sources. Future research will need to apply multiple methods to optimize the ecological network from multiple perspectives. For example, identifying pinch points (Sun et al., 2021) and barriers (McRae et al., 2012), implementing area-specific conservation (Wang et al., 2022b) and resistance areas restoration (McRae et al., 2008) as well as the construction of ecological corridors of different widths (Li et al., 2021).

6. Conclusion

In this study, an ecological network construction and optimization study was conducted for the urban–rural fringe, and a comprehensive optimization strategy of ecological network with multi-scenario coupling was proposed considering the spatial differences of urban–rural gradients. Through a case study in Licheng District of Jinan City in China, the strategy was proved to be effective in improving the spatial structure of ecological network and providing scientific references for urban biodiversity conservation, green ecological infrastructure construction and planning, ecological protection, and sustainable development. The main findings are as follows.

(1) Urbanization has led to a high degree of fragmentation of ecological core patches in Licheng District, with 99% of core patches less than 0.5km^2. Wherein, the degree of fragmentation of ecological core patches within the urban edge gradient zone is much higher than that in the rural gradient zone, and the proportion is much lower than that in the rural gradient zone.
(2) In Licheng District, the places with high ecological resistance are mainly distributed in the directions of northern urban expansion and southern mountainous. Urban expansion and topography are the dominant factors that hinder the ecological process in Licheng District.
(3) The initially constructed ecological network consists of 14 ecological sources and 56 potential corridors, among which 14 important corridors are located in the urban–rural fringe. However, the ecological sources and corridors are mainly distributed in the center and south, and their spatial distribution is extremely uneven, which is not conducive to the north–south ecological exchange in Licheng district.
(4) The optimized ecological network consists of 23 ecological sources and 99 potential corridors, which balanced the overall distribution of ecological sources and corridors in Licheng District. Of these, 27 important corridors are mainly distributed between the northern urban–rural gradient, and their priority construction can help reduce the barrier of ecological processes in the direction of urban–rural gradient.
(5) With improved connectedness, accessibility, and a more complete network structure than the ecological network that was initially built, the optimized ecological network is better able to support the region's overall ecological process cycle. Moreover, the comprehensive benefits of ecological protection and urban development are maintained, which increases the feasibility of the optimization strategy.

CRediT authorship contribution statement

Jianpeng Fan: Conceptualization, Methodology, Software, Validation, Writing – original draft. **Qi Wang:** Conceptualization, Funding acquisition, Methodology, Writing – review & editing. **Min Ji:** Methodology, Writing – review & editing. **Yingjun Sun:** Supervision, Writing – review & editing. **Yougui Feng:** Methodology, Writing – review & editing. **Fengshuo Yang:** Validation. **Zhe Zhang:** Software.

Declaration of Competing Interest

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.

Data availability

Data will be made available on request.

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