Identification of a wetland ecological network for urban heat island effect mitigation in Changchun, China

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ABSTRACT

The rapid development of cities has led to severe fragmentation of wetland landscapes, destroying their ecological function in climate regulation. However, most studies on the climate regulation services of wetlands focused on isolated wetland units, ignoring the overall function of wetland networks. The climate regulation function of wetlands can be improved by integrating fragmented wetland resources and building a stable wetland network. A case study was carried out in Changchun City, China, to improve the method of identifying ecological networks by considering the network energy flows. First, morphological spatial pattern analysis and landscape connectivity index combined with the wetland cooling index were used to identify ecological sources with high cooling capacity, and an ecological resistance surface was constructed with surface temperature as the main factor. The minimum cumulative resistance model was then used to identify the ecological network, which was then optimized by integrating patches as stepping stones to form the optimized ecological network. Finally, the importance of ecological corridors was evaluated by identifying ventilation corridors and integrated with the complex network theory to determine the ecological network robustness. We found that the degree of fragmentation in the studied wetlands was relatively high, and that construction of an ecological network with patches as stepping stones can improve its robustness. Each component in the ecological network had a high potential to mitigate the urban heat island effect, which can be further promoted by ecological corridors with high ventilation potential. Mutations in ecological nodes that cause network robustness played a key role in maintaining ecological network stability. This improved methodology effectively improves the scientific and practical application of wetland networks to mitigate the urban heat island effect and provides regions facing the contradiction of rapid development and wetland protection with strategies to reduce the threat of this effect.

1. Introduction

Wetlands are one of the most important and unique ecosystems on Earth, providing a variety of ecosystem services for human survival and development (Song et al., 2021a; Song et al., 2021b). Because of their important role in mitigating the urban heat island effect, particularly through their function of climate regulation, wetlands are also known as "cold islands" (Chang et al., 2007). However, rapid urbanization seriously threatens wetlands, gradually decreasing their ability to provide ecosystem services (Sizo et al., 2016; Torres-Lima et al., 2018). In addition, the synergistic effect of urban heat islands and heatwaves poses tremendous risks to human health and daily productive activities (Debbage and Shepherd, 2015; Wang et al., 2021). The scientific construction and maintenance of wetland ecological networks can effectively improve their ecological services, which is significant for improving the urban thermal environment (Peng et al., 2022).

As a scientific method used for spatial planning and conservation, ecological networks were first proposed in Europe in the 1980 s to prevent regional patch isolation and maintain or restore the connectivity of natural ecosystems (Biondi et al., 2012; Pili et al., 2019). Ecological
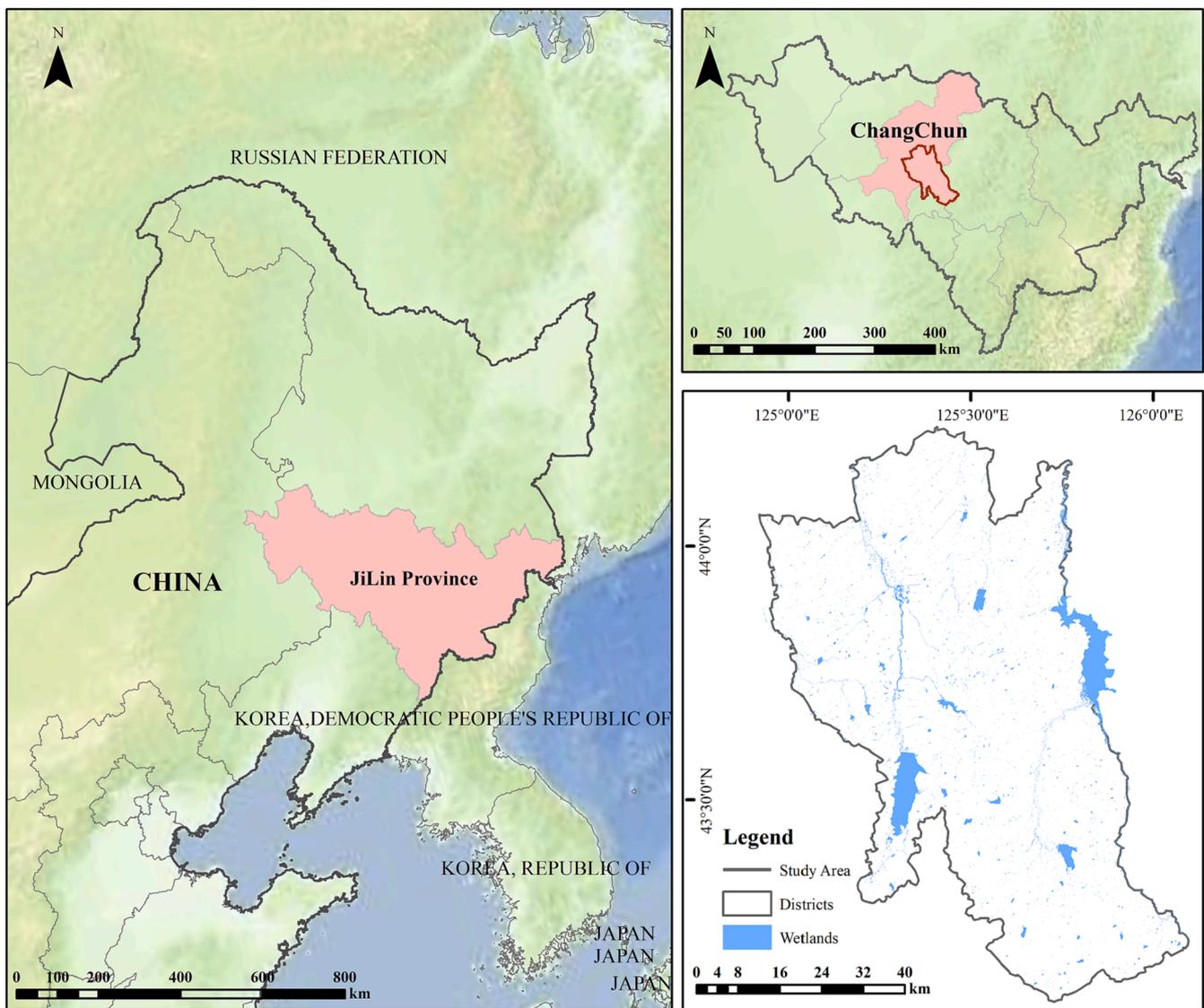
Fig. 1. Location and wetland distribution of Changchun.

networks composed of ecological sources and potential ecological corridors can effectively increase the connection between isolated patches in a region, promote material and energy flow between patches, and enhance network structure and functional connectivity, thereby significantly improving the services provided by regional natural systems (Chen et al., 2017). With the development of ecological networks and integration of interdisciplinary theories and methods, the method of construction ecological networks has gradually followed this model: source identification, resistance surface construction, ecological corridor identification, and corridor optimization and evaluation (Guo et al., 2021; Tang et al., 2021). Among the components of this model, identification of ecological sources and extraction of ecological corridors are key research areas. Methods of identifying ecological sources are largely based on subjective evaluation (Wang et al., 2021; Wei et al., 2022), ecological service value, and the combination of morphological spatial pattern analysis (MSPA) and landscape connectivity index evaluation (Hu et al., 2022). Based on the source-sink theory, the minimum cumulative resistance model has become the conventional method for extracting ecological corridors because of its practicality (Peng et al., 2018; Santos et al., 2018). In addition, combining circuit theory (McRae et al., 2008), gravity models (Wanghe et al., 2020), and hydrological analysis (Wei et al., 2022) with the minimum cumulative resistance (MCR) model is also an effective method for extracting ecological

corridors. Ecological networks can be regarded as complex networks composed of ecological sources, stepping stone patches, and ecological corridors. Complex network theory is a topological analytical method derived from graph theory, which mainly focuses on the topological structure between nodes in a network system (Zamberletti et al., 2018). It has been widely used in research on the robustness of transportation, computer, and social networks, and can effectively solve the problems of risk control in complex networks and improve network robustness (Song et al., 2021a; Song et al., 2021b). Exploring the robustness and network efficiency of ecological networks under different experimental scenarios can provide a reliable basis for network construction and maintenance (Luo et al., 2020).

Because of their high cooling capacity, urban blue/green spaces are considered economical and effective means of mitigating the urban heat island effect (Yu et al., 2020). The climate regulation services of wetlands account for an extremely high proportion of environmental regulation services (Wang et al., 2021), and the ability of wetlands to mitigate the urban heat island effect has been proven to be greater than that of other green spaces (Xue et al., 2019). The shape, size, number, and distribution of surrounding heat sources, along with the hydrological connectivity of wetlands, affect the cooling effect of wetlands (Peng et al., 2020; Sun et al., 2012). Mitigation of the urban heat island effect is primarily achieved through strong evaporation, high specific heat
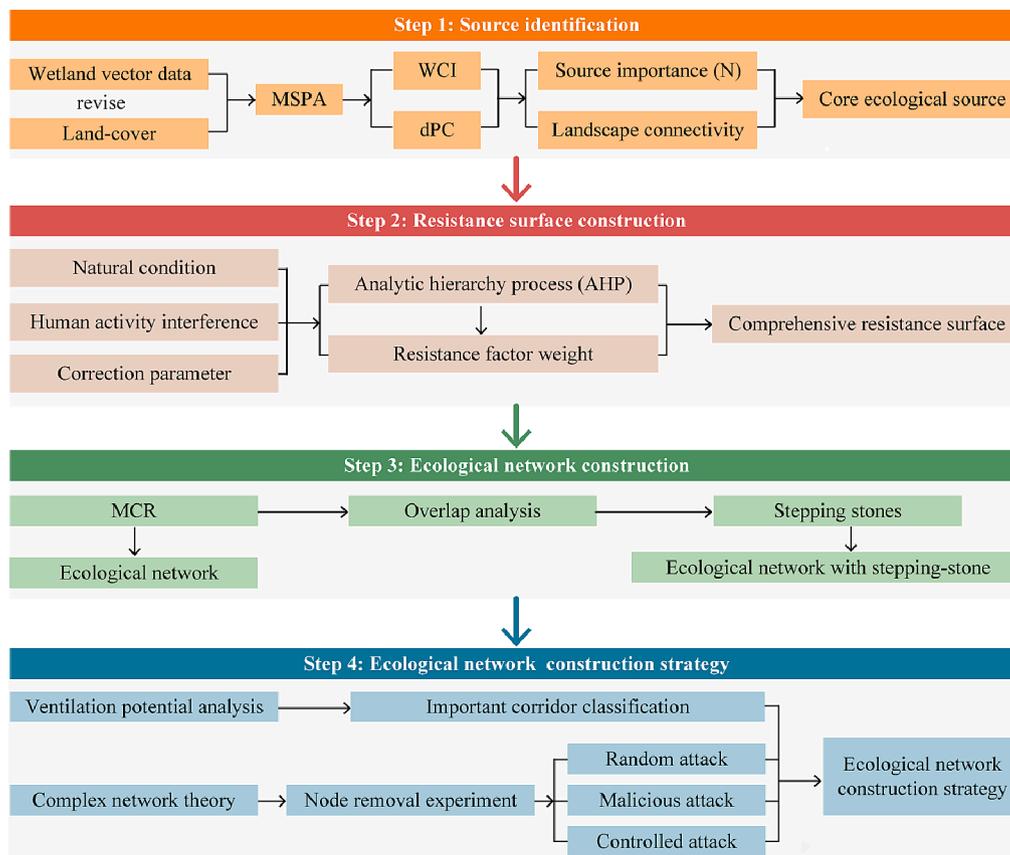
Fig. 2. Workflow of ecological network identification and evaluation. MSPA - morphological spatial pattern analysis; WCI - wetland cooling index; dPC - patch importance index; MCR - minimum cumulative resistance model.

capacity, and influences on the water cycle (Gunawardena et al., 2017). In addition, urban ventilation is another important means of alleviating urban heat islands in urban planning. By building urban ventilation pathways, introducing fresh air, and promoting airflow, the urban heat island effect can be significantly weakened (Guo et al., 2018; Shi et al., 2022). Sufficient ventilation can also promote evaporation of the water surface, which increases the cooling effect of wetlands (Stathopoulos, 2006). Ecological corridors with high ventilation potential can contribute positively to the cooling effect of the overall network. In addition, Peng et al. (2022) identified a cooling network that can reduce the cross-regional urban heat island effect by identifying ecological corridors to connect urban blue/green landscapes. However, it is insufficient to only consider ecological source selection in constructing wetlands as efficient cold islands. By enhancing hydrological connectivity, the cold island effect of wetlands can be amplified; therefore, establishing landscape connections between isolated wetlands based on heat exchange can help improve the climate regulation function of wetland networks (Wu et al., 2021; Xue et al., 2019). Dense urban buildings can also contribute to heat accumulation, thereby limiting the extent of wetlands in mitigating the urban heat island effect (Xue et al., 2019). The impact of urban heat islands on the cooling extent of wetlands requires careful consideration. For areas with highly fragmented wetland landscapes, stepping stones have become an important solution for promoting ecological network connectivity (Luo et al., 2020; Lynch, 2019). Stepping stones located in corridors are not only transit points for ecological processes, a potential stepping stone network formed based on ecological functions can also carry material and energy flows (Luo et al., 2021). However, the role of stepping stone patches within corridors has often been ignored in previous studies.

In general, the climate regulation function of wetlands can effectively alleviate the heat island effect. The use of fragmented wetland

resources for constructing an ecological network can broadly improve the climate regulation function of wetlands. As a region with a high degree of fragmentation in its wetland landscape, Changchun City in China is an appropriate research area. Considering energy flow obstacles, in which the cyclical process of thermal exchange and energy transfer is the energy flow process, high temperature areas usually prevent the establishment of energy flow connections between cold islands (Hathway and Sharples, 2012; Peng et al., 2022). Therefore, a characteristic resistance surface can be constructed by integrating surface temperature. Wetlands are regarded as the "cold cores", and corridors are regarded as channels of energy transfer. By identifying a network that fully leverages the climate regulation function of wetlands, the problems of dense urban heat islands and increasingly serious heatwaves can be addressed. The objectives of the present study were to: (1) identify an ecological network of wetlands in Changchun City to improve their climate regulation services; (2) simulate the stepping stone ecological network by integrating stepping stone patches; (3) conduct an analysis of ecological network robustness and its ventilation through which to evaluate the potential of important ecological corridors and nodes in the network, thereby providing a scientific basis for ecological network construction and maintenance.

2. Materials and methods

2.1. Study area

Changchun (43°05′–45°15′E,124°18′–127°02′N; Fig. 1) is located in central Songnen Plain in Northeast China, on the eastern coast of Eurasia, and is the capital city of Jilin Province. It is located in the mid-temperate monsoon, semi-humid continental climatic zone, with hot and humid summers and long cold winters. The annual mean

temperature of Changchun City is 4.8 °C, with the maximum temperature reaching 39.5 °C. Southeasterly wind prevails in summer, and moisture from the Bohai Sea passes over the land.

2.2. Data sources

The data used in the present study included: (1) Landsat8 data (September 4, 2021) at the C2L2 level and Sentinel 2A data (September 2, 2021) which were obtained from the United States Geological Survey (USGS) (https://earthexplorer.usgs.gov/); (2) elevation data of the study area obtained from GDEMV3 data provided by the Geospatial Data Cloud (https://www.gscloud.cn/); (3) Changchun City administrative boundary vector and highway vector data in 2020 obtained from the National Geographic Information Resource Catalog Service System; (4) wetland distribution data in the study area visually interpreted from Google Earth from June-September 2021; (5) meteorological data in the study area in 2021 extracted from the public FTP server (ftp://ftp.ncdc.noaa.gov/pub/data/noaa/isd-lite/) provided by the National Climatic Data Center (NCDC); and (6) nighttime light data derived from Luojia-1 with 130-m resolution (note: the image acquisition data was from September 5, 2018, since Loujia-1 had only been in service for 1 year).

A neural network classification was used to supervise and classify Sentinel 2A data and extract wetlands, built-up land, woodlands, cultivated land, grasslands, bare land, tidal flats, and other landscape elements. Wetland data in the study area were visually interpreted and vectorized using images from Google Earth, and then used to correct the land-cover classification results. All data were resampled to a 30-m resolution.

2.3. Methodology

The overall framework of the present study included the following four points (Fig. 2). First, wetland areas were extracted from high-resolution images, and ecological sources were identified by the MSPA method combined with the wetland cooling index and patch importance. Second, a comprehensive resistance surface was constructed by synthesizing natural conditions and anthropogenic disturbances, and the resistance value of the land-cover data was corrected with nighttime light data. Third, the ecological network (EN) was identified based on the MCR model and stepping stone patches were extracted according to the EN to identify the optimized ecological network (OEN). Fourth, the importance of corridors was classified by analyzing the prevailing wind direction, and the importance of nodes was derived from the theoretical analysis of complex networks. Based on these data, strategies for the construction and maintenance of ecological networks were proposed.

2.3.1. Ecological source identification

MSPA is a mapping algorithm based on mathematical morphology developed by Soille and Vogt (2009). At the pixel level, the algorithm can divide the binary grid (which is composed of a foreground and background) into seven non-overlapping landscape types with different ecological functions (Ye et al., 2020). Using GuidosToolbox2.8 and the revised land-cover classification results of Changchun City, wetlands were extracted as the foreground and other land-cover types were used as the background. Considering that the resolution of Landsat8 TIRS band is 100 m, core areas with an area > 1 hm^2 in the extracted results were considered potential ecological sources. Area thresholds for wetlands are shown in Appendix A Section 2.3.

Landscape connectivity can be used to measure the connectivity level of patches in a region and is an important index for evaluating landscape patterns and functions (Clergeau and Burel, 1997). In the present study, the possible connectivity index (PC) and patch importance index (dPC) indices were used to evaluate the core patches (Appendix A).

Urban wetlands as cooling islands contribute negatively to regional surface temperature, and this temperature gradient is one of the important factors for wetlands to perform the thermal exchange function

Table 1

Comprehensive resistance surface assessment system. ΔLST - difference with mean temperature, LST – land-surface temperature, NDVI – normalized difference vegetation index, DEM – digital elevation model.

Resistance factor	Grading method		Resistance value	Weight
Land-cover type	Grassland		30	0.24193
	Woodland		50	
	Cultivated land		50	
	Other land		70	
	Built-up land		90	
	Wetland	ΔLST > 4	1	
		$1 \leq$ ΔLST ≤ 3	3	
		$-1 \leq$ ΔLST ≤ 1	5	
		$-3 \leq$ ΔLST ≤ -1	7	
		ΔLST < −3	9	
	Tidal flat		10	
Slope (°)	< 3		10	0.04553
	3–8		30	
	8–15		50	
	15–25		70	
	> 25		90	
NDVI	< 0		10	0.12014
	> 0.7		30	
	0.5–0.7		50	
	0.3–0.5		70	
	0–0.3		90	
DEM (m)	< 200		10	0.06138
	200–300		30	
	300–400		50	
	400–500		70	
	> 500		90	
Road distance (m)	< 300		10	0.12014
	300–600		30	
	600–900		50	
	900–1200		70	
	> 1200		90	
LST	$R_{LST} = \left[\dfrac{LST_i - LST_{min}}{LST_{max} - LST_{min}}\right]*100$			0.41088
ΔLST	$\Delta LST = L\overline{S}T - LST_i$			
Nighttime light	$R^* = (TLI_i / TLI_a) + R_{LC}$			

where R_{LC} is the resistance value of the land-cover type.

(Hathway and Sharples, 2012). In this study, the WCI intensity of a wetland was defined as the difference between the minimum temperature of the wetland and the mean temperature of the study area. Through a normalization formula for the wetland area, the WCI, source importance (N), and the above indices were calculated as follows:

$$X = (x - x_{min})/(x_{max} - x_{min}) \tag{1}$$

$$WCI = -1*(L\overline{S}T - LST_{water}) \tag{2}$$

$$N = A_x + WCI_x \tag{3}$$

where X is the sample value; x_{min} and x_{max} are the minimum and maximum sample values, respectively; $L\overline{S}T$ is the mean temperature of the study area; LST_{water} is the minimum temperature of the wetlands; A_x is the normalized area index; and WCI_x is the normalized WCI.

The source importance (N) results were ranked to select the core

Table 2
Statistics of landscape type based on morphological spatial pattern analysis (MSPA) and land-cover type.

Landscape type	Area (hm²)	Accounting for wetland area (%)	Land-cover type	Accounting for study area (%)
Core	17,315.55	70.60	Built-up land	17.61
Bridge	620.73	2.53	Woodland	15.06
Islet	2,780.91	11.34	Wetland	5.08
Edge	2,737.80	11.16	Cultivated land	52.89
Perforation	26.55	0.11	Tidal flat	0.35
Branch	937.17	3.82	Other land	0.71
Loop	108.90	0.44	Grassland	8.30
Total	24,527.61	100		100

ecological sources (Appendix A) and the dPC value was used to supplement the selection of core sources with important patches characterized by higher landscape connectivity.

2.3.2. Construction of ecological resistance surface

Settings of the resistance surface can directly affect the simulation results of the ecological corridors in the study area. Areas with excessive surface temperature hinder the connections between cold islands (Peng et al., 2022), and other factors such as land cover and elevation can facilitate or hinder the construction of corridors. Therefore, a combination of natural conditions and anthropogenic disturbances is needed in the construction of the resistance surface (Dai et al., 2021; Hu et al., 2022; Zhang et al., 2021). Natural conditions include elevation, slope, and vegetation coverage, with the latter represented by normalized

difference vegetation index (NDVI) data in the study area. Human disturbances are characterized by surface temperature, land-cover type, and distance from roads, and surface temperature is used to characterize the degree of energy flow impediment in ecological networks.

Generally, places with high building density or significant human activities always appear as strong heat sources, and regional thermal environments near blue/green landscapes tend to fare better than other regions. To reflect the differences in the resistance of built-up land, the nighttime light index was used to correct the assigned land-cover types. The data was calibrated for radiation, and the following nighttime light index correction formula (Table 1) proposed by Liu et al. (2021) was used:

$$TLI^* = (TLI_i / TLI_a) \qquad (4)$$

where TLI_i is the nighttime light intensity value of pixel i; TLI_a is the average (Table 2.) nighttime light intensity value of land-type a; and TLI^* is the corrected nighttime light intensity value.

Based on differences in the wetland cooling effect, wetland pixels were further classified using ΔLST (Table 1). Surface temperature (Appendix A) was calculated by the mono-window algorithm proposed by Qin et al. (2001) and the parameters followed the improved algorithm developed by Wang et al. (2015). The surface temperature results were normalized and multiplied by the coefficient to be integrated into the comprehensive resistance assessment system, with the resistance value ranging from 0 to 100.

Each resistance factor was graded with reference to previous studies (Fu et al., 2020; Nie et al., 2021) and actual conditions in the study area. The analytic hierarchy process, along with expert scoring, was used to determine the weight of each factor in the resistance surface (Table 1).
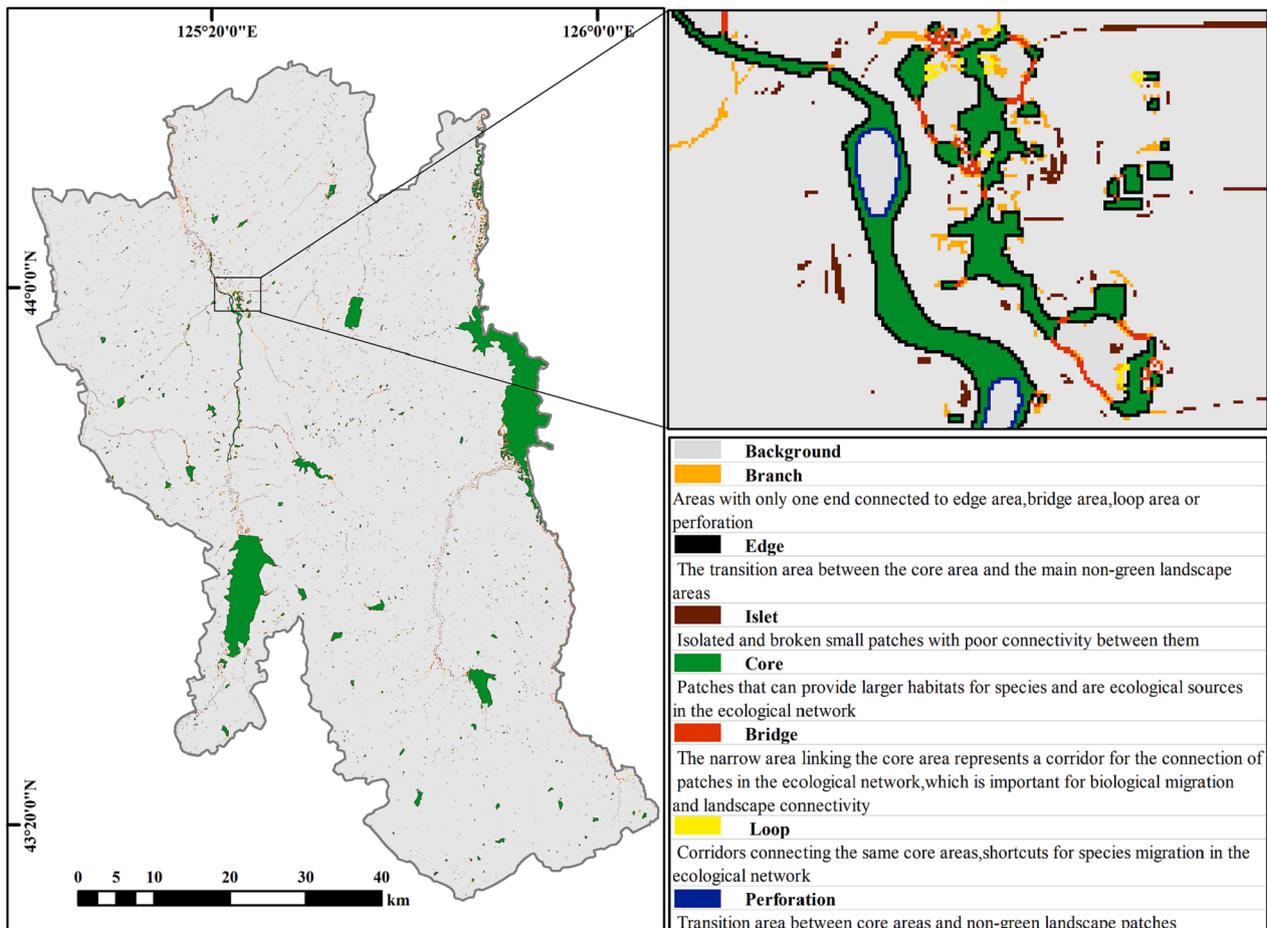

Background	
Branch	
Areas with only one end connected to edge area, bridge area, loop area or perforation	
Edge	
The transition area between the core area and the main non-green landscape areas	
Islet	
Isolated and broken small patches with poor connectivity between them	
Core	
Patches that can provide larger habitats for species and are ecological sources in the ecological network	
Bridge	
The narrow area linking the core area represents a corridor for the connection of patches in the ecological network, which is important for biological migration and landscape connectivity	
Loop	
Corridors connecting the same core areas, shortcuts for species migration in the ecological network	
Perforation	
Transition area between core areas and non-green landscape patches	

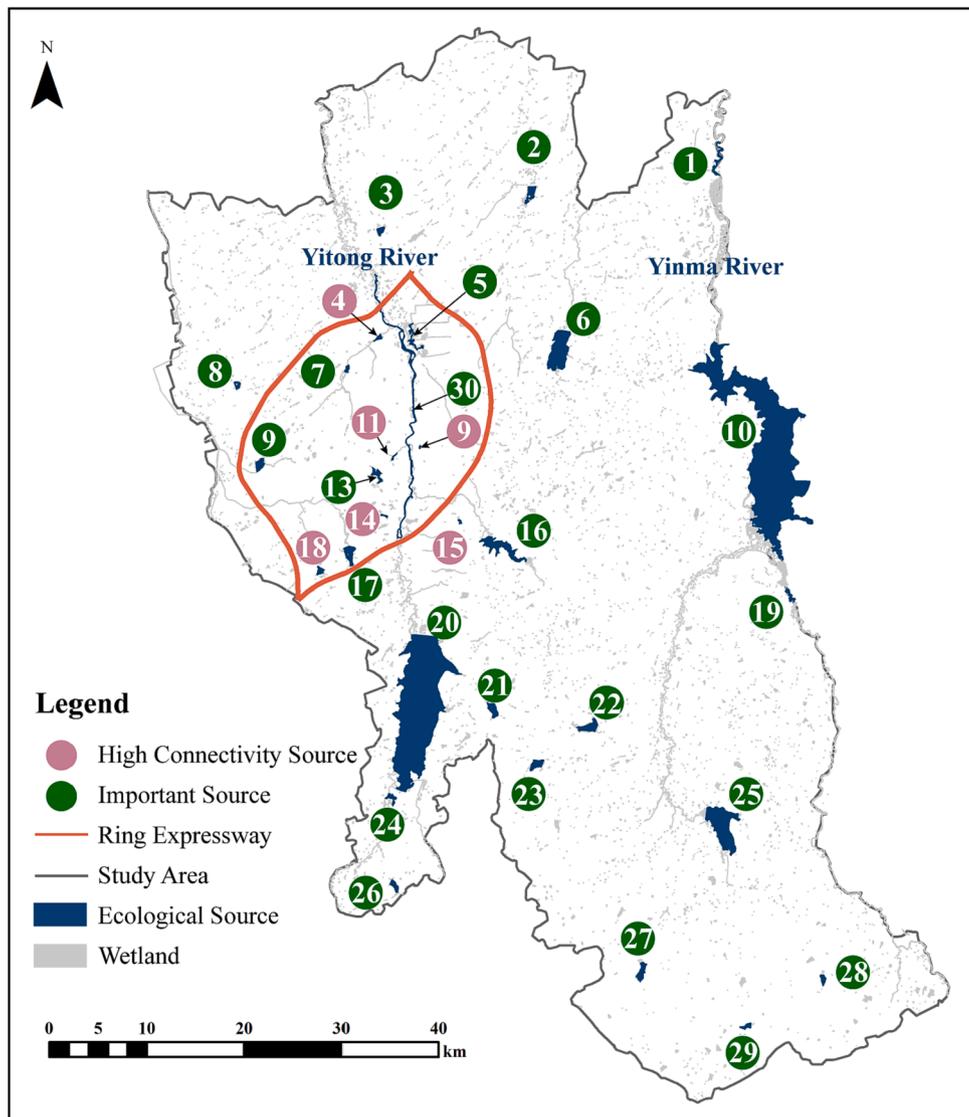**Fig. 3.** Landscape type pattern and meaning based on morphological spatial pattern analysis (MSPA).

Fig. 4. Spatial distribution of ecological sources in the study area.

The comprehensive resistance surface assessment system is shown in Table 1.

2.3.3. Extraction of potential ecological corridors and stepping stone patches

The Linkagemapper toolbox is an operation tool based on the MCR model, and was used to extract potential ecological corridors in the present study. Among the extracted corridors, duplicates, overlaps, and corridors with a length > 40 km were screened and removed to obtain the ecological network. The calculation formula of the MCR model was as follows (Knaapen et al., 1992):

$$MCR = f_{min} \sum_{j=n}^{i=m} (D_{ij} * R_i), \tag{5}$$

where MCR is the cumulative resistance value between source patches; f_{min} represents a positive function; D_{ij} is the spatial distance between two source patches; and R_i is the grid resistance value of pixel i.

As important patches that connect large ecological patches, stepping stone patches are important node components in ecological networks (Lynch, 2019). In the present study, the overlap tool in ArcGIS was used to extract the stepping stone patches, with wetland patches > 1 hm² along the ecological corridor considered stepping stone patches.

2.3.4. Ecological network optimization and evaluation

Ventilation corridors have been shown to be effective in mitigating the urban heat island effect (Fang and Zhao, 2022). In the present study, the mean angle between the potential ecological corridor and the prevailing wind direction in Changchun in summer was calculated, and the corridors were divided into three categories according to their ventilation potential.

The ecological network can be regarded as a complex network with spatial information, and the stability of its structure guarantees its full ecological function (Yu et al., 2018). The source patches and stepping stone patches were abstracted into nodes, and the ecological corridors were abstracted into undirected edges for topological processing, with the length of the edge represented by the cumulative resistance value. Connectivity robustness (Rc) and global efficiency (E) were selected to evaluate ecological network stability. Both indices were used to evaluate the stability of the network structure and its ability to transfer material and energy in the network when the network is shocked. Robustness of the complex network was assessed by node removal experiments to observe the changes in the above indicators after the node was removed, and the following formulas were used:

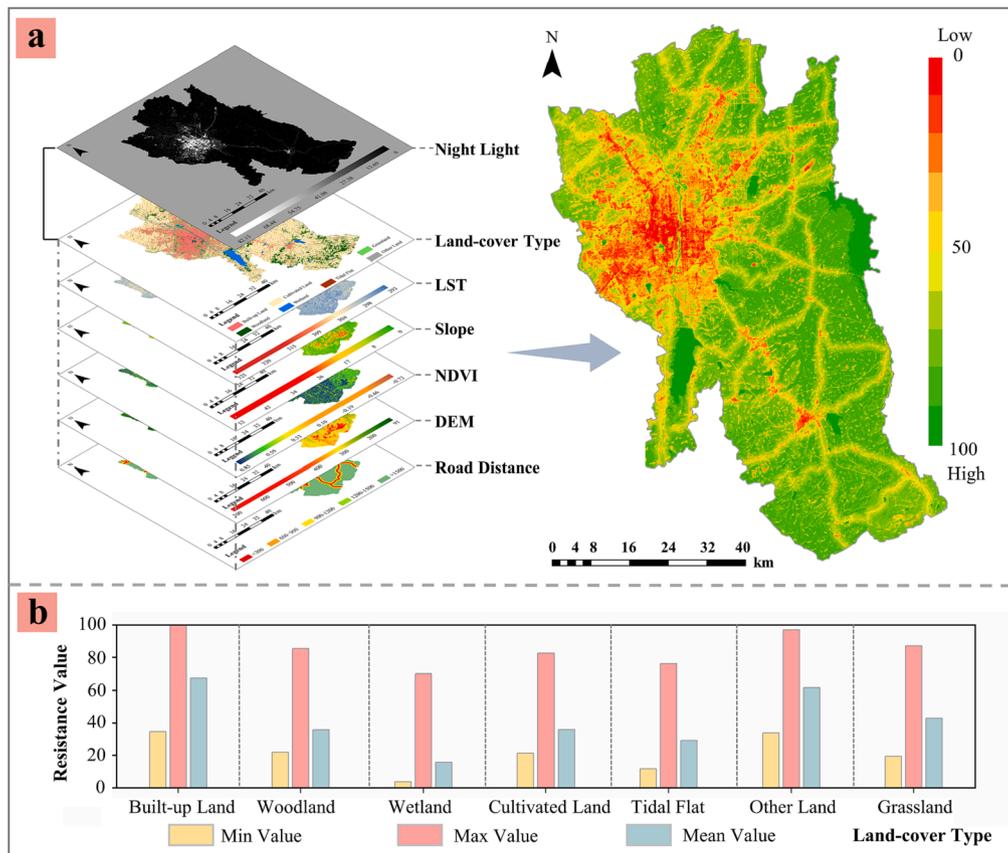$$R_c = \frac{C_{max}}{n - n'} \tag{6}$$

Fig. 5. Comprehensive ecological resistance surface in Changchun: (a) ecological resistance surface; (b) comparison of resistance values by landscape type.

$$E = \sum_{i \neq j \in G} (\frac{1}{d_{ij}}) * (1/n(n-1)) \qquad (7)$$

where C_{max} is the number of nodes in the maximal connected subgraph of the current network; n is the total number of nodes; n' is the number of removed nodes; i and j represent the nodes; G represents the set of nodes; and E_0 is the efficiency of the initial network.

Three scenarios for removing nodes were established: (1) random shock, i.e., simulation of sudden natural disasters; (2) malicious shock, i. e., shock on the node with the largest node degree in the current network; (3) controllable shock, i.e., simulation of interference and effect of urban development and human activities on the surrounding ecological nodes (Appendix A). Calculation of the node centrality index and analysis of network robustness were performed using the NetworkX package in the Python language.

3. Results

3.1. Wetland landscape pattern and ecological source identification

Wetlands in the study area accounted for 5.08 % of the total study area; however, this encompassed few large wetlands, and the wetland distribution was generally relatively scattered. The MSPA results (Fig. 3) showed that the core area of the study area was 17315.55 hm², comprising 70.60 % of the total foreground area, and that the remaining area was < 30 %. Bridge areas accounted for 2.53 % of the overall landscape and were mainly located in Yitong and Yinma rivers, as well as a small area of constructed wetlands.

Analysis of the wetland cooling capacity (Appendix A) showed that wetlands with high cooling capacity were mainly distributed in the eastern part of the study area as a strong "cold core". According to the comprehensive score and wetland area, several core area patches > 100

hm² contributed 87.99 % of the total core area patches, and these wetlands occupied the majority of the wetland resources in the study area that need to be considered in a focused manner. It is worth noting that, considering the integrity of the Yinma River, some patches with a composite score > 1 were discarded and one patch with a score of 0.95 was added. In addition, according to the dPC value, six small but highly connected wetland patches were also added. A total of 30 wetland patches were selected as ecological sources (Fig. 4).

3.2. Identification of ecological network

According to the comprehensive resistance surface (Fig. 5a), areas with high resistance values in the study area were concentrated in urban areas and highways, and the distribution of urban areas with high resistance values was consistent with the distribution of urban heat islands. The comprehensive resistance value showed a decreasing trend from the center to the edge. As shown in Fig. 5b, the land-cover types with high resistance values were mainly built-up land and other land, with mean values of 67.55 and 61.69, respectively. The mean resistance value of wetlands was 15.76. The resistance values of the same landscape showed significant differences.

According to the ecological source and resistance surface, 435 potential ecological corridors were identified using the MCR model. After eliminating redundant and overlapping corridors, 65 ecological corridors were finally determined to form EN (Fig. 6). The mean length of the ecological corridor in the study area was 16.27 km and the mean resistance value was 16,234.86 (Fig. 6c). Most of the ecological corridors were located in urban areas, among which the Yitong River (node 30) and North Lake Wetland (node 5) were the key wetlands connecting the ecological sources in the east and west, respectively (Fig. 10).
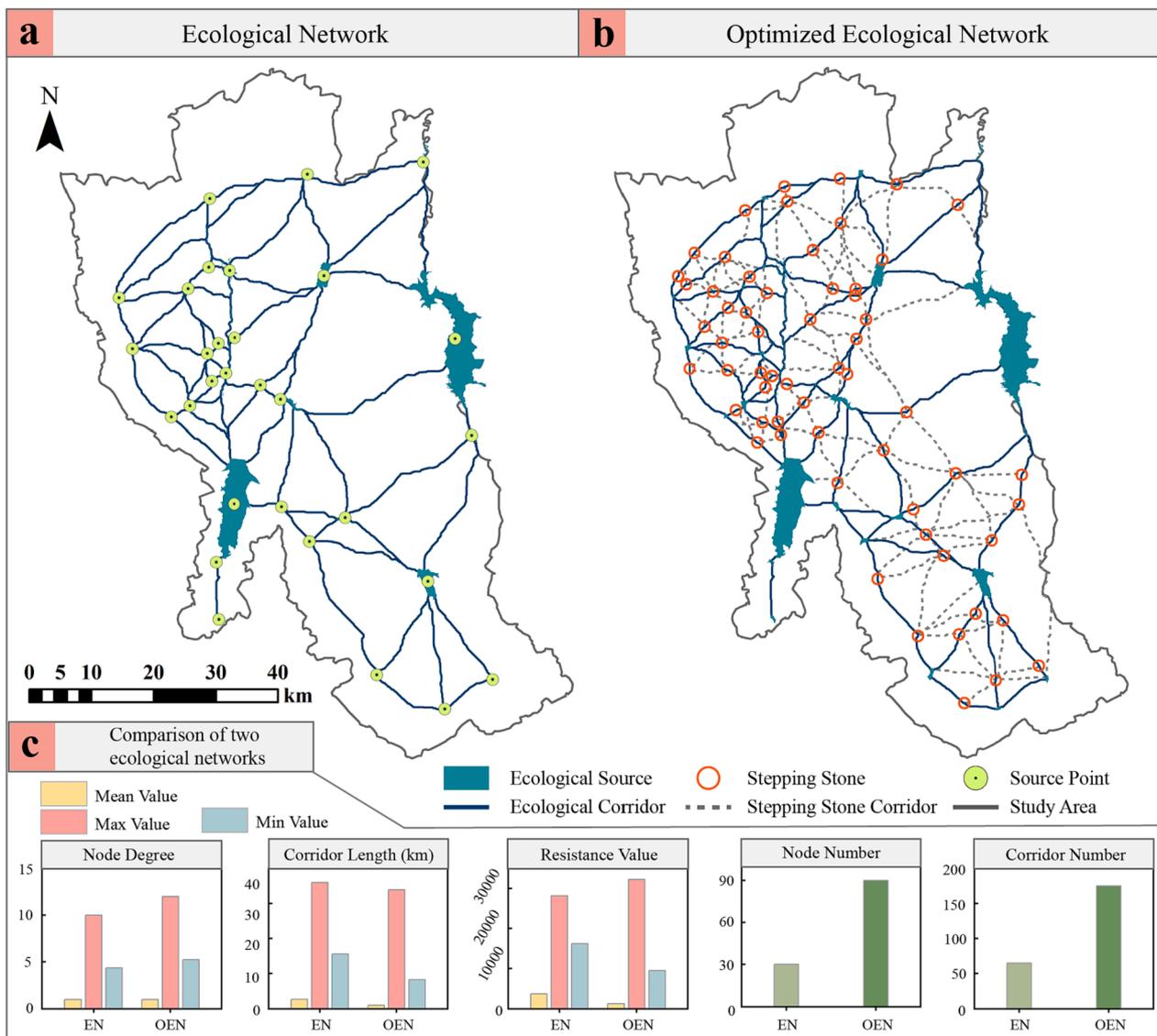
Fig. 6. Ecological network identification and corridor information statistics in the study area: (a) ecological network (EN); (b) optimized ecological network (OEN); (c) comparison of the two networks.

3.3. Ecological network optimization

According to the EN determined in the study area, a total of 60 stepping stone patches were identified based on the overlay analysis (Fig. 7). Stepping stone patches were mostly located in urban areas; specifically, mainly smaller wetland patches, regions composed of isolated wetland patches, and river wetlands. Combining the stepping stones and ecological sources, a total of 110 potential stepping stone corridors were extracted, and a total of 175 ecological corridors were obtained after superimposing EN. The mean length of the OEN corridor was 8.25 km and the mean resistance value was 9,461.37 (Fig. 6c).

Fig. 8 shows that southwesterly winds prevail in Changchun throughout the year, with the annual wind speed being mostly < 5.56 m/s. The wind speed in spring is higher than that in the other seasons, and the prevailing wind direction in summer is south-southwest. Based on the prevailing wind direction in summer, 52 important corridors (which connect most of the strong cold sources) were extracted. The classification of corridor importance is shown in Fig. 9, which shows that 27 corridors in EN and 25 corridors in the stepping stone network served as important ventilation corridors, accounting for 30 % of the OEN.

3.4. Robustness evaluation of ecological networks

3.4.1. Random shock scenario

Fig. 10a shows the changes in the connectivity robustness and global efficiency of the network under the random shock scenario, and fluctuations in the curve reflect network fragmentation. For EN, when the network lost 16 % of the nodes, the rate of decline in the connectivity robustness started to increase and was accompanied by a decrease in global efficiency, indicating that the rate of network fragmentation was increasing. When 53 % of the nodes were lost in the network, the connectivity robustness decreased by 0.38. After this point, changes in the connectivity robustness and global efficiency became smaller and the network was paralyzed. For OEN, when the network lost 25 % of the nodes, the rate of network fragmentation started to increase. The network was paralyzed when it lost 66 % of the nodes. The trend of global efficiency was similar to that of connectivity robustness.

3.4.2. Malicious and controlled shocks

Fig. 10b shows the changes in the connectivity robustness and global efficiency of the network under the scenarios of malicious and controlled shocks. In the case of shocking the node to the highest degree, the
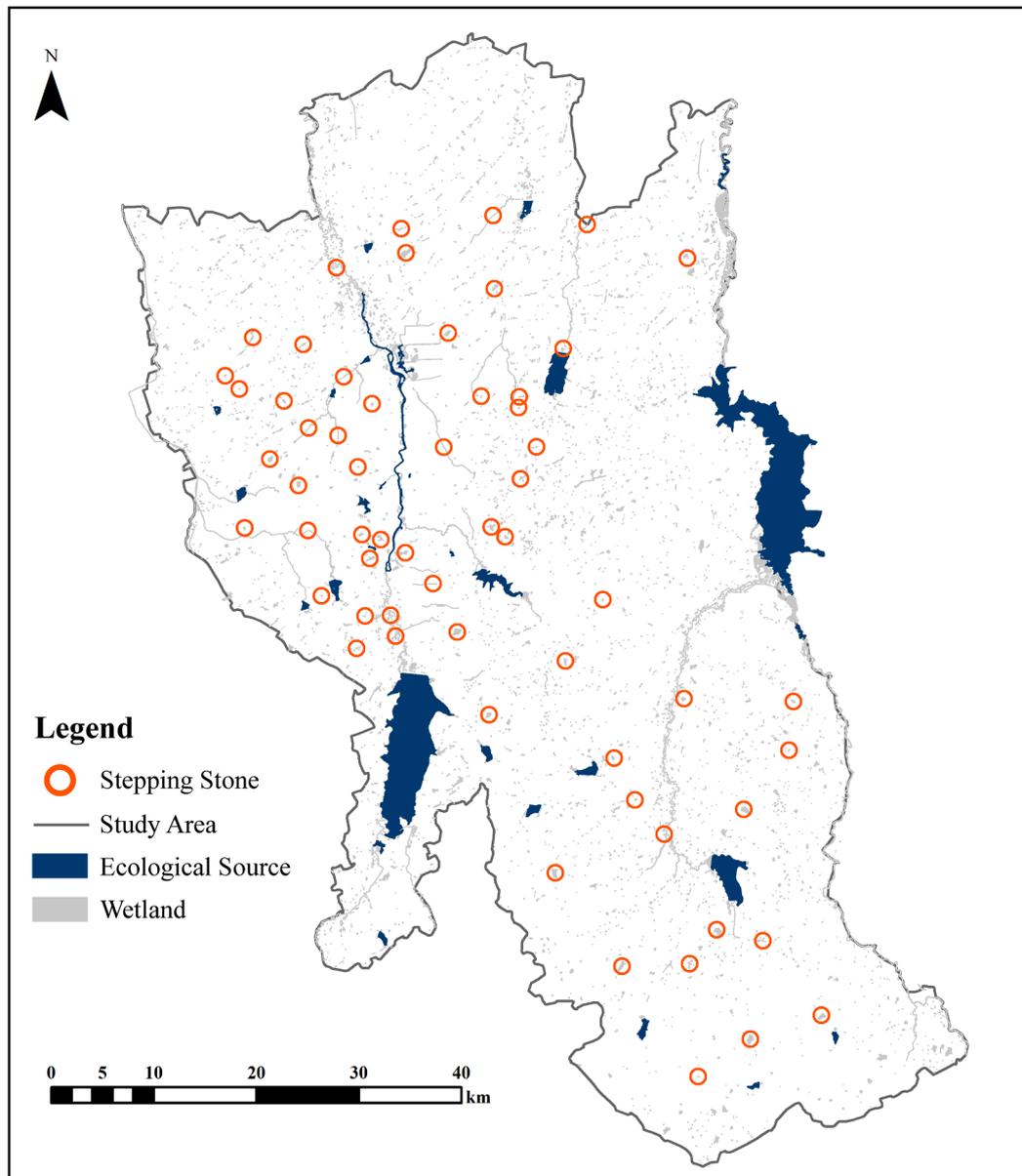
Fig. 7. Spatial distribution of stepping stones in the study area.

connectivity robustness and global efficiency of both networks decreased more rapidly than those under the random shock and showed a downward trend. For EN, when 16 % of nodes were lost, the connectivity robustness decreased by 0.12 and global efficiency began to decrease sharply. When 53 % of nodes were lost, global efficiency decreased to 0.01, rendering the network completely broken. Global efficiency already decreased sharply when the first node was removed (node 30). The connectivity robustness of the ecological network decreased sharply when the source nodes 12, 20, 22, and 23 were lost. For OEN, when 20 % of the nodes were removed, the connectivity robustness began to decrease significantly, albeit with a gentler change in global efficiency compared to that of EN.

The controlled shock scenario simulated the situation whereby all ecological sources are protected. As shown in Fig. 10b, the robustness of the controlled shock scenario was higher than that of the other shock scenarios in terms of connectivity robustness and global efficiency. The connectivity robustness started to decrease significantly only when 32 % of the stepping stones were lost, and the connectivity robustness and global efficiency could be maintained at 0.11 and 0.30, respectively,

when all stepping stones were lost. The connectivity robustness of the ecological network decreased sharply when stepping stones 77, 51, 37, and 31 were lost.

4. Discussion

4.1. Optimization of the ecological network identification method

Identification of ecological networks is limited by the selection of ecological sources and evaluation of resistance surfaces, and different application purposes of ecological networks determine different evaluation methods of ecological sources and resistance factors (Zhang et al., 2017). In the present study, some commonly used assessment methods were improved to enhance the climate regulation services of urban wetlands. We showed that large core areas of the study area were mainly located in rural areas and that wetlands in cities were mostly small and scattered. The area-based screening may have overlooked small areas of wetlands surrounded by green spaces in the cities, which tend to have higher cooling efficiencies (Peng et al., 2020). The inclusion of WCI in
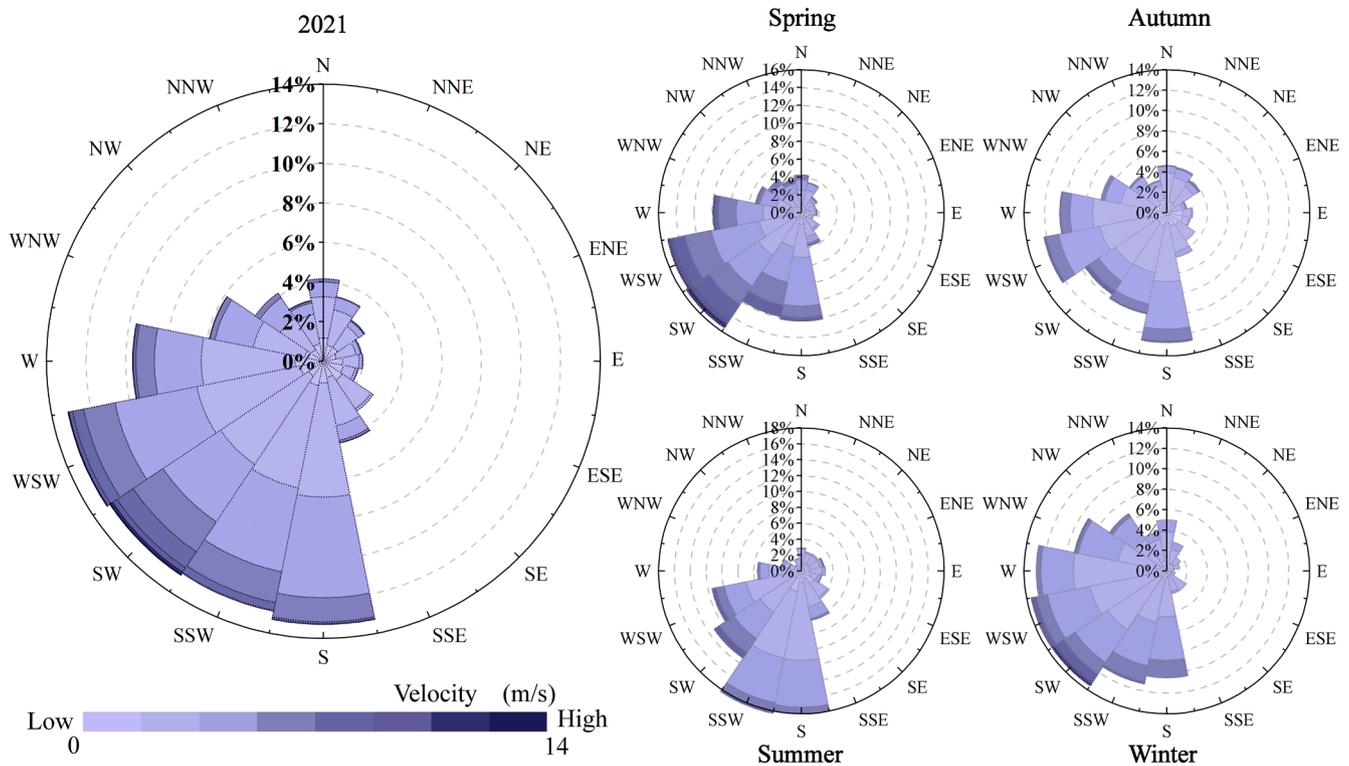
Fig. 8. Wind direction and frequency in Changchun in 2021.

the source assessment ensured that the extracted sources had a higher cooling effect, such that the higher cooling capacity of these wetlands was enhanced by constructing a network. Evaluation of resistance factors is a key process affecting corridor extraction (Nie et al., 2021). However, some studies used land-cover types as the main factor of resistance value, ignoring the fact that land cover is not directly related to the impediment of energy flows (Peng et al., 2022; Zhang et al., 2021). However, heat exchange and local circulation are the key processes in the mitigation of the heat island effect by wetlands (Wilson et al., 2003). According to Fig. 5c, the resistance values not only showed significant heterogeneity among different landscapes, but also showed differences at the pixel level in the same landscape. Industrial areas, commercial centers, and urban centers with low greenery had more concentrated heat island effects, and their resistance values were higher than those of built-up land located near ecological sites. Conversely, because of the influence of strong heat sources in the city, the resistance values of some blue/green landscapes were high and were excluded from the optimal path of ecological network identification. To summarize, for the purpose of strengthening the climate regulation service of wetlands, this method renders the identification of ecological networks more feasible and reasonable.

4.2. Effects of ecological network components on the heat island effect

Isolated wetlands play a limited role in climate regulation; whereas, cooling networks can amplify the "cooling effect" of wetlands (Peng et al., 2022). Our results showed that the cooling capacity of wetlands varied between urban and rural areas, with wetlands located in urban areas having a lower cooling capacity (Fig. 4). This finding is significantly related to the influence of the heat island effect. Urbanization leads to concentration of heat sources, limiting the climate regulation function of isolated wetlands in cities. Furthermore, the high specific heat capacity of wetlands reduces the cooling rate at night. Shade provided by trees around the wetlands is also an important factor in this difference (Brans et al., 2018). However, the variations in temperature between wetlands and the surrounding environment suggest that

wetlands located in cities have a higher cooling efficiency than those in rural areas (Peng et al., 2020). In our study, the wetlands with high cooling efficiency in the city fully contributed to alleviating the urban heat island effect; whereas, those in rural areas could supply fresh cold air to the wetlands in the urban area, which can not only drive energy flow in the ecological network but can also prevent thermal pollution in wetlands in urban areas.

Stepping stones in a network are transit points for ecological processes and can form a potential stepping stone network by attracting ecological flows and exchanging ecological resources (Luo et al., 2021). With 60 stepping stone patches included in the network, the mean node degree and number of corridors increased by 0.89 and 110, respectively (Fig. 6), indicating that more connections were added to the network, and a more complex network is known to be more stable (Luo et al., 2020). The length and resistance value of the corridors in the network decreased by 7.30 km and 6,773.49, respectively, indicating that energy could reach another ecological source in the network more easily. Therefore, stepping stones can not only increase the stability of the ecological network, but also recharge energy flows and provide additional paths while the cooling path is operating. The ecological corridor analysis showed that the corridors were denser in urban areas than in rural areas and formed a ring of defense in urban and rural areas (Fig. 6). Ecological corridors act as carriers of energy flows, and the segmentation is an effective means to prevent the spread of heat islands (Peng et al., 2022; Roy et al., 2010). Corridors located in rural areas are distributed around wetlands with strong cooling capacity, driving the operation of the entire cooling network.

4.3. Ecological network evaluation

Scenario analysis can elucidate the impact of different ecological patch changes on ecological network stability to determine the ideal conservation scenarios (Wimberly et al., 2018), which can assist in formulating more effective conservation strategies. Comparing EN and OEN when shocked, EN lost 16 % of the nodes and was the first to become fragmented, indicating that it was vulnerable to damage under
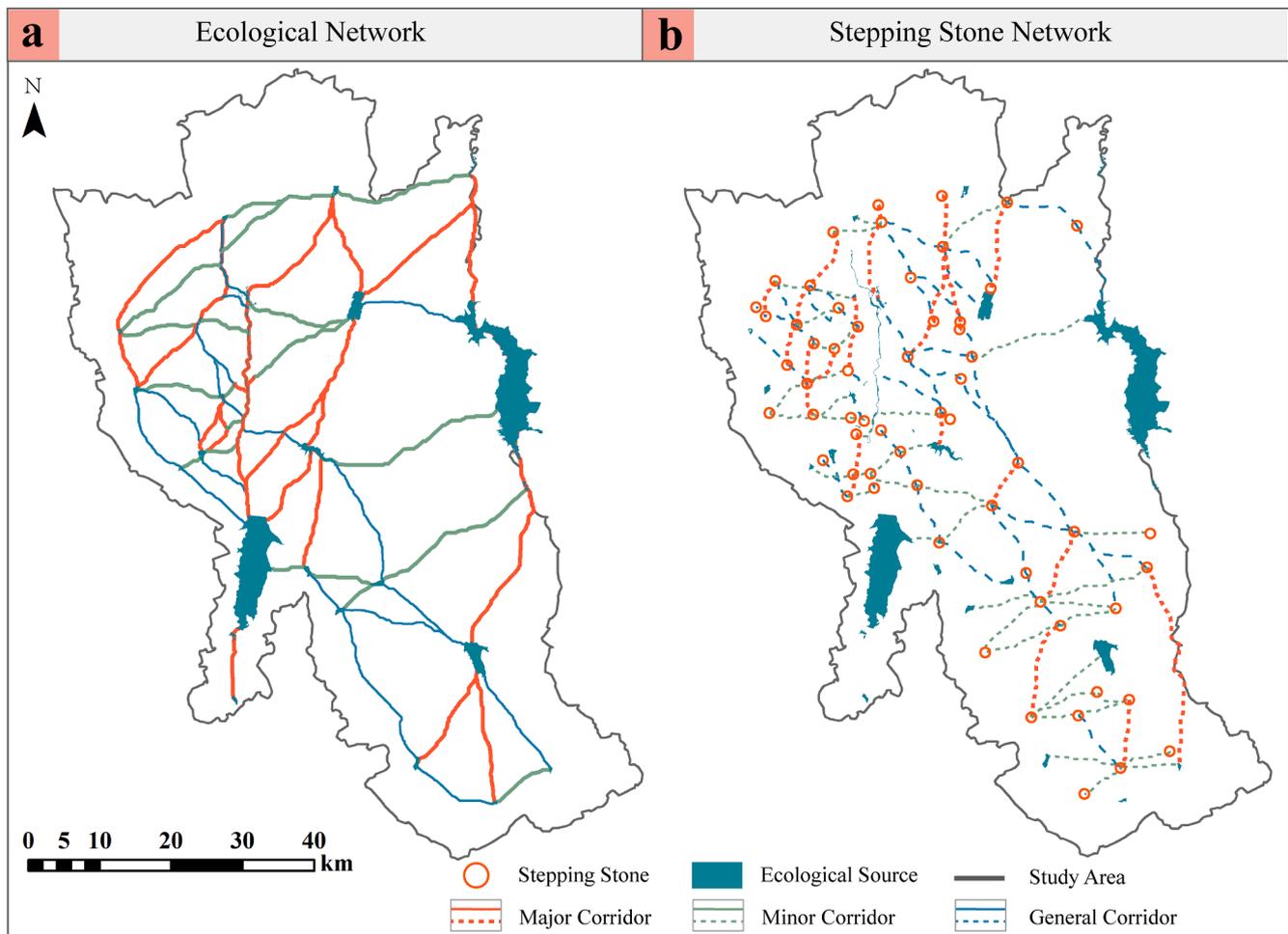
Fig. 9. Classification of the importance of corridors in the study area: (a) distribution of important corridors in EN; (b) distribution of important corridors in the stepping stone network.

shock. The share of nodes required to paralyze OEN was 66 %, compared to 53 % for EN, suggesting that OEN had a greater ability to withstand shocks. The node failure ratios of 16 % and 25 % were the key values required for EN and OEN, respectively, to maintain their integrity. However, the global efficiency of OEN was slightly lower than that of EN (Fig. 10b), mainly because as more nodes and corridors were added to the network, longer corridors in EN were divided into multiple shorter corridors by stepping stones, thereby affecting the transmission efficiency of the network. In the controlled shock scenario, the disappearance of some stepping stone patches had a strong impact on network robustness. In the malicious shock scenario, the main reason for the stepwise decline in connectivity robustness and global efficiency was the lack of protection for the nodes with high centrality. If nodes with high centrality cannot be protected, it will be difficult for these nodes to maintain the stability of the ecological network (Luo et al., 2020). Therefore, policies on ecological node protection should focus on patches with high centrality.

In addition, urban ventilation is considered an important method for mitigating the heat island effect through the replenishment of cold air. Ecological corridors are advantageous over ventilation corridors composed of urban roads, of which the materials may exacerbate the urban heat island effect (Shi et al., 2022). Fig. 9 shows the ventilation corridor determined in the present study. The main ventilation corridor in Changchun City accounted for 30 % of the total corridors, which indicated that the identified ecological network had a very high ventilation potential and that promoting the rate of energy flow within a network with wind is a cost-effective method. The ecological network

construction strategy is shown in Appendix A Section 5.

4.4. Future research directions

The OEN established in this study was able to enhance the function of wetland climate regulation services and improve the regional thermal environment, providing a reference for the construction of a wetland ecological network in Changchun City. The extraction of ecological corridors mainly depends on the construction of a comprehensive resistance surface. All data used in the present study had a 30-m spatial resolution. In future studies, higher-resolution data can be used to extract corridors with higher accuracy, which is also useful for simulating suitable corridor widths. In addition, the node removal experiment only simulated node disappearance. In reality, it is unlikely that nodes would disappear completely; however, they would undergo a certain process. Vulnerable nodes may face a reduction in area, degradation of ecological functions, and the occurrence of periodicity. The impact of these changes on ecological network stability warrants further discussion.

5. Conclusions

In the context of the contradiction between the demand of land resources for rapid urban development and wetland conservation planning, wetland ecological networks can provide an effective means of preventing further fragmentation of wetland landscapes and improving their ecological service functions. In the present study, the methods of
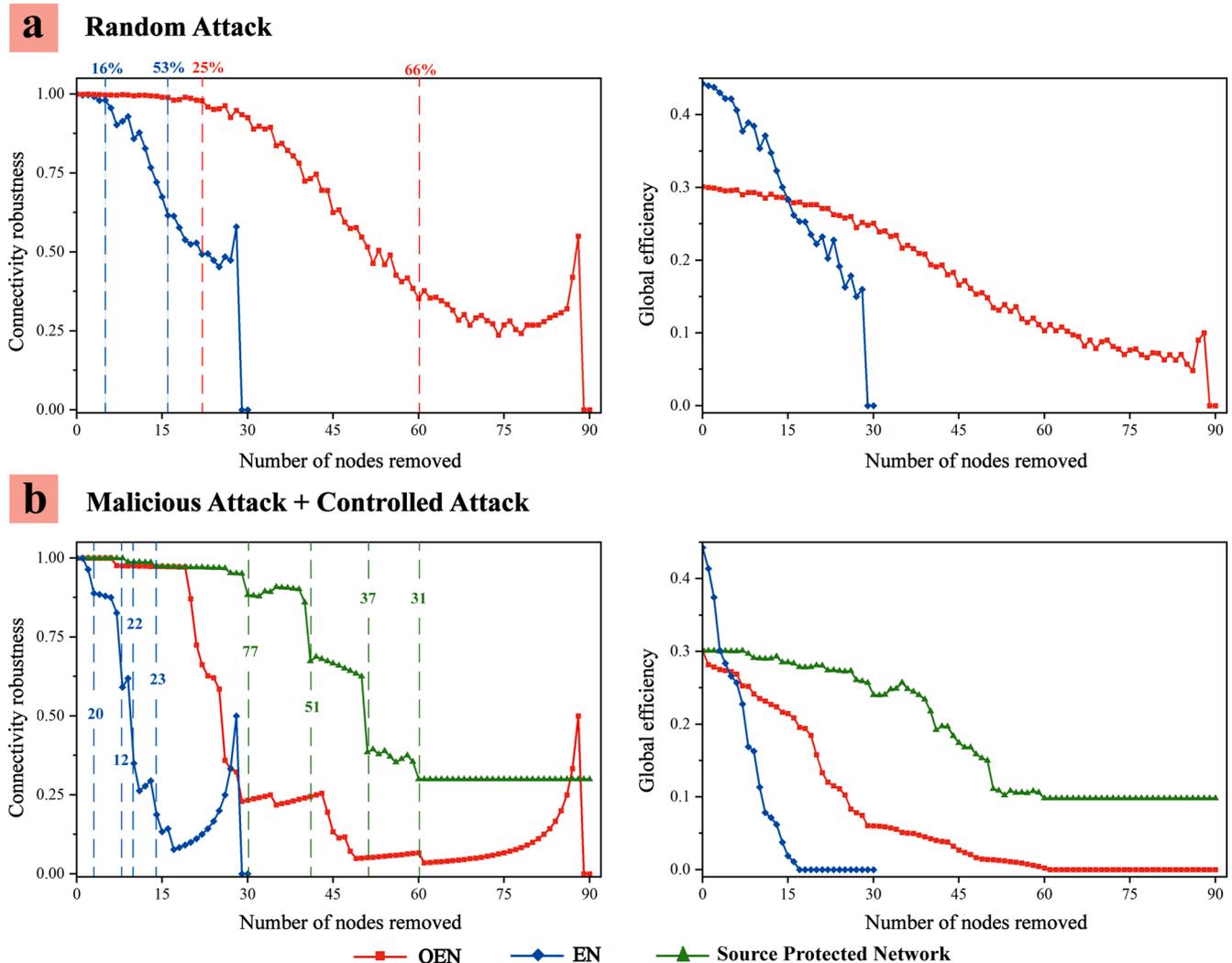
Fig. 10. Variation in network robustness under different scenarios: (a) random shock scenario; (b) malicious and controlled shock scenarios.

source identification and resistance surface construction were improved and a wetland ecological network with the function of alleviating the heat island effect was identified by integrating stepping stone patches. Our main findings were as follows.

First, the ecological network was identified by considering energy flow and cooling capacity, which ensured that the extracted sources had a higher cooling effect. In addition, it allowed identification of heat source areas as well as ecological lands affected by heat sources, which were excluded from the optimal path of the ecological network.

Second, the cooling capacity of ecological sources in Changchun showed urban–rural differences, which were the source of energy flow in the network. On the basis of the MCR model, we obtained 30 ecological sources and 65 ecological corridors, with each component playing a different role in the network.

Third, the wetland landscape was severely fragmented, and incorporating stepping stone patches within the corridors into the network construction was found to increase the network complexity and accessibility of internal energy.

Fourth, the identified ecological network had a high ventilation capacity. The corridors with high ventilation potential were the key corridors for promoting energy flow within the ecological network and should be prioritized and maintained.

Finally, the results of the node removal experiments showed that the optimized network was more stable and exhibited stronger resistance when shocked. To maintain the network robustness, not only should a

certain number of nodes be maintained, but attention should also be given to the nodes that cause the decrease in connectivity robustness, as these nodes play a key role in maintaining the status quo of the network structure.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2023.110248.

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