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ORIGINAL RESEARCH ARTICLE

Urban biodiversity conservation planning integrating the analysis of green space structure and functional connection

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ABSTRACT

The process of urbanization and population growth lead to the fragmentation of biological habitat and the loss of biodiversity. It is of great significance to use effective models and indicators to evaluate landscape connectivity and construct green space network for habitat restoration and biodiversity conservation. Taking Fengtai District of Beijing as an example, firstly, the optimal distance threshold of green space construction suitable for biological migration is discussed by using the connectivity index based on graph theory, and the source patches are selected according to the evaluation results of landscape connectivity. Secondly, the resistance surface is constructed by using the minimum cost path model, and the potential connection path of species migration is determined by Linkage Mapper tool. Finally, according to the relative importance of patch and corridor in the quantitative source of current density, the "pinch" area, which is very important to species migration, is identified, and the model recognition results are compared with the empirical observation results of remote sensing satellite map and bird abundance. The results showed that the ecological base of green space in the western part of the study area was good, which provided the main habitat for species, and the patch fragmentation of green space in the central and eastern regions was serious, so it was necessary to increase urban green space as a stepping stone for species migration in pinch areas. The circuit model focusing on species diffusion is introduced in the study, which makes up for the lack of urban green space network construction method at the level of biodiversity conservation, clarifies the present situation of habitat quality and the future development of green space network in Fengtai District of Beijing, and provides scientific reference for the optimization of regional green space pattern and biodiversity conservation planning strategy.

Keywords: landscape architecture; urban biodiversity; landscape connectivity; green space network; circuit theory

1. Introduction

Biodiversity conservation is an important ecosystem service function provided by urban green space[1], especially in the central urban area where high intensity construction and frequent human activities, ecosystem degradation and landscape fragmentation seriously hinder biological migration, resulting in a significant decline in biodiversity[2]. In addition, urban green space is usually subjected to different degrees of human intervention, the complexity of its landscape composition determines its dynamic process and mechanism are very different from the natural ecosystem[3], which is the

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central urban green space different from rural areas and natural ecological space. This makes it difficult for traditional conservation measures focusing on species themselves, with genetic diversity and species diversity as the starting point, to play a good role in complex urban environment, while biodiversity protection from the perspective of landscape architecture emphasizes the protection of species living environment, and it is an effective way to protect local or overall urban green space habitat through landscape ecological planning[4]. This approach pays attention to the influence of landscape pattern change on biological migration activities under human disturbance, and gradually changes from individual habitat protection to green space network under the in-depth study of landscape ecology. Therefore, how to construct a reasonable green space network and protect biodiversity in order to provide a variety of ecosystem services has become an important issue in urban landscape ecology research. The perfect green space network construction method needs to consider not only the interaction between land spatial pattern and landscape fragmentation, but also the formulation of strategies conducive to species survival, reproduction and migration, as well as supporting the priority protection of biological habitat environment[5].

Improving the connectivity between population migration and habitat is very important for a wider range of ecological processes. It is an important research basis and evaluation index for biodiversity conservation planning[6–8]. Many studies use habitat quality index as an index to directly apply to the evaluation of biodiversity, ignoring the internal relationship between habitat connectivity and biodiversity[9]. Understanding, protecting and restoring landscape ecological connections in complex environments requires reliable, efficient and process-based connection models and measurement methods. Landscape connections are usually divided into structural connections and functional connections[10].

The main results are as follows:

1) Structural connection emphasizes the influence of patch shape and structure on biological migration, such as corridor width, patch distance and so on. Structural connection has shown strong practicability in the construction and optimization of green space network pattern[11], and its measurement is relatively simple. It has been studied to quantify its connection degree through various measurement indexes, such as Frags tats software, with its rapidity and simplicity, has been widely used in a variety of ecosystems. However, the number and type of existing landscape index are many, and there is a definite overlap in the meaning of the characterization results of some indexes, and the rationality of the evaluation index selection directly affects the accuracy of the evaluation results[12]. In addition, most indexes can’t accurately explain the ecological process and function of the ecosystem[13]. In fact, the complexity and high heterogeneity of urban environment make the study of structural connection difficult[14]. For example, the shape of green space and the width of corridors are difficult to meet the threshold requirements of the optimal structure. However, patch distance, as an important factor affecting structural connectivity, can effectively guide the planning radius and construction scope of urban green space to meet the needs of species activities. The quantitative method of landscape connectivity based on graph theory and the introduction of distance threshold, an important parameter, can be used to judge the existence and strength of ecological flow between green space patches in the region[15], which makes up for the defect of neglecting the response of ecological process to landscape pattern in the calculation of traditional landscape index.

2) Functional connectivity takes more into account the specific needs and behaviors of species or populations, and is an important indicator to explore the organic relationship between species and landscape elements. Functional connection has a high maneuverability in ensuring the integrity and continuity of urban ecological process[16], which is very important for the survival and reproduction of animal and plant species[17]. The measurement is

represented by the minimum cost path model, which assumes that the degree of connectivity between patches can be estimated according to the landscape matrix characteristics that can promote or hinder species migration[18], but this method assumes that the movement of species is limited to a single optimal path, which is difficult to accurately simulate the species migration and energy flow in the region, and can't identify the key pinch positions in the migration path, so it is difficult to effectively improve corridor connectivity.

In recent years, the connectivity model[17,19] based on graph theory and the network analysis method[20] can couple structural connection and functional connection, thus improving the accuracy of connectivity measurement, but a large number of observation materials and species data needed by network analysis are usually difficult to obtain, and species migration has great random wandering, so it is limited to simulate the best potential corridor only according to the migration law of representative species. There is a possibility that it cannot be used by other species[21].

Therefore, some scholars began to try and explore new theoretical methods and models, such as circuit model, to make up for the defects of the existing research. McRae first introduced the circuit theory in physics into landscape ecology[22]. The model has been proved to be used to predict the model of gene flow in heterogeneous landscape[23], and based on simple landscape data, the diffusion rate between populations can be predicted in order to parametrize the meta-population model and ensure ecological security pattern construction network, biodiversity conservation planning[24] and landscape genetics[25] have been applied in the field of landscape genetics, and have also achieved some results in the optimization of urban green space pattern guided by biodiversity conservation[26–29]. The simulation does not only respond to the diffusion of a species, but to the diffusion of several species with similar diffusion ability or habitat requirements. Although this simulation results in a certain degree of inappropriateness due to a large number of species migration processes, its efficient algorithm can quickly deal with networks containing millions of nodes or grid units, especially for complex urban environments. It has irreplaceable advantages in predicting the movement pattern of random walking species, the probability of successful migration or death, the identification of habitat patches, and the measurement of connectivity of populations or protected areas. At the same time, it can also identify important connection elements and be used for protection planning. It has high accuracy in corridor construction in the absence of absolute population size, mobility and other data[22].

In this study, Fengtai District of Beijing is taken as the research area, and the connection degree quantitative method based on graph theory is used to analyze the structural characteristics of different patches under distance, and to explore the optimal green space construction distance to meet the needs of biological migration. The resistance surface is constructed by using the minimum cost path model, and the potential connection path of species migration is determined by Linkage Mapper tool. In this paper, the circuit model in physics is introduced to quantify the contribution of patches and connection paths to the connectivity of the whole green space pattern by current density, and the pinch regions which have an important influence on species migration are identified. The overall connectivity of the green space network. The model simulation results are compared with the empirical observation results of bird abundance in order to explore the ability of this method to explain the habitat suitability and deepen the understanding of the relationship between urban landscape morphology and ecological function. The results of this study can provide a certain scientific basis for the protection of urban biodiversity, the formulation of priority protection strategies for biological habitats and the planning of urban green space.

2. Research areas and data sources

2.1. Research location

Fengtai District is located in the southwest of the city center of Beijing, with a total area of about 306 km”, belonging to the warm temperate semi-humid continental monsoon climate, the northwest high and the southeast low. Due to the demand of urban infrastructure, a large area of green space in the eastern plain of Fengtai District has been replaced by other land use types to support economic development, and the planning and construction of green space is under great pressure, and urban biodiversity is also affected by land expansion and human activity zones the threat. Because it is located in the first and second greening isolation zone of Beijing, it is urgent to play an important role in the construction of ecological space, establish the organic relationship between different ecological spaces, form a perfect green space network, and ensure the migration path of species. By carrying out relocation and retreat of greening isolation area, regional landscape transformation, plain afforestation, river regulation and so on, 17 new urban parks have been added to Fengtai District by 2019, which not only provides habitat for insects, birds and other wild animals, but also meets the needs of the masses for livable environment.

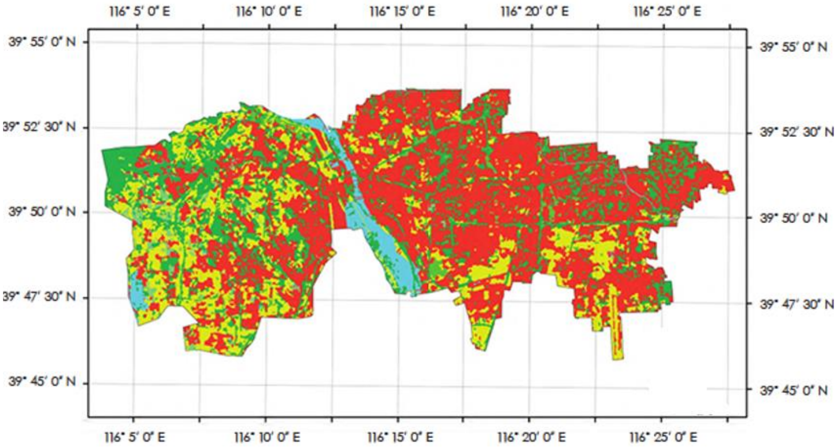

Figure 1. Study area and current land use.

2.2. Data sources and processing

The main data used in this study are: land-sat8 remote sensing satellite data on July 11, 2017, digital elevation model data with spatial resolution of 30 m ×30 m. Related atlas of Beijing Urban Master Plan (2016–2035). Through ENVI 5.3 remote sensing interpretation, the present land cover map with grid size of 30 m × 30 m is obtained. Because of the large area of the study area, the interpretation accuracy meets the requirements of analysis accuracy. The human-computer interaction supervision classification is used to refer to the classification of the first class in GB/T2010—2017 Land use status Classification. According to the resistance of land types to biological migration in the relevant research literature[18,27], the types of land used in the study area were divided into forest land, grassland, garden land, water area, cultivated land and construction land (**Figure 1**). Among them, commercial land, industrial and mining storage land, residential land, public management and public service land, special land, transportation land, etc. The land which has great hindrance to species migration is classified as construction land. Finally, with the help of Google Map, Baidu Map and other large-scale topographic map data, it is repeatedly compared with the Beijing Urban Master Planning Atlas and other data, and constantly revised and corrected.

3. Research methods

3.1. Study on the optimal distance threshold of green patches suitable for biological migration

The size of area plays a decisive role in habitat heterogeneity and species carrying capacity, and the scattered small patches play a limited role in regional ecological security maintenance and ecosystem function. According to the contribution degree of different area green patch to regional ecological land area[30], that is, the cumulative proportion of patches in different areas, the piecemeal patches are screened and eliminated. It was found that the contribution of green patch area less than 10 hm^2 to the total ecological land area was less than 23%, so the extraction area was greater than or equal to 10 hm^2. Land, grassland and water patches are used as basic patch data.

Distance threshold is often used as a reference for regional biodiversity conservation and urban green space planning decision-making, so it should not only be based on species migration characteristics, but also adapt to urban landscape spatial structure, in order to improve the application and scientific nature of planning results. The climate zone and geographical location of Beijing are the channels for the migration of many kinds of migratory birds in spring and autumn, and they are important in the protection network of migratory birds in northern China the status of. Therefore, according to the species situation[31,32] recorded in Fengtai District, the range of bird activity diffusion, such as Parus Venustulus, which is greatly affected by human activities such as agriculture, is selected as the reference range of distance threshold. According to the literature[33], the average search range of birds is 30 ≤ 32,000 m, so 16 distance threshold values of 0.5, 1, 2, 3, 4, 5, 6, 7.8, 9, 10, 11, 12 and 13, 14, 15 km are set up, and the landscape connectivity index and importance index between patches under each distance threshold are calculated respectively, and the variation of each index under different distance threshold is discussed, and the distance threshold suitable for the study area is obtained. According to the order of plaque importance, the source plaque was determined.

Using the Cone for software based on graph theory, the connection is selected. Connection number of like (NL), number of component (NC), integral index of connectivity (IIC), connectivity probability of connectivity (PC) and deltas IIC or deltas PC (dI) quantitatively reflect whether landscape characteristics are beneficial to species migration between patches. NC represents the two patches that are connected to each other in the case of connection (structure or function) or no connection between plaques. NL represents the number of connections between plaques, and the more connections there are, the higher the degree of connectivity, and IIC determines whether the ecological functions between any two ecological patches are connected by setting a specific distance threshold. PC indicates the maximum connection probability between the two ecological patches, and its calculation is not affected by adjacent habitat compared with IC. DI indicates that the change range of landscape connectivity after removal of a patch can quantify the contribution of a patch to landscape connectivity, and represents the importance of patches, including the overall connectivity index (deltas IIC, dIIC) and connectivity probability index (deltas PC, dPC). The formulas for calculating the IIC, PC and dI indices are as follows:

In the formula, represents the total number of patches in the landscape, and a represents the area of patch *I* and patch *j*, *I*, respectively, represents the number of connections between patch *I* and patch *j*. A is the total area of the landscape, and is the most likely species to spread directly in patch *I* and *j*.

$$\mathrm{IIC}=\frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\frac{a_i\times a_j}{1+I_{ij}}}{A_L^2} \tag{1}$$

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

$$\mathrm{dI}=\frac{I-I_{\mathrm{remove}}}{\mathrm{I}}\times 100\% \tag{3}$$

I is the index value of landscape connectivity. This study refers to IIC and PC. *I* move as the remove of the landscape after the patch *I* is removed from the landscape.

Connectivity index value. The method of normalization is as follows:

$$dI' = 0.5 \times dIIC + 0.5 \times dPC \tag{4}$$

In the equation, *d* represents the importance index after normalization, dIIC is the variation range of the whole connectivity index, and dPC is the variation amplitude of the connectivity probability index.

3.2. Green space network construction under the threshold of optimal distance of biological migration

Landscape resistance refers to the difficult degree network of species migration between different landscape units[34]. The difference of land use transformation within urban ecosystem is an important driving force to determine the pattern of urban biodiversity[3]. In addition, the density of road networks (socio-economic development) and regional natural topography also affect biological migration, it will have a definite effect. Therefore, considering the resistance of land use type, road density and slope, referring to the relevant references[19,27,34] and AHP to determine the corresponding resistance value (Table 1). Under the optimal distance threshold, the Linkage Mapper software of ArcGIS platform is used to draw the potential connection corridor between patches by using the vector diagram of the source patch and the construction of resistance surface[35]. Through the relevant literature records to implement the main distribution points of the focus species pool herons in Fengtai District, compare the spatial relationship between the distribution points and the green space network, and further verify the effect of the constructed green space network on the protection of regional biodiversity.

Table 1. Resistance value setting of biological migration in Fengtai District[19,27,34]

Resistance factor	Weight	Classification and division	Resistance value
Land use types	0.55	Woodland	20
		Lawn	30
		Plough	50
		Fields	40
		Waters	70
		Construction land	100
Road density/ (km/km²)	0.35	0–2.58	20
		2.59–5.90	50
		5.91–10.01	70
		10.02–16.17	80
		16.18–32.73	100
Slope	0.10	$i \leq 5°$	1
		$5° < i \leq 15°$	20
		$15° < i \leq 25°$	60
		$25° < i \leq 30°$	80
		$i > 30°$	100

3.3. Identification of patches and corridors in the core green space of biodiversity priority protection

Judging the importance of landscape elements to the overall degree of connection, and identifying the key areas to effectively improve the connectivity in the corridor is the core content to ensure the smooth migration of organisms. In this study, the current density in circuit theory is used to quantify the relative importance of patches or corridors, and to identify the priority protection areas of biodiversity. The importance of plaques is evaluated by calculating the current center degree by Centrality Mapper tool. The greater the center of the current, the more important the patch is to maintain the overall connectivity of the whole network. Centrality represents the possibility of the relationship between the source patch and other patches in the whole network, which is related to the type of vegetation, the area and the number of potential corridors between patches. The current density through the corridor is calculated by Pinchpoint Mapper tool, and the pinch area in the connecting corridor to ensure the smooth migration of organisms and maximize the connectivity of the corridor is determined, which indicates that the species has a greater probability of passing through the area or without other alternative paths. The significance is that if the area is removed or changed, it will have a greater impact on the functional connection. The calculation principle is to ground one green patch in the area, input 1 A current for other patches, obtain the cumulative current value of the grid element by iterative operation, and identify the current density by the current density the pinch area in the corridor determines the key space for biological migration to be protected or restored first.

4. Research results

4.1. Threshold analysis of optimal distance of green patches suitable for biological migration

The variation of connectivity index under different distance threshold is analyzed

The numerical changes of NL and NC under different distance threshold are analyzed (**Figure 2, Figure 3**). The results show that the NL value increases with the increase of distance threshold. In the range of 3 ≤10 km threshold, the growth rate of NL is the fastest, and when the distance threshold is higher than 10 km, the growth rate tends to slow down gradually. The NC value shows a logarithmic trend with the increase of distance. When the initial distance is 0.5 km, the NC value is 121. When the landscape components are more and the degree of fragmentation is high, the connectivity between green patches is poor. When the distance threshold is 0.5–2 km, the NC value drops sharply and the connectivity of green patches increases rapidly. When the distance threshold ≥3 km, the NC value tends to 1, indicating that most green patches can reach the state of interconnection with each other. The IIC value and PC value increased with the increase of distance threshold. The IIC value increased rapidly in the range of 0.5–6 km, and the growth rate decreased significantly at 3 km, reaching 0.34 at 6 km, and then the growth rate tended to slow down gradually. The PC value reached 0.36 at 6 km, and then the growth rate was gradually slow (**Figure 4**).

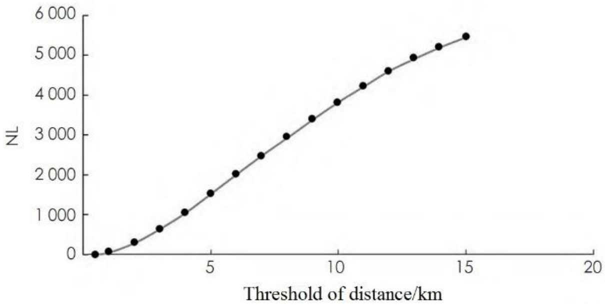

Figure 2. The change of NL with the distance threshold.

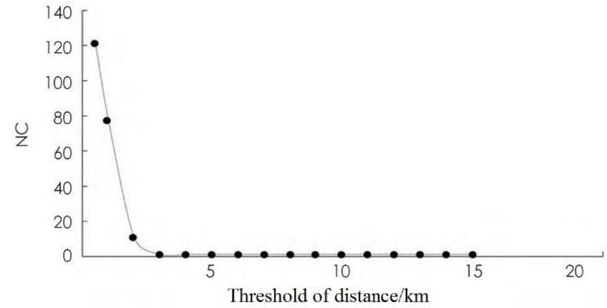

Figure 3. The change of NC with the distance threshold.

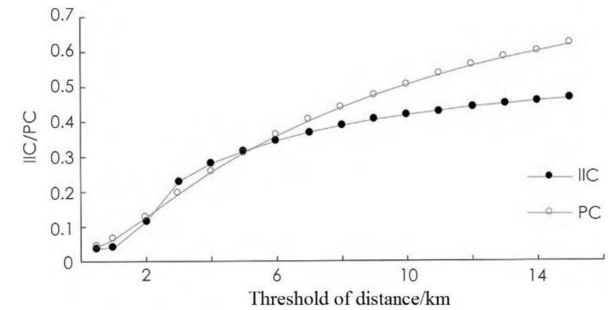

Figure 4. The change of IIC/PC with the distance threshold.

The changes of dI' of each green patch under different distance threshold were analyzed

The changes of single green patch area and dI' of each green patch under different distance threshold were analyzed (**Figure 5**). The results showed that in any distance threshold range, the importance of plaques was closely related to the area of plaques. The larger the area, the higher the importance index. When the distance is less than 1 km, the importance of small and medium-sized green patches in the region can't be reflected, and the proportion of patches with dI' >1 is only 12%. When the distance is 3 km, the importance of small and

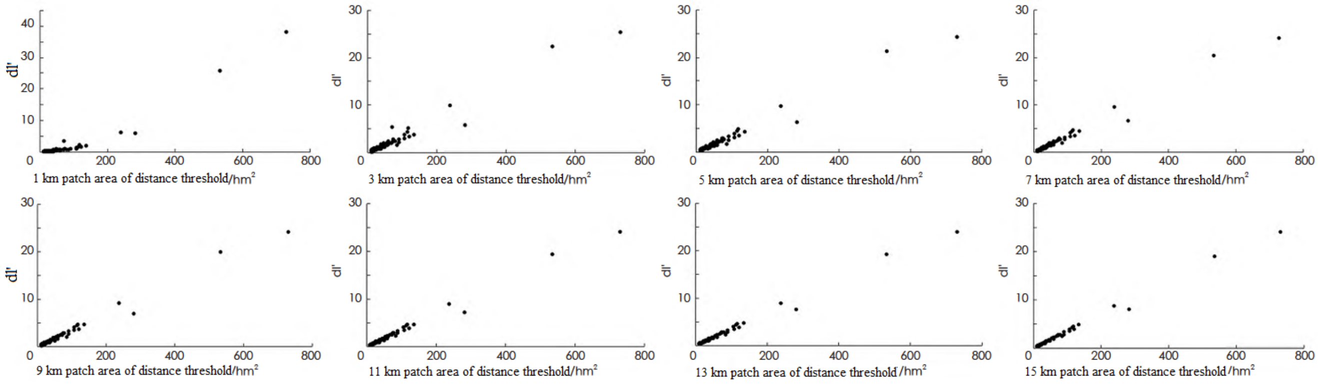

Figure 5. Area and normalized importance index of a single green patch under different distance thresholds.

medium-sized patches is significantly improved, dI' >1, when the distance threshold is within the range of 3~15 km, the importance of small and medium-sized patches is still increasing and stable, and the proportion of patches with dI' >1 is stable at about 33%. At this time, the contribution of green patches of different areas to maintaining regional landscape connectivity and ensuring the smooth migration of species has been relatively clear.

To sum up, 2~6 km is the distance threshold range of IIC and PC value growth rate, and the growth rate decreases after >6 km. Combined with the mutation of NL, NC and dI at 3 km, it is considered that the range of 3 ≤6 km can be used as a suitable distance threshold range for the construction of green space network aimed at biodiversity conservation in Fengtai District, and because the primary protection range of focus species in Fengtai District is between 0.2 km and 3 km[30]. In order to ensure that there are enough green patches in the ecosystem to provide positive ecosystem service function and in line with the policy guidance of garden city construction in Fengtai District. It is finally decided to take 3 km as the best performance distance between the construction and optimization of green space network in Fengtai District.

4.2. Under the optimal distance of biological migration

39 green patches with Dai value > 1 was selected as the source of species survival and migration under the optimal distance of 3 km. The ecological source area of Fengtai District is 4,122.66 hm^2, accounting for 13.47% of the total area (**Figure 6**). There are 83 potential corridors between sources, the length is between 100–6,652 m, and the total length is 142 km. Compared with the spatial relationship between the distribution point of the target species pool heron and the green space network in Fengtai District, it is found that 95% of the distribution points are located around the source or the necessary migration path of the pool heron, which can prove that the construction of the green space network has definite credibility.

4.3. Identification results of patches and corridors in the core green space of biodiversity priority protection

The ranking results of patch centrality and corridor current density (**Figure 7**) reveal the relative contribution of each patch and corridor to the overall connectivity of the region and the order of biodiversity conservation, which plays an important role in formulating priority protection strategy to achieve the optimal protection effect. The center value of plaques in 39 sources was between 38 and 270 A. The small center degree is often closely related to the patch area and the number of potential corridors between plaques. The results show that although the ecological source area of the western mountain area is the largest, but the center degree is low, the reason for this situation is that the administrative division boundary has an inevitable impact on the calculation of patch center degree, so it can't be used as a decisive factor to judge its importance. It can be clear that the relationship

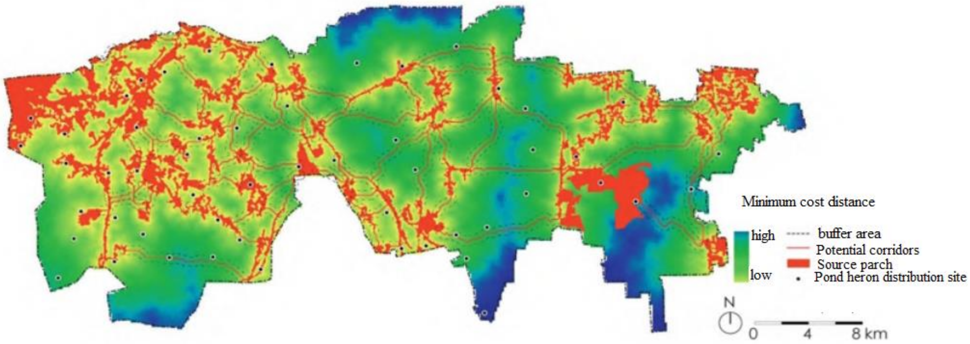

Figure 6. Source patches selection and potential corridors identification results.

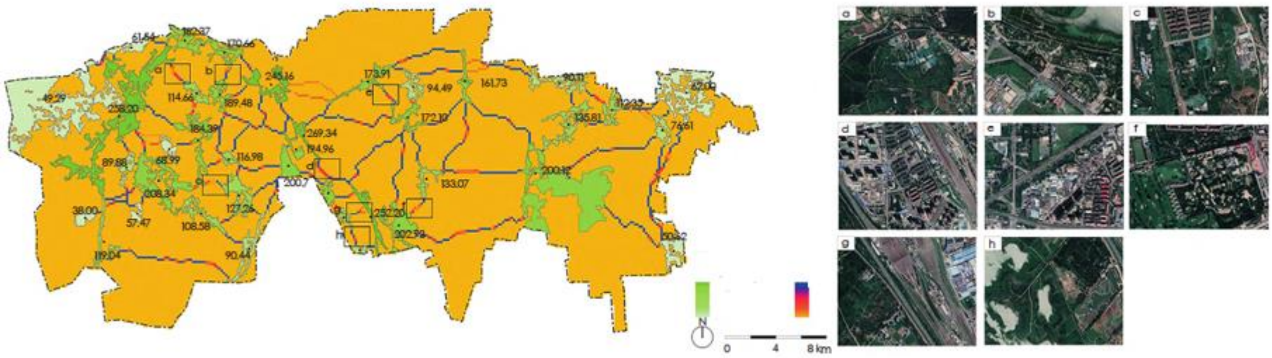

Figure 7. The relative importance of patches and potential corridors, and the identification of key pinch points on the corridor evaluated based on the current density.

between the patch and other green patches in Fengtai District is weak, and the number of potential ecological corridors is small. The north and south sources of the western China Unicom connect the Beigong National Forest Park, Tai Ping Ling Woodland, Tai Hui Chang Village Woodland and other ecological land, and are related to Yungang Forest Park, Huai Shuling Park, Nangong Ecotourism area and so on. The center is the highest, which is the core patch of biodiversity protection. On the whole, the current density of the corridor is relatively high, which indicates that most corridors are essential for species migration. There are pinch areas with high current values in some low current density corridors, which are very important to maintain the connectivity of the entire network. Compared with satellite images, most of the pinch areas are located at the edge of patches, and are gradually surrounded by construction land and farmland or cut by roads. Due to the change of the nature of underlying surface and vegetation type, the segmentation effect on habitat is very obvious, which causes great resistance to species migration.

4.4. Priority of biodiversity protection core green patch and corridor optimization strategy

According to the importance of all sources and corridors, the natural breakpoint classification is carried out (**Figure 7**). The patches of the important sources in the western part of Fengtai District are close to Qianling Mountain Scenic spot. The quality of the environment is good and the connectivity is high, and the plaque development is more stable. The No. 3 patch has a long north-south span, through the Beigong National Forest Park, Taiping Ridge Forest Land and Dachichang Village Forest Land, which is connected with the mountain green space in the west and Yungang Forest Park in the east (**Figure 8**) Yingshan Forest Park and Lianshhu Wetland Park. Its own health status and connection importance are high. The No. 10 patch, with Fengtai Science and Technology Park in Zhongguancun as the core, connects the important urban green space such as Huaishuling Park and Yongding River Garden Expo Park. The No. 14 patch is mainly rural forest land in

Prince Yu Village and Houlu Village of Changxindian. Its radiation branches connect more nodes such as Yungang Forest Park, Zhongguancun Fengtai Science and Technology Park, Huai Shuling Park, China Sports Olympic Garden and so on. The patches of Yongding River Ecological Corridor are distributed in Lianshi Lake Wetland Park, Yongding River Leisure Forest Park, Beijing Garden Expo, Xiaoyue Lake country Park-Green Dike Park and Century Forest Park. It is an important habitat or migration corridor for swans and other migratory birds. The area of urban construction land in the eastern region is relatively high, with No. 4, 26 and 5 being linear roadside green patches along the road. Block 12 is composed of residential green space, which is still an important stepping stone for the migration of insects, hedgehogs and other small mammals in urban built-up areas, although it is greatly affected by human activities. Patch No. 28 and No. 19 are large source patches, which are the key foothold of species migration in high-density built-up areas, but at present, No. 28 patches are golf clubs. Although the greening problem has been solved on the surface, in fact, the species abundance has been seriously affected by the single vegetation type.

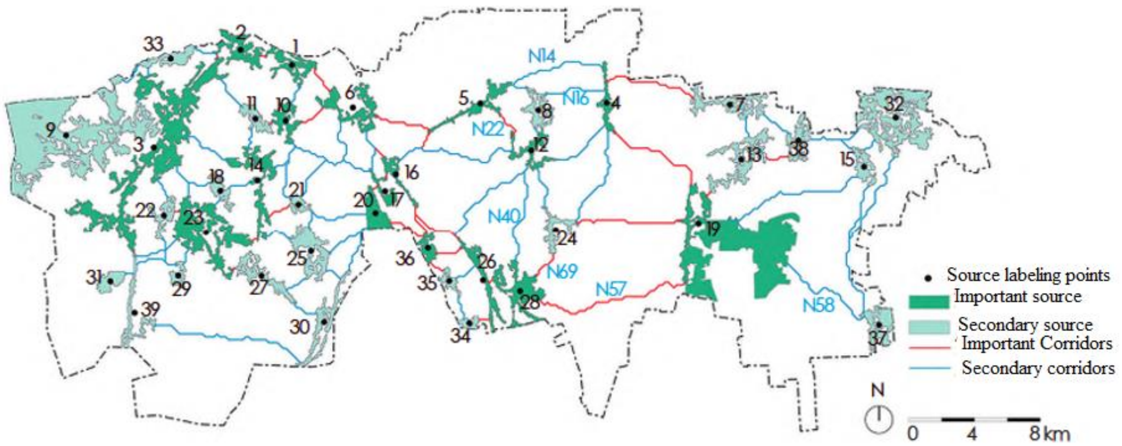

Figure 8. Importance classification of source patches and potential corridors.

On the one hand, because it is located in the residual vein of Qianling Mountain, it can form a complete network with mountain ecological green space. On the other hand, they also play an important role in connecting the western mountain area and the central Yongding River ecological corridor. The patches in the ecological corridor of Yongding River in the middle of China are located on the path of migratory bird migration and reproduction, which is the key position to improve the degree of connectivity between the north and the south. The above two ecological bases are good, and the radiation range is wide, which can be connected with more plaques. In this area, the scope of urban construction land must be strictly controlled in order to avoid the progressive fragmentation of large patches, the golf course in the lower reaches of Dinghe Ecological Corridor has seriously affected the regional ecological environment and formed great resistance to species migration. It is suggested that the strategy of land release should be implemented. In the eastern region, it is suggested that the green land rate and plant community abundance of roads and residential areas should be increased through the policy of leaving white and green, and a small park should be built to increase the "stepping stone" of species migration.

On this basis, the selected potential corridors and land use status are superimposed and analyzed, and the optimization strategy is put forward according to the size and location of the connected source and the surface cover type of the corridors. The whole. In the west and central Yongding River ecological corridor area, the green space patch area is large and the vegetation cover is good, and the identified potential corridor shows the characteristics of short distance, high density and easy to land construction. The important corridor connects the rural forest land and the urban park, is the key connection to ensure the gene flow and biological migration in the urban plain of the mountain area, and promotes the material circulation and energy flow between the Yongding River ecological corridor and the forest land network. If these corridors are missing, they will lead to the separation of urban green space from the ecological space system on the edge of the city, thus preventing the city from being separated from the ecological space system on the edge of the city the ecological flow between external natural systems. The green space in the eastern urban plain is seriously broken, and the urban roads have a great impact on biological migration. The identified potential corridors show the characteristics of long distance, small number and high difficulty in construction. Compared with the present resistance, it is considered that the new N22, N57 and N69 important corridors and N14, N16, N40, N58 four secondary corridors have higher landing ability. For the intersection of roads with high vehicle circulation and potential corridors, the success rate of biological migration can be improved by building wildlife bridges, increasing the width of corridors, and building green roads.

5. Discussions and conclusions

The process of urbanization and human activities have had a serious impact on the biological habitat environment and migration path in Fengtai District. The construction of green space network is an effective way to improve spatial connectivity and protect biodiversity. In this study, the optimal distance threshold of green patch suitable for species migration is discussed. With the help of circuit model, the biological migration path is simulated and extracted to ensure biological migration, according to the relative importance of the source and corridor, this paper puts forward that in the construction of urban green space, by increasing the green space patches in the key position of biological migration, optimizing the ecological network structure of green space, and promoting the construction of connectivity and integrity of green space landscape to maintain the survival and migration path of species. The results show that:

The main results are as follows:

1) When the distance threshold of patch is 3 km, the importance of small green patch in the region can be reflected, and the large patch can ensure the stability of ecosystem and meet the needs of biological habitat and migration as a "distribution center" of material and energy exchange. At this time, the IIC value is 0.23 and the PC value is 0.19. When the distance threshold was in the range of 0.5–3 km, NL, IIC and PC increased continuously, and IIC and PC increased rapidly at 3 km, indicating that the degree of landscape connectivity increased significantly. NC decreased logarithmically and suddenly turned and tended to smooth at 2 km, indicating that all plaques could reach the state of interconnection when the distance threshold was 2 km. With the increase of distance threshold, IIC and PC still show an upward trend. When the distance threshold reaches 6 km, the growth rate tends to flatten gradually, so 3–6 km is more suitable for distance threshold. In order to meet the migration distance of birds and other focus animals, and to ensure that there are enough green patches in the ecosystem to provide positive ecosystem service function, this study identified 3 km as the best performance distance for species migration and green space construction.

2) Under the 3 km optimal distance threshold, the regional green space network is constructed based on the paradigm of "source-corridor-key node", and the priority protection area of biodiversity is defined. 39 green patches with recognition importance index (dI) >1 and area > 10 hm^2 were used as sources with a total area of 4,122.66 hm^2. There were 83 potential corridors between sources, the width was 400 m, the total length was 142 km, and the total area was 5,753.80 hm^2 . The habitat conditions in the east and west of Fengtai District are obviously different. In the west, most of them are natural villages and towns, the number of green patches is large, and the habitat is

good. There are some large green patches, such as Beigong National Forest Park, Yungang Forest Park, Qinglong Lake Forest Park, Century Forest Park, Yongding River Leisure Forest Park and so on, which provide the main habitat environment for species. This area is in the coordination and trade-off between biodiversity conservation and regional development. In the central and eastern regions, construction land and farmland encroach on a large area of ecological land, green patch area is small and mainly along the road greening linear space, serious fragmentation, lack of biological habitat ecological source and migration of “stepping stone” patches, the number of corridors significantly decreased, biological migration distance increased. Compared with the spatial relationship between the distribution point of the target species pool heron and the green space network in Fengtai District, it is found that more than 95% of the distribution points are located at the source or the edge of the necessary migration path, which can prove that the construction of the green space network has a definite credibility.

3) Using circuit theory to quantify the importance of source patches and corridors for improving landscape connectivity, identifying key connected areas and taking protection and restoration measures have certain guiding significance for the formulation of habitat priority protection strategy and the improvement of biodiversity conservation efficiency. Therefore, it is suggested that priority should be given to the restoration plan of regional key ecological nodes, and the construction land and cultivated land should be transformed into ecological land in local areas as a “stepping stone” for biological migration. Through appropriate land use adjustment, biological migration resistance can be removed or reduced, ecosystem service function can be greatly improved, and the quality of habitat in pinch areas can be effectively protected.

At present, due to the difficulty and cost of obtaining direct measurements of population migration (species type, species distribution data, migration path monitoring, etc.), the construction methods of green space network guided by urban biodiversity or integrated biological protection are mainly morphological spatial pattern analysis, minimum cost path and connectivity index evaluation based on graph theory[36,37]. Although some scholars use the above methods to achieve maximum biological protection[34], it is still difficult to accurately simulate the material and energy flow in the region, because the above methods have a prominent limitation-the movement of hypothetical species is limited to a single optimal path[38]. The circuit theory model is different from the previous landscape connectivity model because it combines the characteristics of electronic random walk, and it is in the continuous mapping layer. Therefore, it considers a variety of optional connection paths, highlights the pinch points that need more close attention (key habitat), and defines priority protection corridors[22], which reflect ecological reality more accurately than graph theory or minimum cost path analysis, and can more accurately and effectively predict the importance of spatial patterns and characteristics to wild animals, and have greater advantages in simulating species diffusion[25].

Based on the landscape index and circuit theory based on graph theory, this study attempts to study a comprehensive green space network construction path to better achieve the protection of urban biodiversity from the two levels of structure and function. In addition, the landscape scale perspective is used to study this problem, which reduces the dependence on a large number of complex species data requirements under this research scale, and uses the observed data in the literature as auxiliary verification. This method can be applied to the study of how landscape structure promotes or hinders the migration of urban wildlife species for urban organisms’ diversity conservation provides research ideas that help relevant urban planning departments to identify priority protection elements in green space networks and complement potential connecting corridors.

Although the method of landscape index and circuit theory based on graph theory has a definite advantage in comprehensively evaluating the connectivity of green space, it should be noted that the roles of structural connection evaluation and functional connection evaluation in the process of green space network construction are not simply progressive complementarities. On the one hand, in this study, structural connection assessment is mainly used to solve the optimal distance threshold of patches and determine the ecological source, and structural connection assessment is more used in the identification process of potential corridors and key migration pinch points. In fact, no matter which process contains the influence of structural connection and functional connection, this study discusses the construction of green space network with structural connection and functional connection separately. In the future research, it is necessary to further explore the role and relationship of structural connection and functional connection in the whole green space network construction process. In addition, based on the present situation of green space in Fengtai District, this study determines the priority protection sequence of source and corridor and the key pinch areas that need to be protected urgently. By comparing the present situation of land use and the construction of green space network, the optimization strategy and planning landing of identified source patches and potential corridors are classified and discussed, so that the regional biodiversity conservation planning policy can be connected more accurately. From the perspective of sustainable development, if can be based on this. The establishment of optimization scenario, the selection of green space with development potential as the "stepping stone" of network optimization and the re-evaluation of green space connectivity potential will produce more positive and sustainable ecological benefits.

Finally, it should be noted that because of the strong randomness of species migration, the research scope of biodiversity is often larger than that of green space network. In this study, administrative divisions are used as the scope of study, which will bring inevitable errors in the evaluation of patches near the boundary line. Therefore, it is necessary to weigh the importance of patches reasonably from the overall point of view, which is also one of the limitations of this study. In further research, consideration may be given to reducing the error impact caused by administrative boundaries by expanding the scope of the study or establishing buffer zones.

Conflict of interest

The authors declare no conflict of interest.

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