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Ecological Processes

RESEARCH

Multiple scenario simulation and optimization of an urban green infrastructure network based on complex network theory: a case study in Harbin City, China

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Abstract

Background: Urban green infrastructure (GI) networks play a significant role in ensuring regional ecological security; however, they are highly vulnerable to the influence of urban development, and the optimization of GI networks with better connectivity and resilience under different development scenarios has become a practical problem that urgently needs to be solved. Taking Harbin, a megacity in Northeast China, as the case study, we set five simulation scenarios by adjusting the economic growth rate and extracted the GI network in multiple scenarios by integrating the minimal cumulative resistance model and the gravity model. The low-degree-first (LDF) strategy of complex network theory was introduced to optimize the GI network, and the optimization effect was verified by robustness analysis.

Results: The results showed that in the 5% economic growth scenario, the GI network structure was more complex, and the connectivity of the network was better, while in the other scenarios, the network structure gradually degraded with economic growth. After optimization by the LDF strategy, the average degree of the GI network in multiple scenarios increased from 2.368, 2.651, 2.189, 1.972, and 1.847 to 2.783, 3.125, 2.643, 2.414, and 2.322, respectively, and the GI network structure connectivity and resilience were significantly enhanced in all scenarios.

Conclusions: Economic growth did not necessarily lead to degradation of the GI network; there was still room for economic development in the study area, but it was limited under existing GI conditions, and the LDF strategy was an effective method to optimize the GI network. The research results provide a new perspective for the study of GI network protection with urban economic growth and serve as a methodological reference for urban GI network optimization.

Keywords: GI network, Simulation, Complex network theory, LDF strategy, Robustness

Introduction

With the high development of the urban economy, natural resources are overexploited, which has led to a series of urban environmental problems, such as intensified heat islands, severe waterlogging, frequent flooding, deteriorating air quality, and reduced biodiversity (Artmann et al. 2019; Chatzimentor et al. 2020). Green

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infrastructure (GI) plays an irreplaceable role in promoting the connectivity of urban natural spaces, maintaining the proper functioning of ecosystem services, alleviating urban ecological problems, and ensuring coordinated urban development (Hansen et al.2019; Lamond and Everett 2019). GI is a cross-scale, multilevel, and closely linked urban green space network composed of greenways, rain gardens, vegetation, wetlands, forests, and other multiple elements (Li et al. 2017; Zhang et al. 2018), and the optimization of its network structure is considered a shrewd strategy to effectively mitigate the conflict between economic development and ecological conservation (Zhao et al. 2019).

A GI network is a fragile and dynamic system that is highly vulnerable to urban development (Zhang et al. 2018; Kim and Miller 2019). When urban development gives priority to economic growth, it will inevitably lead to GI degradation, causing regional ecosystems to lose balance and be unrecoverable (Jiang et al. 2011; Elbakidze et al. 2017). Therefore, effectively managing the conflict between economic development and GI resource conservation has always been a pressing problem for urban sustainable development (Elbakidze et al. 2017). At present, existing GI research has mainly focused on concepts, case analysis, and functional evaluation (Arcidiacono and Salata 2016; Elbakidze et al.2017), and research on the optimization of GI networks currently only focuses on the current landscape pattern and process coupling basis. The study of combining different development scenarios to optimize the GI network has more realistic guidance for urban ecological construction, but it is still lacking.

The construction of the GI network has formed the basic research paradigm: identification of ecological sources and extraction of ecological corridors (Zhang et al. 2018; Kim and Miller 2019). The identification of ecological sources is mainly through the assessment of ecological stability, importance, or connectivity, among which ecological importance is commonly assessed based on ecosystem services (Tzoulas et al. 2007; Wickham et al. 2009). The extraction of ecological corridors usually begins with the construction of resistance surfaces based on land-cover data. The minimal cumulative resistance (MCR) model has been favoured in resistance surface construction due to its operability and practicality. Finally, ecological corridors are often extracted using cost path analysis (Li et al. 2020), but this method ignores the gravitational force between ecological sources (Li et al. 2015). With the development of 3S technology, optimization approaches for GI networks have been proposed, such as the "source-sink" theory, GIS-based hierarchical overlay method, ecological network index, gap analysis, morphological spatial pattern analysis, circuit theory, and graph theory, which have laid the foundation for optimizing GI networks (Jiang et al. 2015; Kim and Miller 2019).

The urban GI network can be understood as a complex network system composed of ecological sources, ecological corridors, and ecological nodes (Meng et al. 2008). Complex network theory is mainly used to study the systematic nature and behaviour resulting from the interaction between individuals in complex network topology from a new perspective and method (Hou et al. 2020), and the abstract research approach of complex network theory has become a new trend in the research of complex systems. Compared with other system analysis methods, complex network analysis has two major advantages. First, it analyses the relationship between individuals rather than individual actors in the network, emphasizing the systemic and global view (Song et al. 2021a). Second, it can analyse the position and role of subsystems or individuals in the whole system, identify key nodes or core shortcomings, and provide decision support for system regulation (Zhang et al. 2015; Song et al. 2021a).

At the end of the twentieth century, with the publication of two significant academic papers on small-world networks and scale-free networks, the complex network theory received attention (Song et al. 2021a). To date, scholars have proposed a variety of complex network topology models in different fields (Slota et al. 2016). Pascual-Hortal (2008) pioneered the application of complex network theory to ecological networks, but the method of topology network optimization was still based on traditional landscape pattern theory (Pei et al. 2020). After that, research using complex network theory to optimize ecological networks gradually advanced and played a role in expanding the application of complex network theory in landscape ecology (Hou et al. 2020; Pei et al. 2020), but it failed to fully prove the optimization effect, and the research objects mainly focused on deserted areas, which has limited guidance for the optimization of urban GI networks with increasingly prominent contradictions between natural ecosystems and economic development.

This study overcame the limitation in which the optimization of the GI network currently focused only on the current landscape pattern and process coupling basis and comprehensively optimized the urban GI network with better connectivity and resilience in multiple scenarios. Thus, the objectives of this study were to (1) set five simulation scenarios by adjusting the economic growth rate, integrated MCR and gravity model to extract the GI network of the study area in multiple scenarios; (2) introduce the low-degree-first (LDF) strategy of complex network theory to optimize the GI network and verify the optimization effect by robustness analysis; and (3) identify key nodes and important corridors based on the integrated forces between ecological sources and complex network topology feature parameters. The research results will provide a new perspective for the study of GI network protection under urban economic growth and a methodological reference for urban GI network optimization. Figure 1 presents the flowchart of the research.

Materials and methods

Study area

Harbin is located in the centre of Northeast Asia, between 44°04'–46°40' N and 125°42'–130°10' E (Fig. 2), and is the provincial capital of Heilongjiang Province (Zhang 2015), and the region is an important hub for the first Eurasian land bridge and air corridor, a crucial central city in Northeast Asia, a significant manufacturing base and a central city for development and opening along the border in China (Song et al. 2021a). The site has a mid-temperate continental monsoon climate, with an average annual temperature of 3.6 °C and an average annual precipitation of 569.1 mm, the main precipitation months are from June to September and account for approximately 60% of the annual precipitation, and

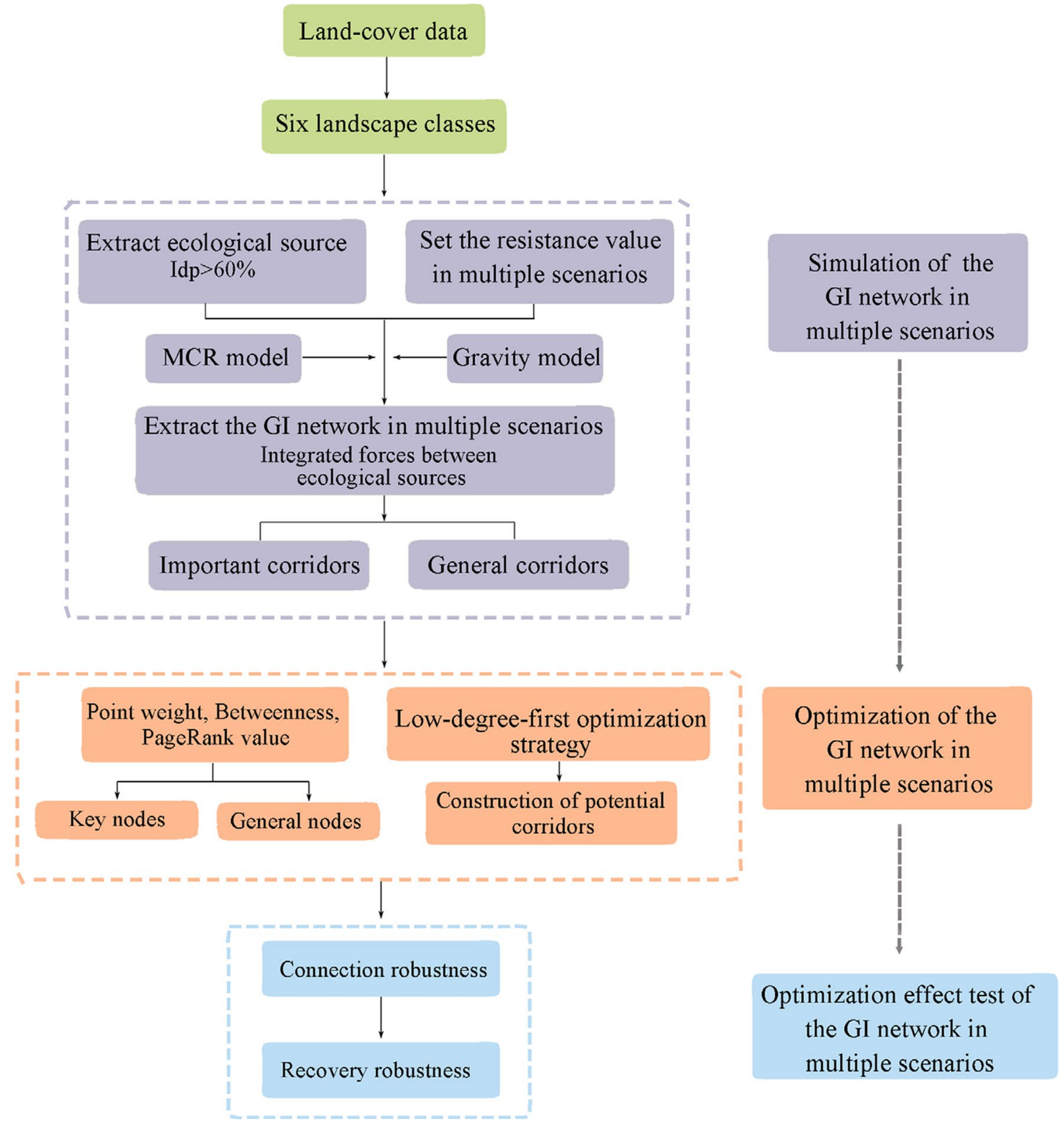

Fig. 1 Flowchart of the present research. *GI* green infrastructure, *MCR* minimal cumulative resistance, *Idp* importance values of the patches

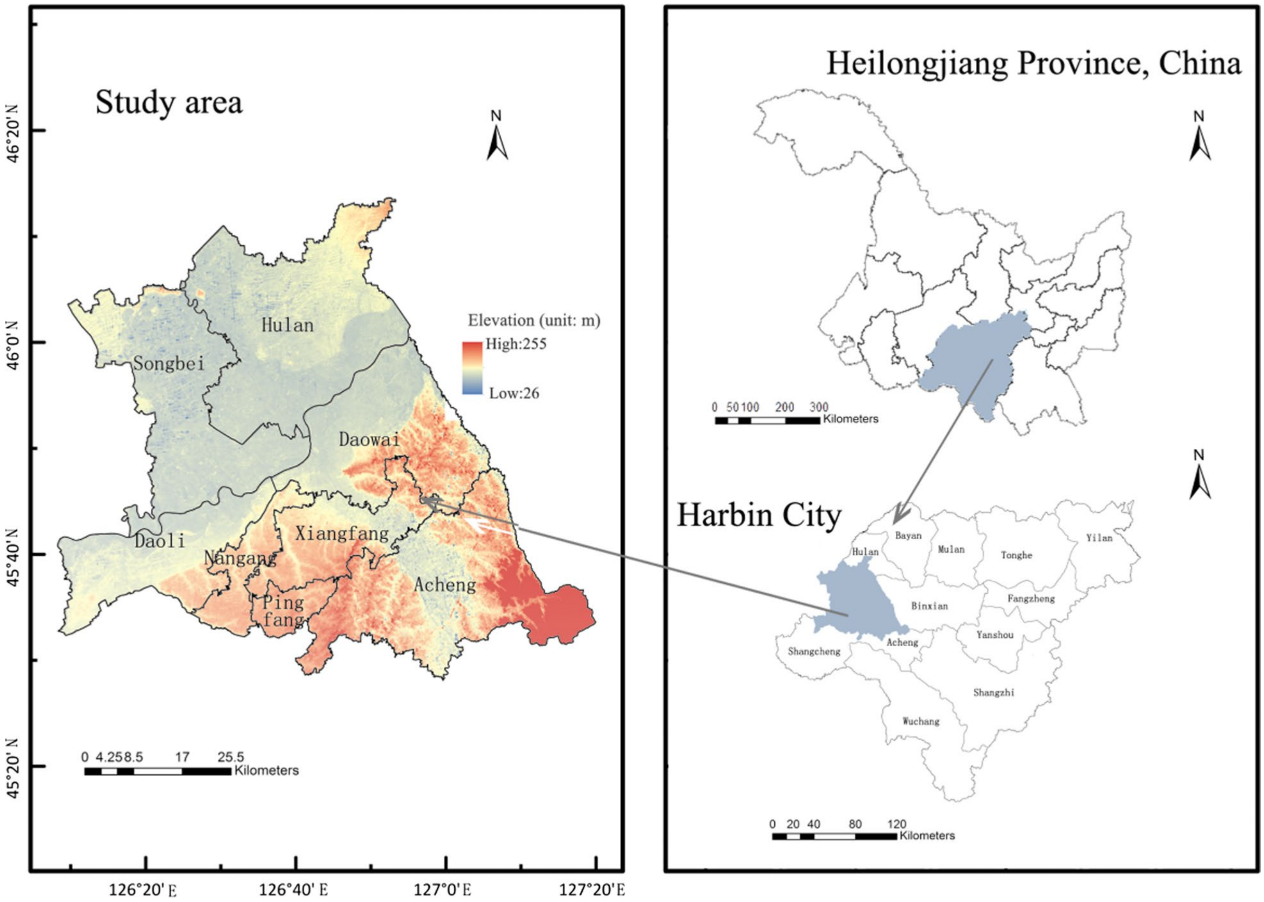

Fig. 2 Location and elevation of the study area. The top-right subgraph shows an administrative map of Heilongjiang Province, China. The bottom-right subgraph shows an administrative map of Harbin City. In addition, the left map shows elevation in the study area

the main snow months span from November to January (Xuan et al. 2020). The overall topography is high in the east and low in the west, with mountains and hills predominating in the east and plains predominating in the west (Zhang 2015; Xuan et al. 2020). We identified the central district of Harbin as the study area, where urban construction activities are frequent and the population is dense.

The GI of the study area consists of watersheds, scenic spots, urban parks, protective woodlands, and so on (Song et al. 2021a). The watershed mainly includes the Songhuajiang, Ash River, and Hulan River, and the wetland systems on both sides of their shores, affected by the tributaries, have varying degrees of obstruction. The scenic spots mainly include Swan Lake, Tianheng Lake, Taiping Lake, Sun Island, and Changling Lake, which have a relatively complete natural system but a small area. There are five urban parks with an area larger than 1 km^2, and these parks occupy an important position in the GI network pattern of Harbin. More than 10 patches of protective woodlands, which can be divided into urban forests and protected greenfields, are mostly sporadically distributed along railroads and in urban–rural areas.

Data sources

The data used in this research included the following: land-cover data with 30 m spatial resolution in 2021 supported by the China Geographic National Conditions Data Cloud Platform (http://www.dsac.cn/), meteorological data sets with 1 km resolution (China Geographic National Conditions Data Cloud Platform, http://www.resdc.cn/), the normalized difference vegetation index (NDVI) and modified normalized difference water index (MNDWI) data with 30 m resolution (National Comprehensive Earth Observation Data Sharing Platform, http://www.chinageoss.org/), ASTER GDFM elevation data with 30 m resolution (Geospatial Data Cloud, http://www.gscloud.cn), and a high-definition urban road density data (http://www.Openstreetmap.org/).

Extraction of the GI network in multiple scenarios

In the GI network, ecological sources are spatial units or ecosystems that provide various materials and energy, and ecological corridors are important channels for the flow of energy and material (Badiu et al. 2019). The interactions between ecological sources generate ecological gravitational forces, and they are subject to resistance from the substrate (Garmendia et al. 2016; Dai et al. 2021). In this research, the extraction of the GI network in multiple scenarios was divided into four steps: (1) determination of ecological sources. (2) Simulation of the ecological resistance between ecological sources. (3) Calculation of the interaction gravitational force between ecological sources. (4) Extraction of the GI network by analysing the integrated forces between ecological sources. We set up four additional development scenarios based on the current scenario, which were scenarios of 5, 10, 15, and 20% economic growth.

Determination of ecological sources

Urban ecological patches are the carriers of ecological sources (Dai et al. 2021; Huang et al. 2020), and the ecological sources in this study refer to greenfields, scenic spots, waters, woodlands, and others that have important conservation values for urban ecology. The ecological sources were selected by the patch area, average NDVI/MNDWI value, and patch shape index, and the entropy weighting method (EWM) was used to determine the weight to calculate the importance values of the patches (Idp). The ecological patches in the top 60% of the Idp ranking were identified as ecological sources, and the ecological nodes were obtained by extracting the spatial distribution centroids of sources (Garmendia et al. 2016).

Construction of the resistance surface

The flow of landscape ecological streams between ecological sources needs to overcome multiple resistances, and resistance surface construction has a significant impact on corridor extraction, for which accurate calculation is still challenging (Elbakidze et al. 2017; Huang et al. 2020). Taking into account the actual ecological characteristics of the study area, an ecological resistance evaluation system was established by considering four groups of variables (Table 1). In view of the current ecological resistance and economic development additional resistance, each ecological resistance factor was divided into five grades and assigned a value of 1, 3, 5, 7, or 9, and the two resistance surfaces were combined for the subsequent study of the GI network simulation in multiple scenarios. Different development scenarios will affect the economic resistance of certain factors, ultimately leading to changes in the ecological resistance surface. For example, areas with high vegetation cover will face greater ecological resistance with economic development. Since each factor has an essential contribution to the maintenance and development of the GI network in the study area, each factor was set with the same weight (Hou et al. 2020; Pei et al. 2020). ArcGIS 10.2 was used to obtain the ecological resistance surface by overlaying raster calculations of each factor, and the MCR model was applied to calculate the minimum cost path from each ecological source to other ecological sources. The general form of the MCR model is as follows:

$$R_{mc} = f_{\min} \sum D_{ij} R_i \tag{1}$$

where R_{mc} is the minimum cumulative resistance, $f_{\min}$ is an unknown negative function, D_{ij} is the spatial distance from the source to the landscape unit, and R_i is the resistance coefficient of the landscape unit to the propagation and diffusion process.

Gravity model

The gravity model is mainly used to study the interaction relationship between two objects or spaces. It was used to calculate the ecological gravitational force between ecological sources in this study (Wang et al. 2019; Song et al. 2021b). The formula of the gravity model is as follows:

$$P_{ij} = G \frac{M_i M_j}{D_{ij}^2} \tag{2}$$

where P_{ij} is the gravitational force between ecological sources i and j; M_i and M_j are the importance of ecological sources i and j, respectively; and G is empirical coefficient of which G is usually 1.

By analysing the integrated forces between ecological sources, the ecological corridors were extracted; when the gravitational force between ecological sources was greater than their resistance, ecological corridors were formed between the sources, and ecological flows were transmitted between them through the corridors (Song et al. 2021b). We used Python scripting language to simulate the interaction between gravitational force and resistance between ecological sources, and the overlapping corridors were processed to extract the GI network of the study area in multiple scenarios.

The greater the interaction forces between ecological sources are, the more important the ecological corridor formed between them in the GI network system is (Kong et al. 2010; Huang et al. 2020). According to the calculation of the interaction force, the corridors in the top 10% of the interaction force ranking were extracted as important corridors (Pei et al. 2020), whereas the other corridors were considered general corridors for the GI network.

Table 1 Ecological resistance evaluation system

Primary factor	Secondary factor	Grade	Ecological resistance	Economic resistance
Land-cover type	Land-use type	Urban land, rural settlement, other construction land	9	1
		Beach, saline-alkali land, bare land	7	3
		Paddy field, dry land,	5	5
		Sparse forest, other woodland, canal, medium coverage grassland, marsh	3	7
		Forestland, high coverage grassland, lake, reservoir, bush,	1	9
Terrain factor	Elevation (*m*)	0–100	1	1
		100–150	3	3
		150–200	5	5
		200–250	7	7
		> 250	9	9
	Slope (°)	0–3	1	1
		3–9	3	3
		9–18	5	5
		18–27	7	7
		> 27	9	9
Hydrological factor	MNDWI	< 0	9	1
		0–0.22	7	3
		0.22–0.6	5	5
		0.6–0.8	3	7
		> 0.8	1	9
Vegetation cover	NDVI	< 0	9	1
		0–0.2	7	3
		0.2–0.33	5	5
		0.33–0.6	3	7
		> 0.6	1	9
Density factor	Road network density	> 1.25	9	1
		0.85–1.25	7	3
		0.52–0.85	5	5
		0.20–0.52	3	7
		0–0.20	1	9
	Settlement density	> 0.80	9	1
		0.60–0.80	7	3
		0.40–0.60	5	5
		0.20–0.40	3	7
		0–0.20	1	9

MNDWI modified normalized difference water index, *NDVI* normalized difference vegetation index

Optimization of the GI network in multiple scenarios

Complex network theory optimizes the topology by four main approaches: edge-deleting, edge-adding, edge-reconnecting, and edge-orienting (Wang et al. 2015; Shi, et al. 2020). The edges of GI networks are actually ecological corridors that connect ecological sources with minimal biological flow costs, and deleting edges means destroying ecological corridors (Vogtet al. 2007; Kim and Miller 2019; Yang et al. 2020), so edge-deleting and edge-reconnecting are not applicable to the optimization of GI networks. As a GI network is an undirected topology, edge-orienting is equally inapplicable to the GI network optimization (Cheng et al. 2020; Song et al. 2021b).

Combined with the current situation of GI in the study area, where there are few ecological patches, sparse ecological corridors, and strong interference from urbanization activities, we introduced the LDF edge-adding strategy to optimize the GI network. Through the comparison of different edge-adding strategies, researchers confirmed that LDF can not only effectively reduce the heterogeneity and make the information flow more stable but also effectively increase the information capacity of the network (Hsu et al. 2020; Song et al. 2021b). Considering the actual difficulty of urban ecological corridor construction, the number of edge additions was set to 30% of the corridors in the original GI network (Pei et al. 2020). There are two important concepts in the LDF strategy, the degree of the node and the average degree of the network, which are calculated as follows:

$$D_i = \sum_i d_{ij} \tag{3}$$

$$\overline{D}_i = \frac{1}{N}\sum_{i-1}^{N} D_i \tag{4}$$

where D_i is the degree of node i, d_{ij} is the connection relationship between node i and node j, $\overline{D}_i$ is the average degree of the network, and N is the number of nodes.

The procedure of the LDF strategy algorithm for GI network optimization was as follows. First, initialized $n=1$, and the network topology was G. Second, calculated the degree of the nodes in the network and defined the weights $W(i,j)=D_i \times D_j$ of any two nodes i and j, and arranged in the order of the weights W from largest to smallest. Third, selected the pair of nodes with the smallest weight value, added an edge (corridor) between the nodes, and the new GI network topology was Ga. Set the calculator $n=n+1$ and G=Ga. If multiple node pairs had equal weights, one of the pairs was randomly selected to add edges. Fourth, when the number of added edges was less than 30% of the original network corridors, edges were added, and when the number of added edges reached 30% of the original network corridors, edges were stopped, and at this time, G was the optimized GI network.

For the identification of key ecological nodes, we synthesized 3 characteristic parameters of nodes in complex network theory, namely, point weight, betweenness, and PageRank value, which are used to measure the importance of nodes in network topology (Zhang et al. 2015), and we extracted the top 10% of statistical results ranked as key nodes. The specific algorithm is as follows:

$$Z_i = \left(\frac{S_i - Min(S)}{Max(S) - Min(S)} + \frac{B_i - Max(B)}{Max(B) - Min(B)} + \frac{P_i - Max(P)}{Max(P) - Min(P)}\right)/3 \tag{5}$$

where S_i is the point weight of node i, B_i is the number of betweenness of node i, P_i is the PageRank of node i, S is the array formed by the point weight of node, B is the array formed by the betweenness of node, and P is the array of PageRank values of node.

Validation of the GI network optimization effect

In complex network theory, robustness is an important parameter used to indicate the ability of a complex system to maintain its function or properties under an attack, which is divided into connection robustness and recovery robustness (Slota et al. 2016). We abstracted the GI network into an undirected and unweighted topology with MATLAB 2018 and conducted random or intentional attacks to test the optimization effect of the GI network based on robustness analysis. Connection robustness is the ability of a network structure to maintain its normal structure and function after being attacked (some nodes or edges are removed) (Jiang et al. 2011). The connection robustness is calculated as follows:

$$R = \frac{C}{N - N_\mathrm{r}} \tag{6}$$

where C is the number of nodes in the maximum connected subgraph of the network, and N_r is the number of nodes that are removed.

Recovery robustness refers to the recovery ability of the network structure after being attacked (Slota et al. 2016; Song et al. 2021a), which includes edge recovery robustness and node recovery robustness, representing the recovery ability of the network after the removal of edges and nodes, respectively (Hou et al. 2020). The edge robustness and node recovery robustness are calculated as follows:

$$D = 1 - \frac{N_r - N_d}{N} \tag{7}$$

$$E = 1 - \frac{M_r - M_e}{M} \tag{8}$$

where N_d is the number of nodes recovered by the network after node removal, M_r is the number of edges removed, M_e is the number of edges recovered, and M is the total number of edges.

Results

Determination of ecological sources

According to the results of the Idp, 119 ecological sources were identified (Fig. 3), with a total area of 42,082.65 hm^2, accounting for 10.05% of the study area, which was mainly divided into three categories: water body ecological sources, grassland ecological sources, and woodland ecological sources. Among them, the water body ecological sources had the largest area of 24,626.37 hm^2, with 29 patches that were concentrated in the Songhuajiang,

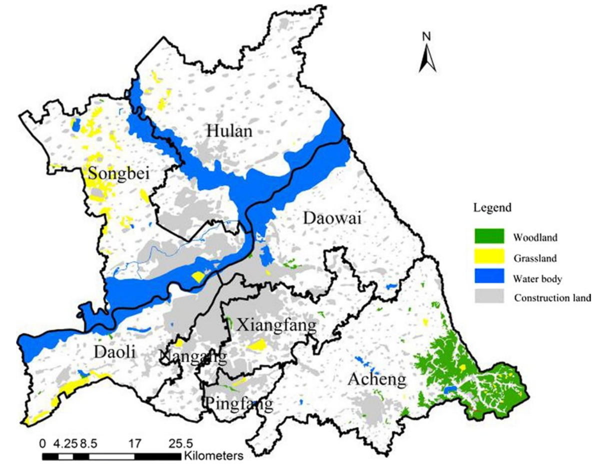

Fig. 3 Ecological sources of the study area

Hulan River, and scattered in the western and southern parts of the study area. The area of woodland ecological sources was 10,524.63 hm^2, with 46 patches, mainly distributed in the south of the study area, with sporadic distribution in the north and east. The grassland ecological source had an area of 6,931.65 hm^2, with 44 patches, and mainly included the grassland in Songbei District, Sun Island, and Changling Lake. Overall, the ecological sources in the study area varied significantly in size and were strongly fragmented, with the number of sources in the northeast, central, and southeast being few, showing an isolated distribution.

The ecological resistance surface in multiple scenarios

The ecological resistance values gradually increased from the northwest to southeast in the study area, and the high values were mainly found in the mountainous and hilly areas in the eastern part of the Acheng District and the agricultural development areas with relatively low elevations in Acheng District and Daowai District (Fig. 4a–e). The low values were mainly distributed in the Songhuajiang, Hulan River, and coastal wetlands. With the transition from the current scenario to the 20% economic growth scenario, the mean value of ecological resistance gradually increased, and the zones with lower resistance values gradually decreased. There was significant growth in matrix resistance in the central part of the study area that could be easily detected, which was mainly driven by the MNDWI resistance factor. This result demonstrated the rationality of the construction of the resistance surface, as the acceleration of the economic development

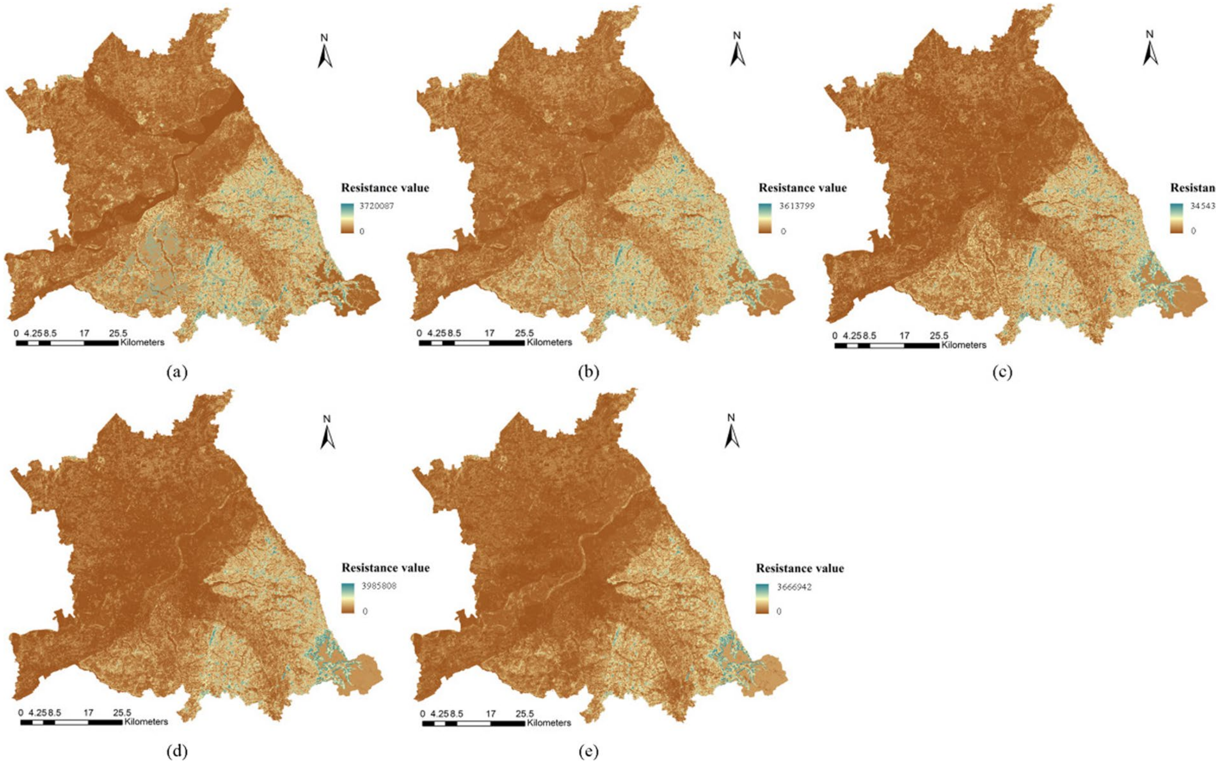

Fig. 4 Resistance surface of the study area in multiple scenarios. **a** Current scenario, **b** 5% economic growth scenario, **c** 10% economic growth scenario, **d** 15% economic growth scenario, **e** 20% economic growth scenario

process and the increasing use of water resources mainly for agricultural production and industrial manufacturing make it less likely that the water and wetland in the study area will exchange energy and materials between ecological patches, and thus, the resistance values must increase.

Extraction of ecological corridors in multiple scenarios

There were fewer easily identifiable ecological corridors in the study area in multiple scenarios, some of which were blocked by urban development, and the GI network connectivity was generally weak (Fig. 5a–e). The main ecological corridors mainly included the Xigou River, the Majiagou River, and the Ash River, which mainly connected the Songhuajiang, Changling Lake, the Botanical Garden, the Eurasian Window, the Yunliang River, and other important ecological sources.

The number of ecological corridors included in multiple scenarios was 127, 136, 114, 96, and 88 (Fig. 5a–e), corresponding to the average degree of the GI network being 2.368, 2.651, 2.189, 1.972, and 1.847, respectively. In the 5% economic growth scenario, the network was more complex and the connectivity was better. In the 10% economic growth scenario, the skeleton of urban ecological planning was basically maintained, and some of the network structures were problematic, with only the ecological corridors in Acheng District and Songbei District having relatively good circularity. In the 15% economic growth scenario, the ecological corridors were gradually sparse and scattered, shrinking in the northeast and south-central parts of the study area, and the corridors between some ecological sources and the surrounding sources were more singular. For the 20% economic growth scenario, the structure was greatly damaged and no longer had the characteristics of a network.

The robustness analysis before optimization showed that the initial values of GI network connectivity robustness were 0.84, 0.85, 0.72, 0.72, and 0.70 in multiple scenarios (Fig. 6a–e), respectively. Under the random attack, the connection robustness significantly decreased when 23.53, 26.89, 22.69, 19.33%, and 16.81% of the ecological nodes were removed, respectively. Under the intentional attack, the connection robustness significantly decreased when 10.92, 13.45, 10.08, 7.56, and 5.88% of the ecological nodes were removed, respectively.

In terms of the recovery robustness before optimization, under the random attack, node recovery robustness could be completely recovered when 13.45, 15.13, 12.61, 10.08, and 8.40% of ecological nodes were removed in multiple scenarios (Fig. 7a–e), and edge recovery robustness could be completely recovered when 14.29, 15.97, 13.45, 10.92, and 9.24% of ecological nodes were removed, respectively. Under the intentional attack, the

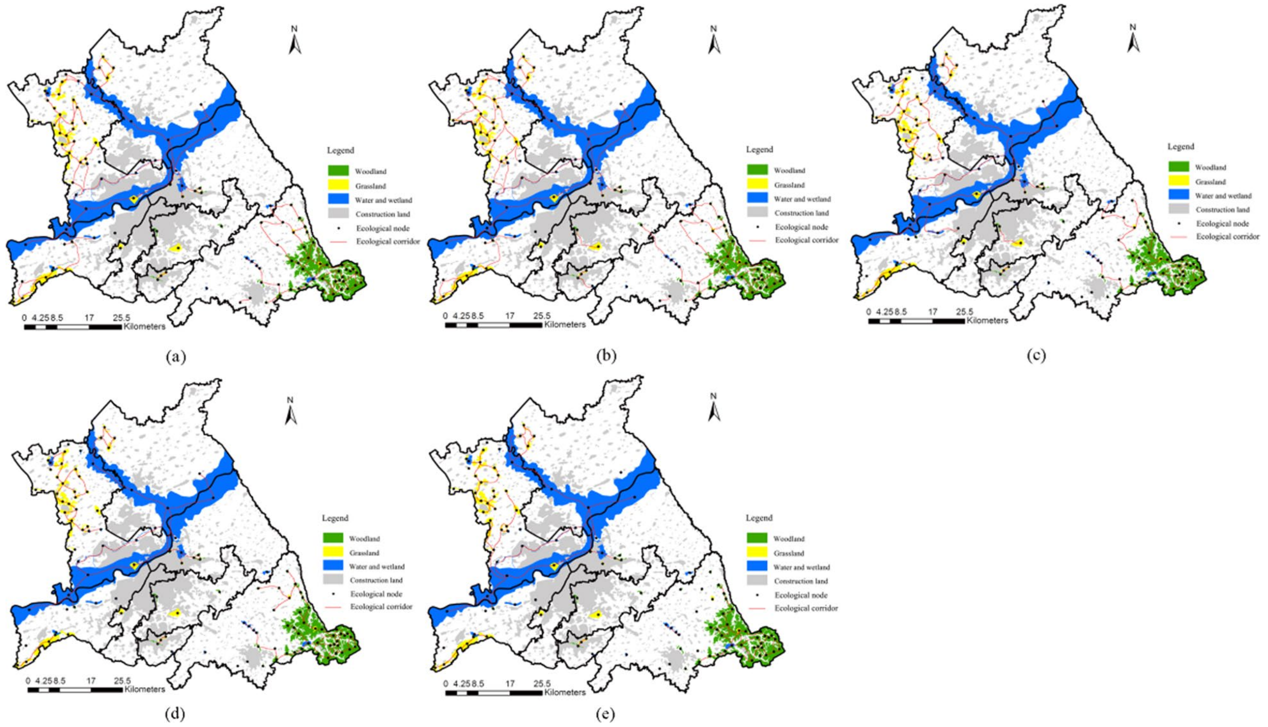

Fig. 5 GI network of the study area in multiple scenarios. **a** Current scenario, **b** 5% economic growth scenario, **c** 10% economic growth scenario, **d** 15% economic growth scenario, **e** 20% economic growth scenario

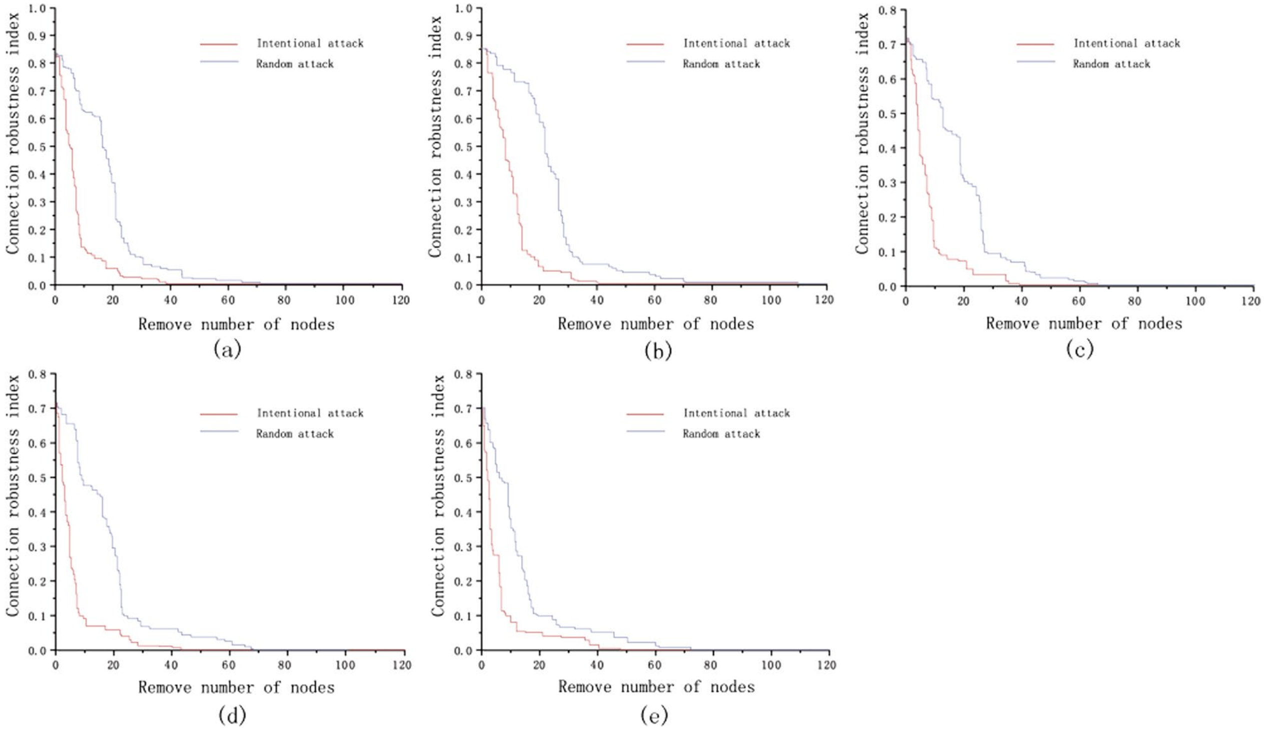

Fig. 6 Connection robustness analysis of the GI network in multiple scenarios. **a** Current scenario, **b** 5% economic growth scenario, **c** 10% economic growth scenario, **d** 15% economic growth scenario, **e** 20% economic growth scenario

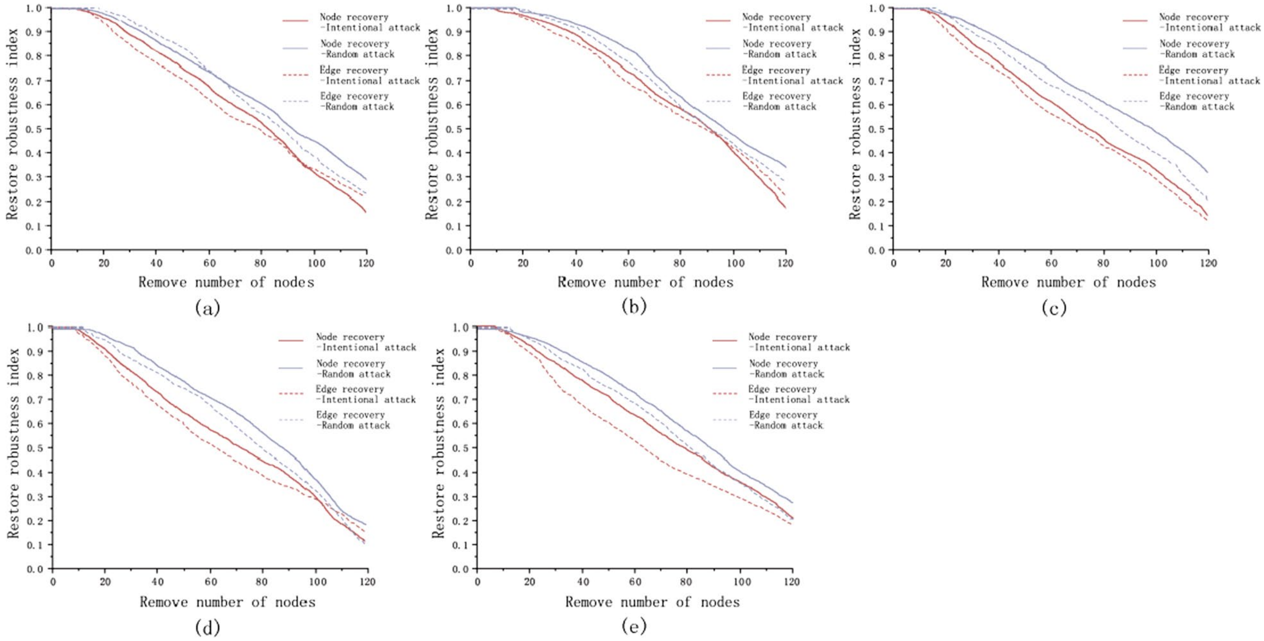

Fig. 7 Recovery robustness analysis of the GI network in multiple scenarios. **a** Current scenario, **b** 5% economic growth scenario, **c** 10% economic growth scenario, **d** 15% economic growth scenario, **e** 20% economic growth scenario

node recovery robustness could be completely recovered when 10.08, 12.61, 9.24, 7.56, and 6.72% of the ecological nodes were removed, respectively, and the edge recovery robustness could be completely recovered when 10.92, 11.76, 10.08, 6.72, and 5.88% of the ecological nodes were removed, respectively.

Optimization of GI network in multiple scenarios

The average degree of the GI network increased to 2.783, 3.125, 2.643, 2.414, and 2.322, respectively, after optimization by the LDF strategy in multiple scenarios (Fig. 8a–e). The Lilac Technology Expo and the Provence Manor were important nodes that acted to increase the connectivity of the network, and the added ecological corridors were mainly concentrated in Nangang District, Xiangfang District, and the north-western part of Acheng District. With the transition from the current scenario to the 20% economic growth scenario, the added ecological corridors were mainly shifted to Songbei District and Acheng District, and the ecological sources of increased connectivity were mainly moved to the grassland and water bodies on the periphery of the study area, such as the Municipal Government, Tiger Garden, and Northern Forest Zoo. From the overall spatial structure, the GI network in multiple scenarios formed a kind of mixed network pattern with primary and secondary after optimization based on the LDF strategy. The large ecological corridors formed the spatial backbone of the GI network, basically covering the whole study area, and the small ecological corridors were evenly distributed in the interstices, which effectively complemented the whole GI network. The GI network of Songbei District and Acheng District contained a circular plus radial structure, and other districts also had a good degree of connectivity.

The robustness analysis after optimization showed that the initial values of GI network connectivity robustness improved to 0.84, 0.85, 0.72, 0.72, and 0.70 in the multiple scenarios, respectively (Fig. 9a–e). Under the random attack, the connection robustness significantly decreased when 33.61, 36.13, 32.77, 29.41, and 26.89% of the ecological nodes were removed, respectively. Under the intentional attack, the connection robustness significantly decreased when 17.6, 19.3, 16.8, 14.2, and 11.8% of the ecological nodes were removed, respectively.

As for the recovery robustness after optimization, under the random attack, node recovery robustness could be completely recovered when 27.73, 31.09, 24.37, 19.33, and 15.97% of ecological nodes were removed in the multiple scenarios, respectively (Fig. 10a–e), and edge recovery robustness could be completely recovered when 28.57, 31.09, 25.21, 21.01, and 13.45% of ecological nodes were removed, respectively. Under the intentional

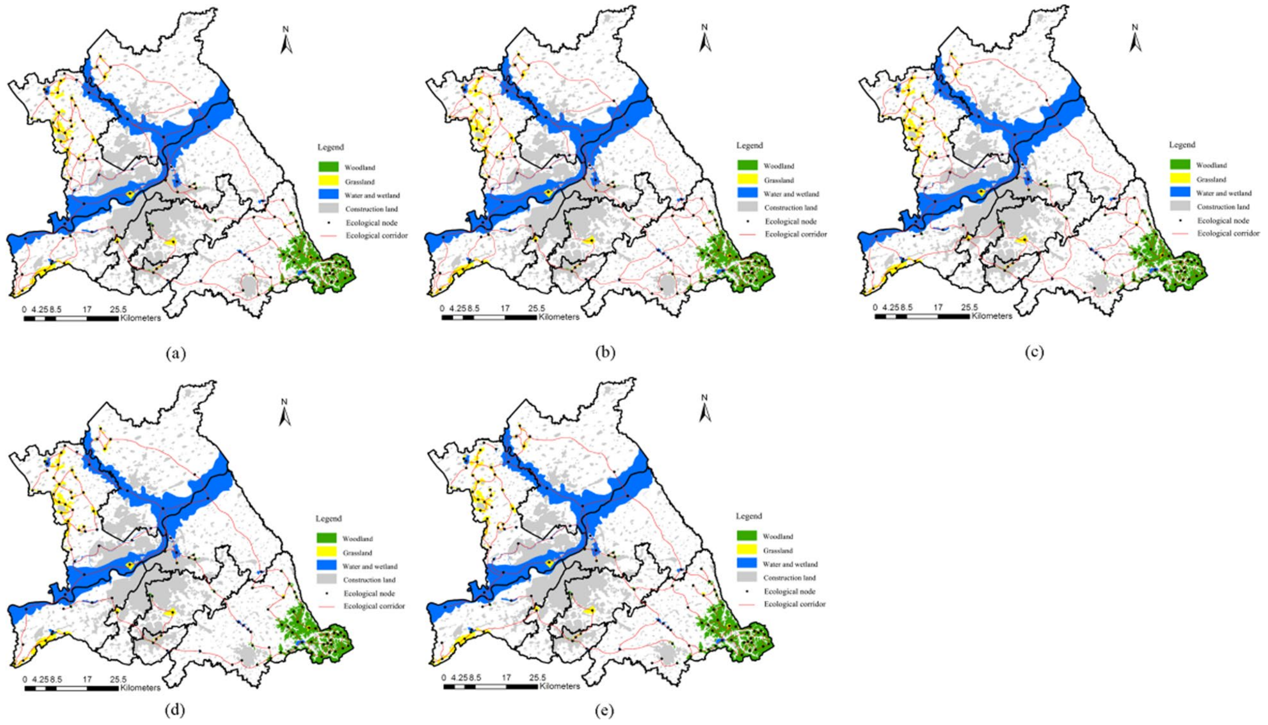

Fig. 8 GI network in multiple scenarios after optimization. **a** Current scenario, **b** 5% economic growth scenario, **c** 10% economic growth scenario, **d** 15% economic growth scenario, **e** 20% economic growth scenario

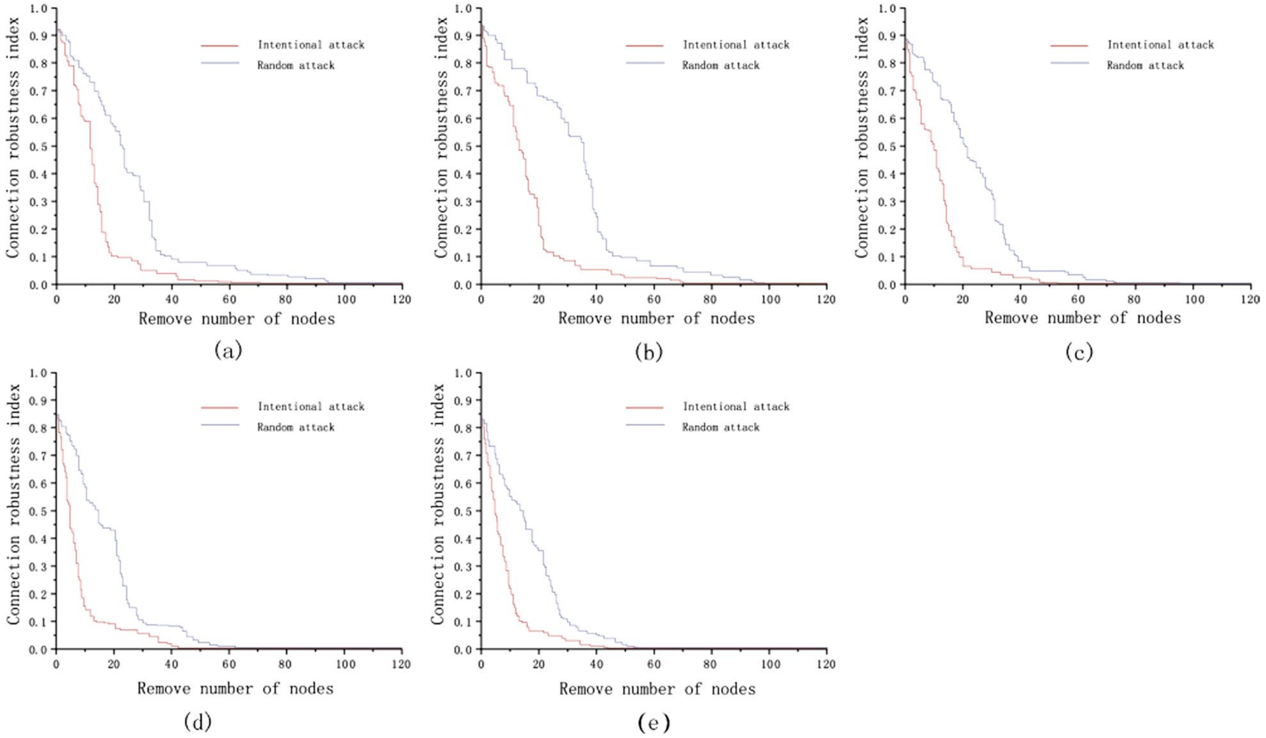

Fig. 9 Connection robustness analysis of the GI network in multiple scenarios after optimization. **a** Current scenario, **b** 5% economic growth scenario, **c** 10% economic growth scenario, **d** 15% economic growth scenario, **e** 20% economic growth scenario

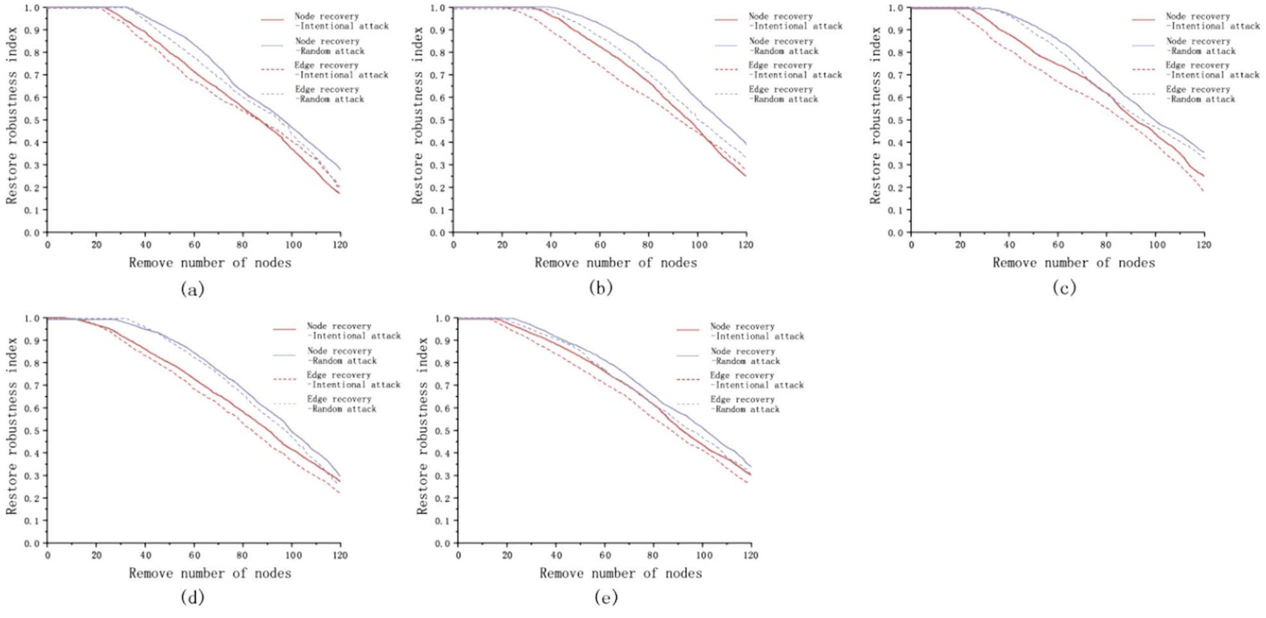

Fig. 10 Recovery robustness analysis of the GI network in multiple scenarios after optimization. **a** Current scenario, **b** 5% economic growth scenario, **c** 10% economic growth scenario, **d** 15% economic growth scenario, **e** 20% economic growth scenario

attack, the node recovery robustness could be completely recovered when 20.17, 21.87, 19.33, 13.45, and 11.76% of the ecological nodes were removed, respectively, and the edge recovery robustness could be completely recovered when 18.49, 16.81, 15.13, 12.61, and 9.30% of the ecological nodes were removed, respectively.

Identification of key nodes and important corridors

Most key ecological nodes were concentrated in the Songhuajiang and its wetlands along the river, as well as in the woodland of Acheng District, and a few were located in the grassland of Hulan District in the multiple scenarios (Fig. 11a–e). With the transition from the current scenario to the 20% economic growth scenario, the key ecological nodes were gradually concentrated in the woodland in the southern part of the Acheng District. In the current scenario and the 5% and 10% economic growth scenarios, the extracted important corridors basically retained the ecological corridors skeleton of the study area. In the 15% and 20% economic growth scenarios, the extracted important corridors were severely fractured and fragmented, and only part of the intact important corridors remained in the southern part of the Acheng District.

Discussion

Contradictions between urban development and GI network conservation

In the process of urban economic development, a slight disturbance and destruction may cause irreversible damage to the fragile ecosystem (Nazir et al. 2015; Patrizia et al. 2018; Jin et al. 2020). The GI network is an effective way to sustain urban ecosystem stability, maintain and restore urban biodiversity (Lamond and Everett 2019; Chatzimentor et al. 2020), and it serves as a management measure that promotes regional economic smart growth (Zhang et al. 2018; Song et al. 2021a), which plays an important role in supporting the coordinated and sustainable development of urban ecosystems and social systems (Pei et al. 2020). How to scientifically construct and optimize a GI network against the background of urban development so that it can fully perform its ecological functions and ensure urban ecological safety has become a practical problem that urgently needs to be addressed (Soille and Vogt 2009; Sawyer et al. 2011). This study discussed the contradiction between urban economic development and GI network construction, and the simulation and optimization study of GI networks in multiple scenarios provides a scientific reference for formulating appropriate development strategies and ecological protection policies.

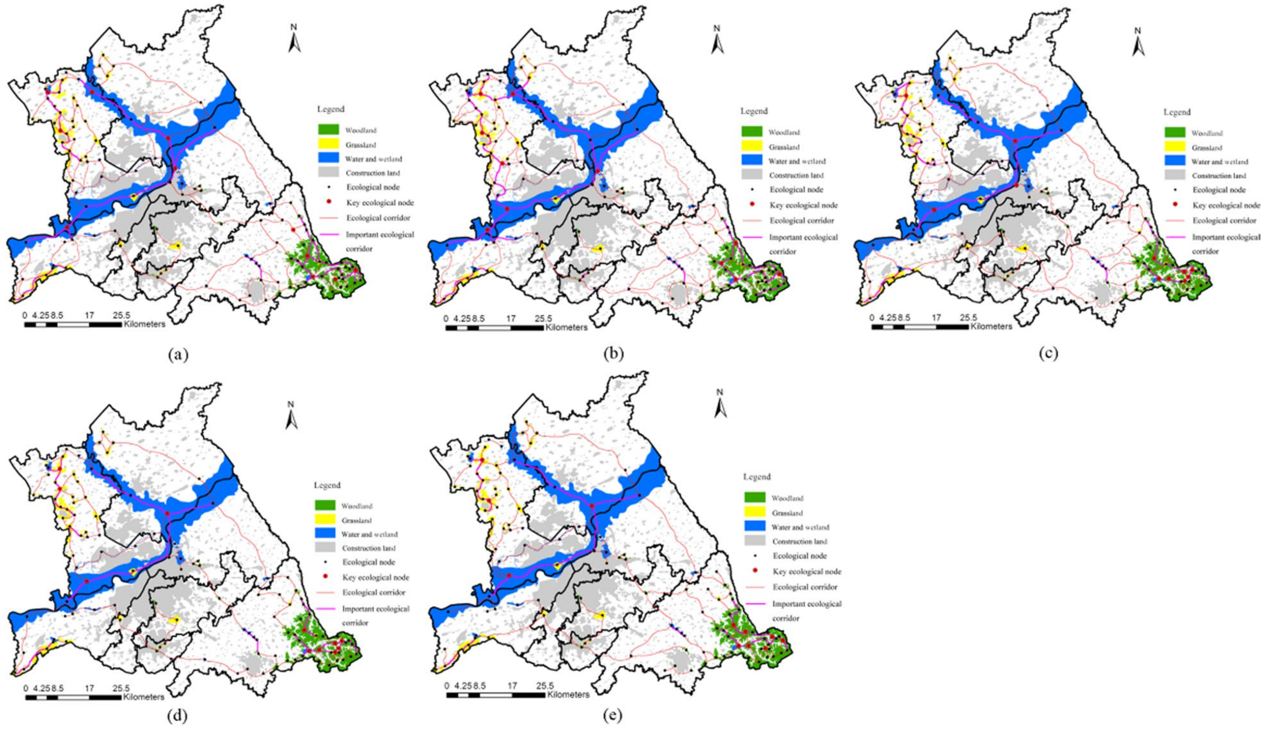

Fig. 11 Key nodes and important corridors of the GI network in multiple scenarios. **a** Current scenario, **b** 5% economic growth scenario, **c** 10% economic growth scenario, **d** 15% economic growth scenario, **e** 20% economic growth scenario

Regarding the study area, the GI network structure was more complex in the 5% economic growth scenario, indicating that there was still room for economic development within the existing GI resource constraints. However, as economic growth continued, the GI network gradually degraded, the corridor gradually fractured, and eventually, the structure no longer had the characteristics of a network, which suggested that large-scale economic development would cause great damage to the GI network. Economic development does not necessarily lead to the degradation of the urban GI network and should be based on its GI conditions (Pei et al. 2020; Song et al. 2021a), it also provides a research direction for a more scientific and systematic threshold definition of economic development space for the construction of GI networks in the future. In this study, the simulation and optimization of urban GI networks in multiple scenarios not only effectively contributes to the sustainability of GI networks in providing various ecological benefits, such as protecting natural resources, promoting ecosystem processes, and enhancing ecological functions in the process of urban economic development, but also plays a key role in containing rapid urban sprawl and outward expansion and forming and promoting a sustainable urban growth pattern.

Realistic refinement based on optimization strategy

Among the many methods used to optimize the topology of complex network theory, the LDF strategy has the best comprehensive performance and can improve efficiency to a great extent (Zhang et al. 2015; Song et al. 2021a). With robustness tests, the LDF strategy also showed excellent performance in optimizing the GI network in this research, the connectivity of the GI network structure was significantly enhanced, and the recovery ability of ecological nodes and ecological corridors against attack was greatly improved. The essence of the LDF strategy is to optimize the network by adding edges, and the advantage of this strategy is that it can optimize the GI network to the greatest extent by adding limited ecological corridors (Wang et al. 2015), effectively reducing the cost of urban GI construction. However, actual ecological corridor construction needs to be considered in conjunction with overall urban ecological planning.

Taking the study area as an example, the public version of the "Master Plan of Land and Space in Harbin City (2020–2035)" emphasized the formation of a GI system pattern of "two watersheds across the city, seven wedges, multiple corridors, and multiple parks" and enhanced the ecological corridors formed by the Songhuajiang, Ash River, and Hulan River. From the perspective of master urban GI planning, Songbei District, Hulan District, and Acheng District are separated from other districts and are far from the urban centre, and they are the main areas, where the Songhuajiang and Hulan River flow. The water system is rich and self-contained and has an excellent original GI foundation. However, these areas are the main directions for the expansion of urban construction in the future; therefore, priority should be given to the construction of ecological corridors. Daoli District, Dawai District, and Nangang District experience the most urban traffic and socioeconomic activities that urgently require GI network regulation. At present, these districts have few ecological patches and serious fragmentation, so the focus should be on the construction of ecological sources. Xiangfang District and Pingfang District, which are mainly responsible for urban housing and economic development, have poor internal connectivity within the same types of ecological sources; thus, the construction of corridors between them needs to be strengthened.

In addition, key ecological nodes and important corridors are the core components of the GI network (Wang et al. 2016). The ecological radiation range and the ecological significance of key ecological nodes are much higher than those of general nodes, and as the dominant attraction of the regional landscape, they have a converging effect on the ecological flow of the surrounding GI network; moreover, the nodes are less costly to maintain than are corridors. The important corridors are the least essential guarantee for the connectivity of the GI network (Hansen et al. 2019; Ariken et al. 2020). Enhancing the protection and optimization of key ecological nodes and skeletal corridors is a very effective strategy for urban central districts with tight land and scarce ecological resources, which could maximize the limited resources and provide key empirical evidence for promoting the protection of areas with high ecological value in multiple scenarios.

Directions for future research

The directions for future research include the following three aspects. First, the study integrated seven environmental characteristic factors to complete the construction of the ecological resistance surface, which will have certain errors compared to the actual situation, and the precision of ecological resistance simulation in multiple scenarios should be a focus of future work. Second, the application of complex network theory to optimize the GI network topology achieved excellent results, but it is worth noting that complex network analysis is used in undirected and unweighted analyses. The development of urbanization will make the importance of regional ecological corridors different, this GI network is undirected and weighted and should be properly adjusted for realistic GI optimization. Third, some of the corridors were located in the built-up areas, and how to integrate these corridors with urban elements must be explored in the future.

Conclusions

In this study, we set five development scenarios by adjusting the economic growth rate, integrated the MCR model and gravity model to extract the GI network of the study area in multiple scenarios, introduced the LDF edge-adding optimization strategy of complex network theory to optimize the GI network, and verified the optimization effect. This research contributes to promoting the transformation of the GI network optimization research paradigm from the current status pattern and process coupling to the simulation of complex environmental systems. It aims to provide a new perspective for the study of GI network protection under urban economic growth and serves as a methodological reference for urban GI network optimization.

The main conclusions of the study include six points. First, the number of ecological sources determined in the study area was 119, covering 42,082.65 hm^2, and they varied significantly in size and were strongly fragmented. Second, with the transition from the current scenario to the 20% economic growth scenario, there was significant growth in matrix resistance in the central part of the study area. Third, there were fewer easily identifiable ecological corridors in the study area. In the 5% economic growth scenario, the network was more complex, and the connectivity was better, while in the other scenarios, the network structure gradually degraded with economic growth, indicating that there was still room for economic development but it was limited under existing GI conditions. Fourth, after optimization by the LDF strategy, the GI network of the study area in multiple scenarios formed a kind of mixed network pattern with primary and secondary. Fifth, with robustness tests, the connectivity of the optimized GI network structure in multiple scenarios was significantly enhanced, and the recovery ability of ecological nodes and ecological corridors against attacks was greatly improved. Sixth, the integrated forces between ecological sources and complex network topology characteristic parameters were combined to complete the identification of key nodes and important corridors in the study area, which highlighted the priority protection and optimization direction for the construction of GI networks in multiple scenarios.

Abbreviations

GI: Green infrastructure; MCR: Minimal cumulative resistance; LDF: Low-degree-first; NDVI: Normalized difference vegetation index; MNDWI: Modified normalized difference water index; EWM: Entropy weighting method; Idp: Importance values of the patches.

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Authors' contributions

SS: conceptualization, software, validation, writing-original draft, and writing—review and editing. SHW: methodology and investigation. MXS: methodology and investigation. SSH: validation and software. DWX: conceptualization, resources, project administration, and funding acquisition. All authors read and approved the final manuscript.

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Availability of data and materials

The data sets used and analysed in this study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

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

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