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Constructing urban ecological corridors to reflect local species diversity and conservation objectives

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Abstract

Ensuring bird diversity can secure key ecosystem services within cities. Building ecological corridors into urban planning is an effective way to protect urban birds, but existing corridor construction methods often ignore locality and diversity of species, leading to homogenization of corridor construction results and orientation. We proposed a corridor construction model that combines local bird surveys and bird threat levels. After constructing differentiated corridors for each bird species by assessing their habits and flight abilities, we used three weighted scenarios (original, weighted abundance, weighted abundance, and phylogeny) to assess the conservation priorities of birds and overlaid them to derive a comprehensive bird corridor model. Our results show significant differences in conservation priority and corridor pattern among different bird species, thus demonstrating the importance of local bird surveys and knowledge of threat levels in accurate corridor simulations. This study provides differential simulation of corridors for each bird species and the identification of important conservation species, and uses these to extend the theory of ecological corridor planning to urban bird populations. These results can be applied to guide biodiversity management, evaluate green space policies, and provide practical assistance for sustainable urban development and management.

Keywords

Ecological corridor, Circuit theory, Bird diversity, Urban planning

1 Introduction

Birds provide multiple services critical to ecosystem health and human well-being (Whelan et al., 2008). Bird diversity is essential to support the ecological functions of bird populations as well as the ecosystem services they provide (Sekercioglu, 2006). Destruction of native habitats and the introduction of invasive species (Williams et al., 2009), has caused significant declines in bird diversity worldwide (Lepczyk et al., 2017), especially in inner cities. However, cities are home to approximately 20% of the world's bird species (Aronson et al., 2014), but because of highly altered nature of urban landscapes and associated habitat fragmentation, urban bird populations are under considerable threat, with only 8% of native bird species present in cities compared to estimates of non-urban species (Aronson et al., 2017). Birds are disappearing from many cities (Evans et al., 2011), causing a significant decline in the value of the ecosystem services they can provide including pest control, seed dispersal, provision of cultural services, etc. (Elmqvist et al., 2015). The conservation of urban bird biodiversity therefore needs urgent consideration within future urban planning frameworks (Threlfall et al., 2016).

The construction of ecological security patterns (ESPs) is regarded as an effective way to integrate landscape patterns and ecosystem services within an ecological connectivity perspective (Hodson & Marvin, 2009). An intrinsic part of urban ESPs are urban ecological corridors. These play an important role in promoting diverse natural flows (Hilty et al., 2012) and counteracting the negative impacts of human activities (McClure et al., 2015) with their effectiveness in protecting urban biodiversity proven by many studies (Hilty et al., 2019; Peng et al., 2017). The construction of bird-specific ecological corridors is an important avenue for research in the conservation of bird diversity (Gilbert-Norton et al., 2010). For native birds that cannot easily adapt to high-density built environments (Patankar et al., 2021), these ecological corridors can help overcome barriers in built-up areas and help dispersal to more suitable areas providing more diverse habitats and abundant food resources (DeGraaf et al., 1991).

There are three main approaches to constructing urban bird ecological corridors: (1) the graph-based network approach (MINOR & URBAN, 2008; Urban & Keitt, 2001), in which the habitat patches of birds are regarded as nodes, and the possible movement paths of study species between patches are regarded as edges connecting these nodes, thus forming an abstract, simplified species landscape movement network; (2) minimum cumulative resistance (MCR) model (Liu et al., 2021; Nor et al., 2017), which assumes that study birds will move and disperse between patches depending on spatial patterns of resistance; (3) circuit theory (Grafius et al., 2017; McRae et al., 2008; Shimazaki et al., 2016), which is based on treating the study area as a conductive surface, assigning different types of land cover with different resistance values, and ultimately identifying multiple possible movement paths for birds depending on resistance values.

These approaches focus on the movement behaviors and habitat requirements of the birds themselves, thus suggesting ways to simulate the movement and dispersal of birds within and across cities. Two problems arise from such an approach. Firstly, there is a general lack of specific studies for local birds and their localized behavior. In most studies, urban birds are treated as one generic population (Bhakti et al., 2021; Liu et al., 2021) or generalized to a few representative focal bird species (Grafius et al., 2017; Nor et al., 2017), while the urban environment actually supports a large number of local bird species, which are not globally homogeneous and whose study is important for the conservation of local sources of biodiversity (Lepczyk et al., 2017). Secondly, because of differences in diet (Gering & Blair, 1999), nesting (James Reynolds et al., 2019) and social behavior (Kark et al., 2007), different urban bird species have species-specific adaptations to urban habitat and food resources (Patankar et al., 2021), with substantial differences in their abundance and spatial distribution (Blair, 1996). For these reasons, studies on the construction of ecological corridors for urban birds need to include all urban bird species as individual research objects and conduct species specific studies on these birds to determine their distribution and preferred habitat characteristics. In addition, within the specific bird biomes, there will be differences in the threat level and conservation value for different bird species (Oliveira Hagen et al., 2017). In mapping and constructing bird corridors, the relative priority of different bird species for conservation needs to be evaluated based on their threat level, population size, and importance, suggesting more attention be paid to birds under higher threat level. This has often been overlooked in previous studies.

This research develops an approach for designing an integrated ecological corridor network based on actual data for local birds. This aims to augment current research in three important aspects: (1) observation and survey of local birds through field observations and citizen science to determine the species, abundance, spatial distribution and other specific characteristics of native birds in the study area; (2) habitat prediction for each bird species, through comprehensive indexes based on the available literature to assess the movement ability of each bird species through different landscape structures and so construct differentiated ecological corridors; (3) the development of three conservation scenarios based on the abundance and phylogenetic importance, enabling the assessment of the importance of protecting each bird species.

2 Data and Methods

2.1 Study area and work flow

We chose the area within the fifth ring road of Beijing as the study area (Figure 1.), which has a total area of 66,600 ha, of which 32.8% of the total study area is green space (Xie et al., 2016b). The reasons for choosing this area are as follows: First, the rapid process of globalization and urbanization that China is experiencing (Tian et al., 2011) has a clear impact on habitat fragmentation and insularity of urban bird populations (Tambosi et al., 2014). Beijing can be considered a typical representative of the landscape structure regarding bird habitat across Chinese cities. It is also one of the main nodes of the East Asia-Australia migration route (Xie et al., 2016a), meaning that strengthening the landscape connectivity within the city will improve the quality and connectivity of important migratory bird habitats. This makes Beijing a good model for testing bird-friendly planning in large cities elsewhere in China and further afield.

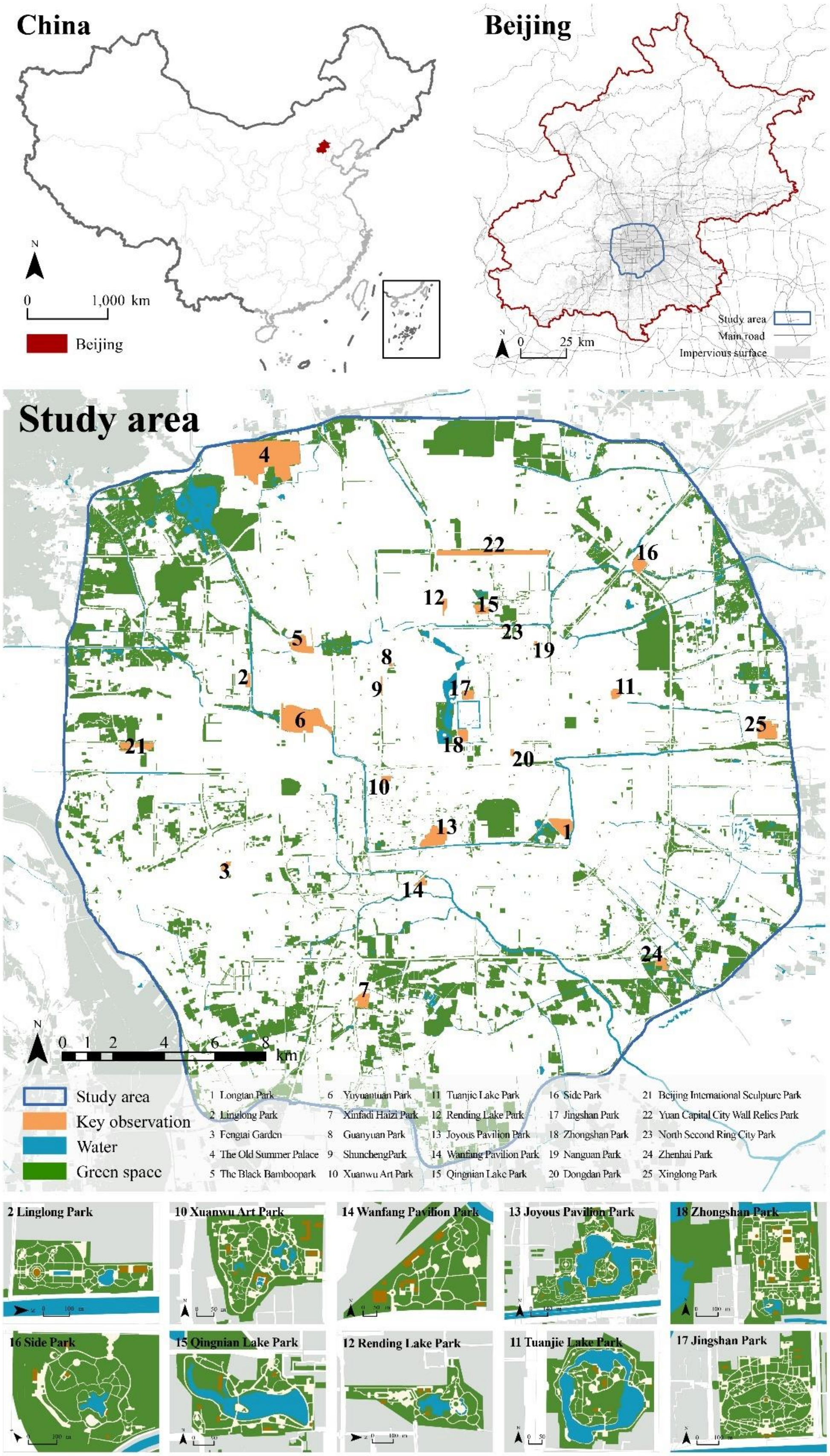

China
N
0 1,000 km
Beijing
Beijing
Study area
Main road
Impervious surface
N 0 25 km
Study area
N
0 1 2 4 6 8 km
Study area
Key observation
Water
Green space
1 Longtan Park
2 Linglong Park
3 Fengtai Garden
4 The Old Summer Palace
5 The Black Bamboopark
6 Yuyuantuan Park
7 Xinfadi Haizi Park
8 Guanyuan Park
9 ShunchengPark
10 Xuanwu Art Park
11 Tuanjie Lake Park
12 Rending Lake Park
13 Joyous Pavilion Park
14 Wanfang Pavilion Park
15 Qingnian Lake Park
16 Side Park
17 Jingshan Park
18 Zhongshan Park
19 Nanguan Park
20 Dongdan Park
21 Beijing International Sculpture Park
22 Yuan Capital City Wall Relics Park
23 North Second Ring City Park
24 Zhenhai Park
25 Xinglong Park
2 Linglong Park
10 Xuanwu Art Park
14 Wanfang Pavilion Park
13 Joyous Pavilion Park
18 Zhongshan Park
16 Side Park
15 Qingnian Lake Park
12 Rending Lake Park
11 Tuanjie Lake Park
17 Jingshan Park

Figure 1. Study area

The flow chart of the entire network construction is shown in graphical abstract. Our focus is on the construction of a connectivity model for birds within the urban environment, with the following main steps: (1) birdwatching (observation), (2) habitat identification (mapping), (3) establishing resistance surfaces (modelling) and (4) corridor system construction under different scenarios (planning).

2.2 Birdwatching (field observation and citizen science)

We used both field observations and citizen science data to obtain information on bird species, numbers and distributions in the Beijing study area. For field observations, 25 parks were selected as field sites based on the following principles: (1) trapezoidal distribution from small to large areas; (2) relatively uniform distribution within the city; (3) established and open for at least 10 years; and (4) high daily use by residents. The distribution of the parks and maps of selected examples are shown in Figure 1.

We conducted surveys for the 25 parks during the period 2012-2014. From April to November 2012, we surveyed each park five times. From 2013-2014, we surveyed the parks three times in each season, for a total of 12 surveys per year. For each park, we used the fixed-distance sample line method to conduct surveys wherein five sample lines were set up in each park, crossing all types of habitat spaces in the park, with each sample line being approximately 1.5-2km in length (Gregory et al., 2004). Survey periods lasted from 7:30 a.m. to approximately 10:30 a.m., excluding periods of rain, wind, and hazy weather. Two surveyors traveled along the fixed sample line at a speed of 1-2km/h using binoculars to observe birds occurring within a distance of 50m on each side of the sample line (Bibby, 2000). The basic data recorded included species, numbers, spatial locations and time of occurrence. The resulting data contains bird observations belonging to 15 orders, 44 families, 113 species, and a total of 97,531 bird sightings creating a detailed and extremely rich dataset suitable for analysis.

In addition, we also obtained observation data sets for each bird species within the five ring roads of Beijing through the China Birding Records Center (http://www.birdreport.cn). Birdwatching records submitted to the platform by birdwatching enthusiasts contain information on location, date, recorder, weather, observation equipment, environment, and route, as well as details such as species and number of birds, with the possibility of attaching photos, audio and video. Each data entry in the dataset includes the scientific name of the observed bird, the ID of the observer, the observation time, and the latitude and longitude of the point of observation. Using citizen science data in this way (Pinho et al., 2021), we obtained a total of 20,105 additional records for the same113 bird species in parks. Considering the potential for bias in the citizen science methodology, these data were cleaned by: (1) filtering out sites with >3 observations of the same bird species to reduce the likelihood of erroneous observations being included in the simulated data, and (2) clustering and merging sites according to their spatial coordinates and environmental variables to avoid spatial clustering.

Based on the corresponding land use classification, we then divided the observed birds into five ecological types: water fowl (15 species), waterfront birds (12 species), grassland birds (16 species), shrub birds (20 species) and forest birds (50 species), which occupy typical habitats found within Beijing's urban green spaces. Water birds mainly live near water bodies, waterfront birds live in the riparian space between land and water, grassland birds live mainly in grassland patches, and shrub birds live in a variety of bushes, while forest birds live in wooded land, including arbor forest, shrub and grassland.

2.3 Habitat identification (MaxEnt combined with MSPA)

We used MaxEnt v3.3 (Merow et al., 2013) to map the habitat suitability of each bird species according to available habitats within the study area. Here we used the available literature indicating the differential response pathways of birds in respect to the natural (Dale 2018) and built up environment (Rodrigues et al., 2018) within cities and how these can affect the spatial distribution seen in urban bird diversity.

Five environmental indictors including land cover, normalized difference vegetation index (NDVI), distance from water, building density, and distance from roads were selected (details can be found in Supplementary Information). In the Maxent model for each bird species, we randomly selected 75% of the records from the observed dataset as the training set and 25% as the test set. We then performed 20 iterations of the model operation, and averaged the results for each time to create a model with an Area Under Curve (AUC) value greater than or equal to 0.75 using the Jackknife test for the probability of the presence of that bird species in the study area map. If the MaxEnt result for a bird species had an AUC less than 0.75 from the Jackknife test, only the field observation park was considered as the ecological source for that bird species in the subsequent corridor model.

We converted the probability distribution maps into binary habitat/non-habitat maps based on a probability threshold of 0.8 for each bird species modelled in MaxEnt. We then used the Morphological Spatial Pattern Analysis (MSPA) segmentation method assembled in the Guidos ToolBox (Vogt & Riitters, 2017) developed by the European Commission Joint Research Centre (JRC) to identify core areas in the habitat raster. The MSPA classification routine starts by identifying core areas, based on user-defined rules for defining connectivity and edge width. We used habitat as foreground and non-habitat as background, setting the landscape width at the edge of one image element and 8 neighborhood connectivity to identify core areas. Work by (Callaghan et al., 2018) has shown that a green space area threshold of 10-35 ha is important in supporting most urban bird diversity. Using this figure we excluded core area patches less than 10 ha in size and identified the remaining core areas as potential habitat patches with high probability of bird occurrence.

2.4 Establishing resistance surfaces (based on circuit theory)

Previous studies have widely agreed on the effectiveness of circuit theory in modeling ecological corridors (Dickson et al., 2019; McRae et al., 2008). By conceptualizing complex landscapes as conductive surfaces, target birds in the landscape are analogized as randomly wandering electrons across landscape surfaces wherein different resistance values are assigned depending on their land cover type and the influence of environmental factors on bird movement processes (Zeller et al., 2012). When the results for each paired source site are stacked, the resulting cumulative current map represents the intensity of bird flow at each pixel (McRae, 2006).

Corridor connectivity for birds depends on the interaction between the spatial arrangement of different land cover types and the ability of birds to traverse these different areas (Bhakti et al., 2021). In addition to land cover, human activities (Isaksson, 2018), built environment (Partridge & Clark, 2018) and green infrastructure (Callaghan et al., 2019) have been confirmed to have a profound impact on the ability of birds to move across complex human-modified landscapes. On the basis of existing literature, we have adopted some indicators related to these four aspects to construct the resistance surface (Table 1.). More detailed description is presented in Supplementary Information.

Table 1. Description of resistance surface data

Indicator	**Data layer**	**Classification method**	**Original value**	**Resistance value**
Land cover	Land cover (grid)	Label classification	Farmland	20/20/20
			Forest	3/2/1
			Grassland	3/3/3
			Shrub	3/3/2
			Wetland	1/1/3
			Water	2/2/3
			Imperious surface	50/50/50
Built environment	Distance from roads (vector)	Grade classification (Buffer)	20m	30
			50m	5
			100m	3
			200m	1
			>200m	0
	Building density (vector)	Grade classification (Natural breaks)	1	0
			2	1
			3	2
			4	5
			5	10
	Building height (vector)	Grade classification (flight capability)	/	/
Human activity	Population density (grid)	Grade classification (Natural breaks)	1	0
			2	1
			3	2
			4	3
			5	5

Green Infrastructure	NDVI (grid)	Grade classification (Natural breaks)	1	20
			2	5
			3	3
			4	2
			5	1
			6	0
	GVI (vector)	Grade classification (Natural breaks)	1	5
			2	3
			3	2
			4	1
			5	0

NDVI refers to normalized difference vegetation index, one of the important parameters reflecting crop growth and nutritional information. GVI refers to green visibility index, the proportion of green plants in objects seen by the eye, representing a higher level of urban greening. Resistance values in land cover represent water/waterfront/forest. Population density data comes from Dianping; Building height data is taken from AMAP; GVI comes from the second land survey in Beijing (gtdc.mnr.gov.cn/shareportal/).

To more accurately characterize the mobility of each bird species, we further refined the composition of the resistance surface for each species, taking the habits of different species into account. We refer to books such as *Chinese Bird Journal* and *Field Manual of Chinese Birds* to evaluate the sensitivity of the studied birds in terms of distance from roads, population density, building density, NDVI, and GVI (Figure 2.). For example, birds that are less sensitive to the effects of human activities will have correspondingly lower resistance values from distance from roads, population density, and building density for each bird species. The specific preferences of each bird species can be found in Supplementary Information.

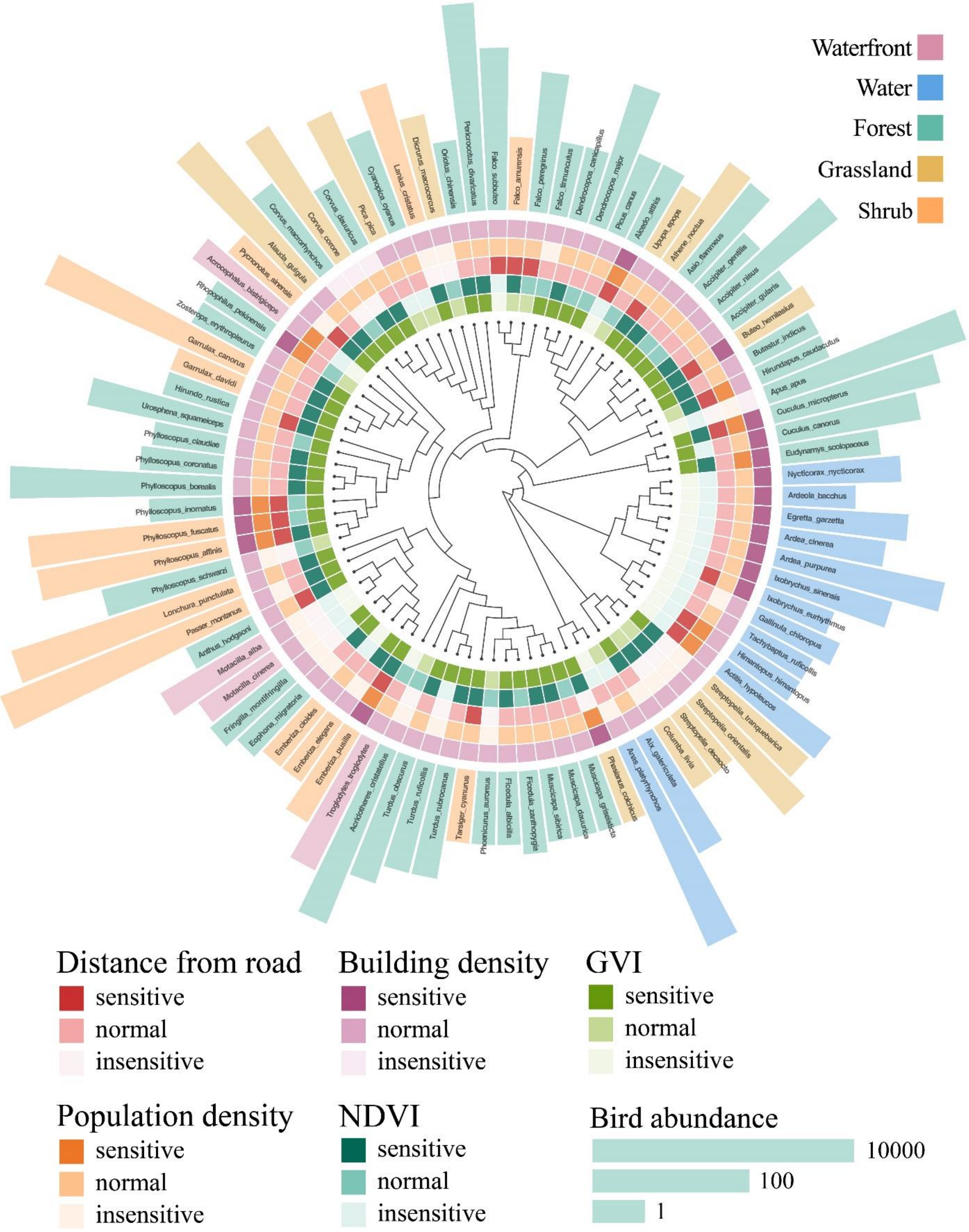


Figure 2. Environmental sensitivity assessment, abundance and phylogenetic tree of study birds

2.5 Corridor system construction under different scenarios

After determining the source sites using the HSM and resistance values via circuit theory, we created ecological corridors between the core patches based on the minimum cumulative resistance (MCR) model (McRae & Kavanagh, 2011) and circuit theory (McRae et al., 2008). We used Linkage Mapper (Adriaensen et al., 2003) and Circuitscape (McRae et al., 2016) to jointly model these into corridors. The advantages here are: (1) Birds have differences in flight ability. Linkage Mapper achieved this by differentiating the input resistance surface and limiting the corridor distance threshold, thus identifying corridors where different birds move over short distances within cities. (2) Considering that circuit theory operates on a continuous map layer and therefore considers multiple alternative connectivity paths, it is considered to reflect ecological reality more accurately than graph theory methods or MCR analysis (Dickson et al., 2019; Ersoy et al., 2019). Pinchpoint Mapper tool in Circuitscape and Linkage Mapper uses circuit theory to analyze the previously identified corridors and differentiate the landscape around the corridors into gradients of different qualities, which are more accurate at the scale of the inner city (Grafius et al., 2017).

Linkage Mapper is designed to support regional analyses of wildlife habitat connectivity. Linkage Mapper is used to identify the source site vector patches and resistance surface raster to map the least costly linkage paths between the source sites. The maximum Euclidean corridor distance for each bird species was set as the estimated maximum flight distance. We set a 100,000 cost-weighted distance limit threshold by default to avoid calculations between overly distant patches.

For the assessment of bird flight distance, we used the AVONET bird database (Tobias et al., 2022) to estimate the flight speed of the target birds, referring to the positive correlation between the flight speed of birds and the overall proportion index of body weight found by (Alerstam et al., 2007). Finally, we used the flight distance of 10 minutes for each bird as its farthest flight distance within the city as a reference for the subsequent corridor length construction. This is because the distances thus estimated are similar to the natal dispersal distances observed in the literature (PARADIS et al., 1998) and meet the mobility needs of the birds.

To identify critical areas that need to be protected or where barriers exist for corridor construction, we used Circuitscape to identify pinch points and barriers in the generated corridors. Regions with high cumulative current density were identified as critical pinch points, which significantly affect the connectivity in the network (McRae et al., 2008). The areas with the highest cumulative improvement scores were identified as barriers, indicating that improving the ecology of this part of the network would significantly improve the overall system connectivity (McRae et al., 2012).

We built a bird corridor network by merging the identified corridors with pinch points and barriers, deciphering the relationship between landscape structure and ecological flows of birds (Desrochers et al., 2011). To improve the conservation of species diversity and genetic diversity in corridor construction, and to assess the scarcity and genetic importance of each studied bird species, we based corridor construction on the following three scenarios: (1) Scenario 1 where all birds are equally important; (2) Scenario 2 with weighted bird abundance, where birds with smaller populations are more important; (3) Scenario 3 where weighted abundance and phylogenetic trees, birds with smaller populations and large phylogenetic differences from other populations are more important. The abundance data were derived from our field observations, and we standardized the inverse of the abundance to assign a value, so that fewer and more scarce bird corridors were observed, reinforcing the balance of biological species diversity in corridor construction. In terms of phylogeny, we used the phylogenetic tree established in the study by (Jetz et al., 2012) to build a phylogenetic tree of the target birds and assign values to each bird according to number of branching nodes and relative step size of branches in the phylogenetic tree to ensure the conservation of genetic diversity in the corridor construction.

3 Result

3.1 Results of core patches identification

After performing the Jackknife test on the MaxEnt results for each bird species, we retained the results of 89 bird species with high prediction model accuracy (AUC>0.75), and the model calculation results for these bird species showed that the factors contributing more to habitat suitability among the environmental factors were land use (44.6%) and NDVI (24.8%), and the total contribution of these two factors amounted to 69.6%. The results for forest birds (65 species), water birds (12 species) and waterfront birds (12 species) were overlaid to create a bird habitat map (Figure 3.), with the value of each pixel indicating the total number of species counts to have a high probability of inhabiting the area. The predicted high-frequency potential ranges of water birds, waterfront birds, and forest birds are generally similar, mainly in woodlands with high vegetation cover and around water sources; other areas where a few birds may be distributed are concentrated in green areas subject to low vegetation cover or fragmented artificial environments with high vegetation cover, such as bare ground, grasslands, and inner cities; compared with water birds and waterfront birds, there are several types of forest birds that have a wider distribution in built urban environments.

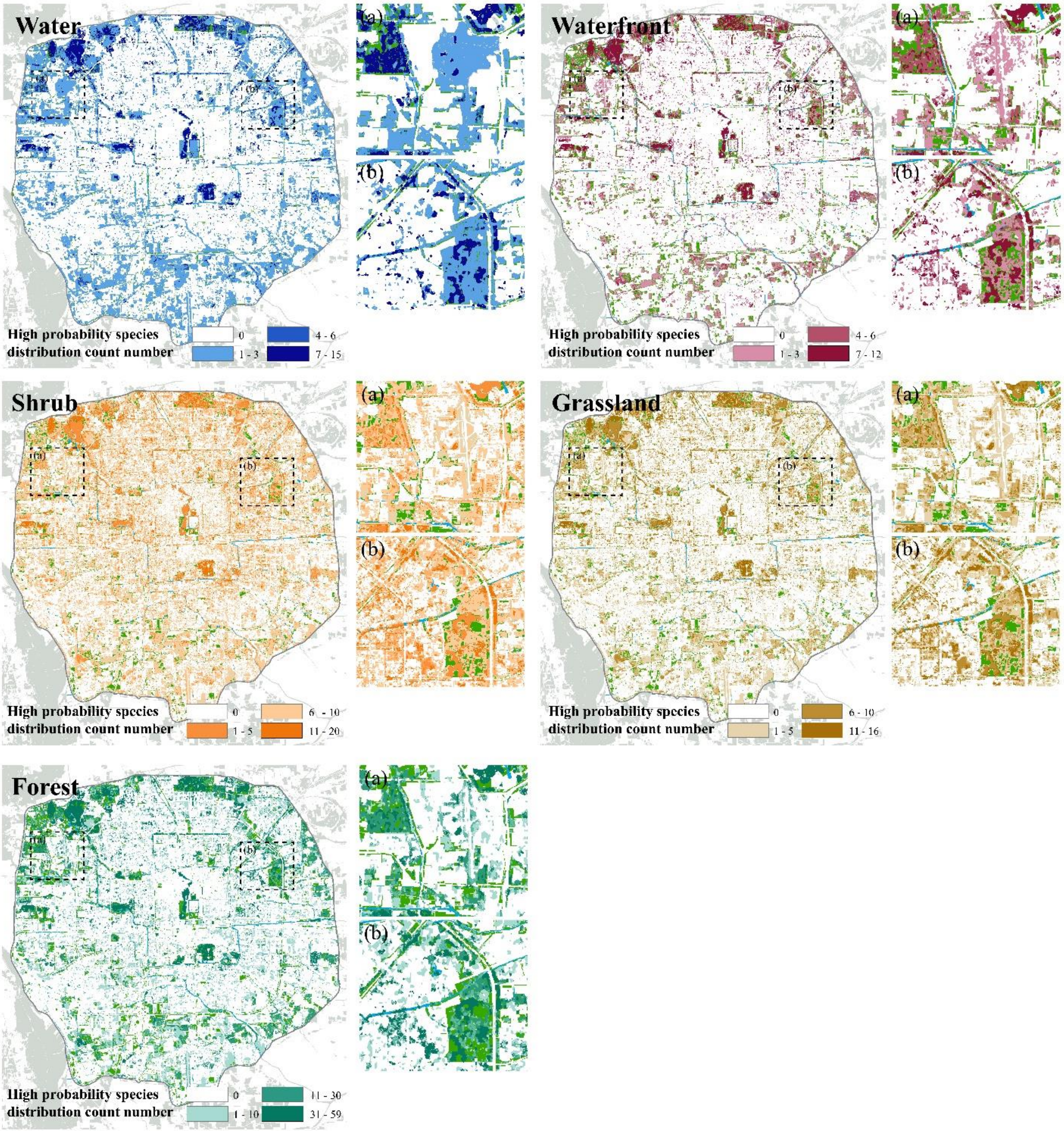


Figure 3. Bird habitat map

3.2 Results of corridor construction, pinch points and barriers identification

Figure 4 shows our composite corridor paths, pinch points, and barriers constructed under three scenarios, where (a) indicates the indicators without weighting, (b) indicates weighting based on abundance data, and (c) indicates weighting based on abundance and phylogenetic data. For corridor paths and core source patches, we measured the importance of corridors in the system in terms of mean centrality. In the unweighted case, corridors connecting the interior of large patches to the urban core have low centrality, while in the abundance weighted case, corridors that were originally low in centrality were identified with reinforcement, and after further weighting the phylogenetic data, there were individual corridors that continued to be reinforced and relatively important corridor paths could be identified. The important core source patches before weighting were mainly distributed within the urban core and large parkland areas in the north, and the importance of the southern woodland increased after weighting.

In the unweighted case, the identification of pinch points was mainly located on the corridor paths in the center of the study area. The abundance weighting strengthened the original path areas while identifying important corridor paths that connect outward, and the phylogenetic weighting weakened the original areas and strengthened the more peripheral corridors that can be connected to the outside. The distribution of barriers is like that of pinch points, which are mainly located around or inside the pinch points where there are strong obstacles to bird flight, such as elevated junctions, intersections, high-rise building clusters and high-density residential areas.

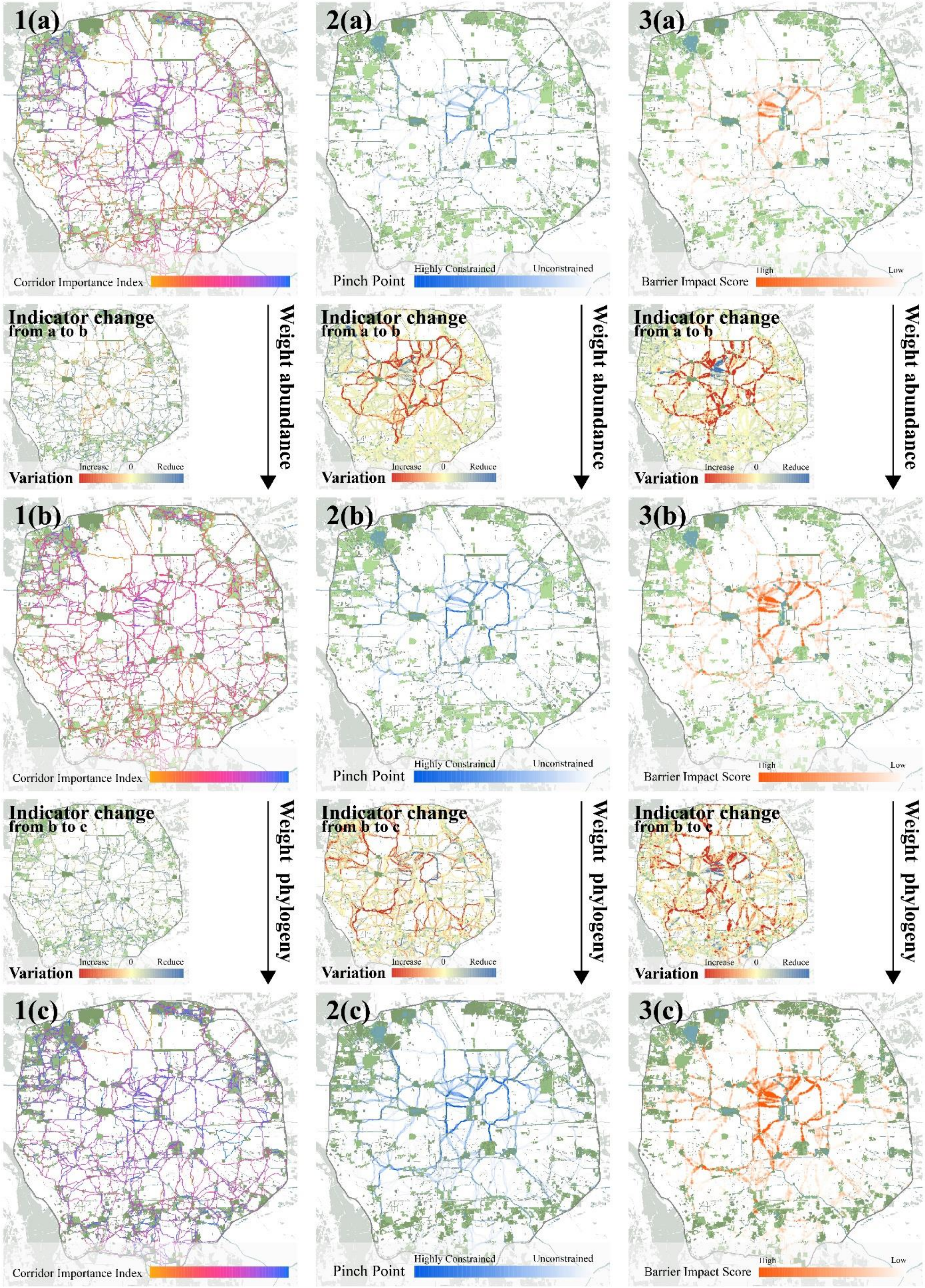

1(a)
Corridor Importance Index
2(a)
Pinch Point
Highly Constrained
Unconstrained
3(a)
Barrier Impact Score
High
Low
Indicator change from a to b
Variation
Increase
0
Reduce
Weight abundance
1(b)
Corridor Importance Index
2(b)
Pinch Point
Highly Constrained
Unconstrained
3(b)
Barrier Impact Score
High
Low
Indicator change from b to c
Variation
Increase
0
Reduce
Weight phylogeny
1(c)
Corridor Importance Index
2(c)
Pinch Point
Highly Constrained
Unconstrained
3(c)
Barrier Impact Score
High
Low

Figure 4. Corridor construction, pinch point and barrier identification results: 1 indicates corridor path identification results; 2 indicates pinch point identification results; 3 indicates barrier identification results; (a) indicates raw unweighted data; (b) indicates weighted based on abundance data; (c) indicates weighted based on abundance and phylogenetic data

3.3 Results of integrated bird corridor network construction

From the previous results, we can see that the constructed model based on abundance and phylogenetic data weighting can emphasize the importance of specific corridors, and at the same time can more obviously identify the pinch points and barriers in the study area, so we decided to conduct the construction of the integrated corridor network based on the abundance and phylogenetic data weighting model in the subsequent study. We used the cumulative current density values of corridor paths to represent the integrated corridor path identification results, and then overlaid the identified ecological source sites, pinch points, and barriers, and the results are shown in Figure 5.

In total, 5694 corridors, 4142.7 ha of core ecological source sites (about 18.9% of green space), 218.7 ha of ecological pinch points and 487.3 ha of ecological barriers were identified in this study. According to the figure, the existing bird corridor groups with high number and frequency of use are concentrated in the core Second Ring Road area, the area around the Beijing-Miyun Aqueduct in the northwest part, the area along the railroad in the southwest part and the green area from Chaoyang Park to Olympic Forest Park in the northeast part, and the bird corridors existing between the patches south of the South Fourth Ring Road are less numerous and less frequently used. The pinch points are mainly distributed inside the Second Ring Road and the roads and built-up areas along the Beijing-Milan Aqueduct, showing a striped pattern. The barriers are mainly distributed in the areas with relatively low current density within the built-up area corridor within the Second Ring Road and some nodes on the corridor in other areas.

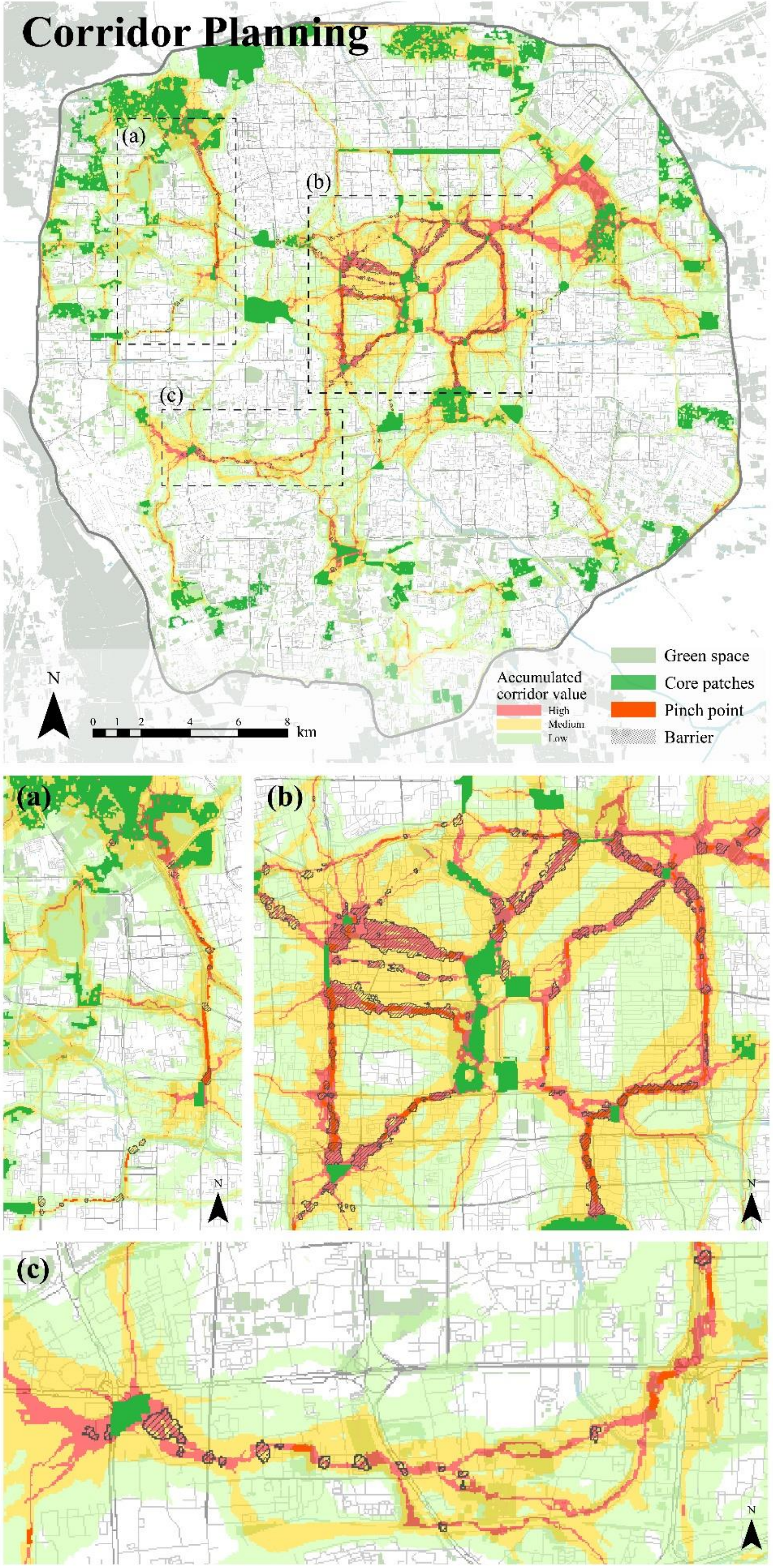

Corridor Planning
(a)
(b)
(c)
N
0 1 2 4 6 8 km
Accumulated corridor value
High
Medium
Low
Green space
Core patches
Pinch point
Barrier
(a)
(b)
(c)
N
N
N

Figure 5. Results of the integrated bird corridor network construction: (a) core area; (b)northwest area; (c) southwest area

4 Discussion

4.1 Why are local bird surveys important for corridor construction?

The diversity of urban birds in habitat and corridor spatial distribution require us to construct differentiated corridors (Hernando et al., 2017; Ortega-Álvarez & MacGregor-Fors, 2009). Through local bird surveys, we can better understand the patterns present in urban bird populations in terms of species diversity, spatial distribution and flight ability, and so avoid problems of assuming homogeneity of habitat prediction and corridor spatial corridor construction seen in existing studies. This provides a more robust and reliable basis for accurately mapping bird ecological corridors.

In terms of habitat, there are two types of habitat prediction for birds in the existing corridor construction: selecting the main habitats of focal birds (Bhakti et al., 2021; Grafius et al., 2017; Shimazaki et al., 2016) or assessing the quality of habitats through comprehensive indicators (Liu et al., 2021; Nor et al., 2017). However, due to the differences in habitat requirements of different bird species in the city (Callaghan et al., 2018), both approaches are considered homogeneous due to the lack of classification of bird habits (Tian et al., 2021).

Comparing the habitat prediction results from this study, we can see there are large differences in distribution among different bird species. We selected four bird species to illustrate this (Figure 6a): egrets (*Egretta garzetta*) and Indian cuckoos (*Cuculus micropterus*), which are less adaptable to urban environments and so were mainly distributed within large green areas, while white wagtails (*Motacilla alba*) and spotted doves (*Streptopelia chinensis*), which are more adaptable, and so can inhabit more fragmented green patches and built environments. With forest birds, the Indian cuckoo and the spotted dove, tend to choose green areas with high vegetation cover, while the egrets and white wagtails, which prefer waterfront habitats, choose areas closer to water sources. The local bird species and spatial distribution data obtained through field observations allowed us to accurately model the potential habitats of each bird species and obtain corridor source locations that match the habitat preferences of each bird species.

For the corridor space, compared with other studies that used the same resistance surface to simulate the obstacles to bird flight (Liu et al., 2021), we used a modified resistance surface for each bird species after observing and assessing its flight ability (McRae et al., 2008), so that it would adopt a strategy more in line with its behavior when facing the same landscape elements (Figure 6b for example). While the other three bird species have more corridors in the core area, Indian cuckoo only identified two passerine corridors. This is probably because they do not have more suitable flight destinations and landscape elements to support their flight in the area, so they choose to pass through the area quickly. The study of native birds can help us understand the flight characteristics and landscape preferences of each bird species, construct corridor spaces that are consistent with the flight abilities of the studied birds, and identify core patches and important corridors that support broader bird diversity (Bhakti et al., 2021).

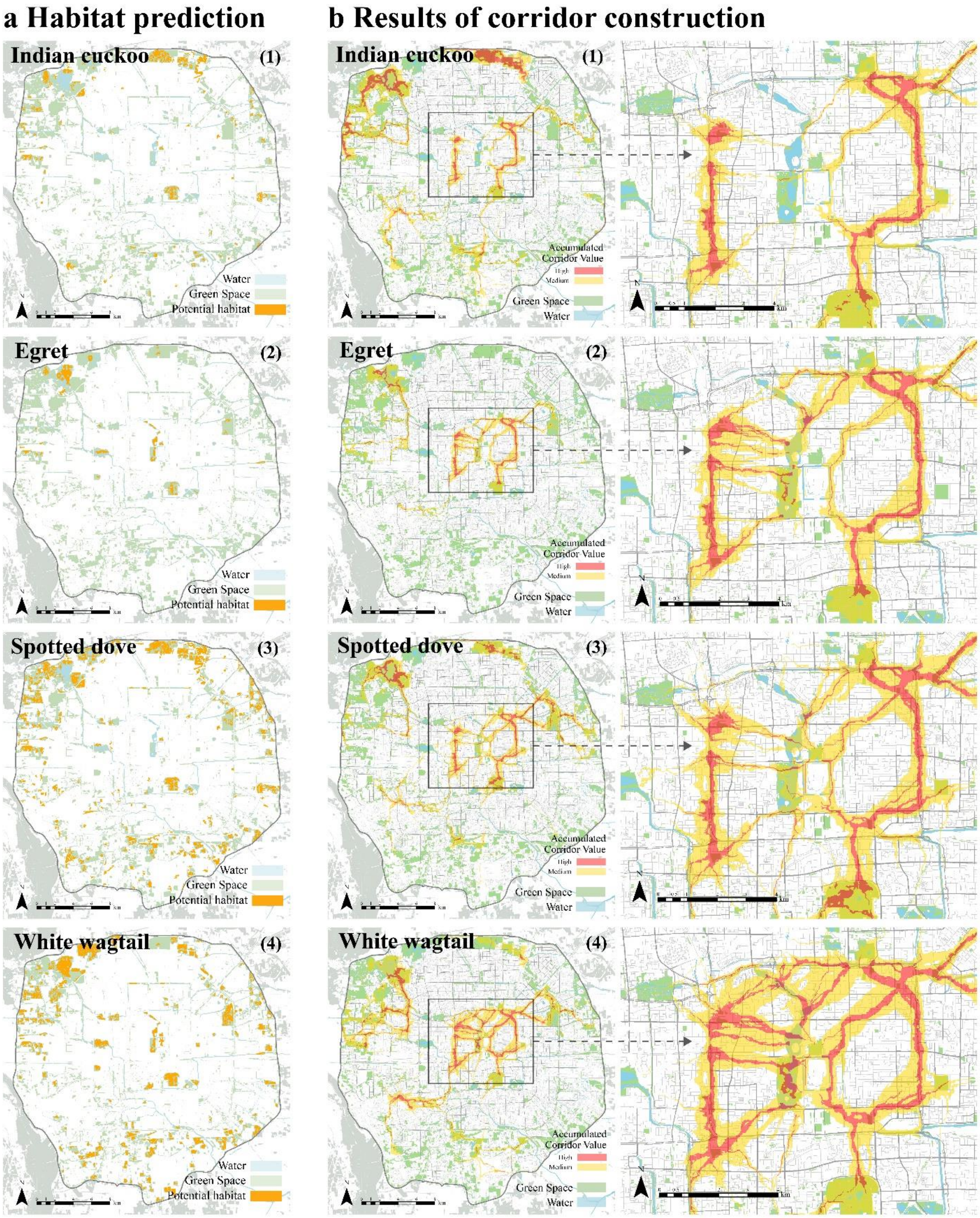


Figure 6. (a) Habitat prediction results, (b) Results of corridor construction; (1) Indian cuckoo (2) egret (3) spotted dove (4) white wagtail

4.2 Why should abundance and phylogenetic importance be considered in corridor construction?

Our observations show a large variation in the abundance of urban bird populations (MacGregor-Fors & Schondube, 2011) and a tendency to homogenize phylogeny (Sol et al., 2017). At the level of abundance, the number of sparrows accounted for 34.8%, and the total number of bird species in the top 20 in terms of abundance accounted for 61.8% of the total number, with a polarized distribution of species number structure in urban bird communities (Aronson et al., 2014); at the level of phylogeny, we observed a total of birds belonging to 16 orders, of which the number of species of *finches* accounted for 59.3% of all birds, and the second most abundant order of *pelagics* accounted for only 7.9%. Most of the birds were on the same developmental branch. Therefore, we used a weighted model based on abundance and phylogenetic data to identify the few bird species that carry more unique genetic resources.

For the overall corridor construction results, we enhanced the weight of those minority bird carrying more unique genetic resources in the corridor construction (Figure 7a). In comparison with the corridor construction results before weighting, some of the linear corridors (rivers, railroads, green belts) connecting the study area to the outside were enhanced, demonstrating the supporting role of this part of the landscape structure for urban bird flow (McClure et al., 2015); more barriers were also identified, indicating that the improvement of the quality of these stepping stones is more important for the corridor connectivity of these birds compared to the overall birds (Baguette et al., 2013).

For the corridor construction results of priority bird species, we identified the priority bird species to be protected, including *Caprimulgiformes* (white-throated needletail (*Hirundapus caudacutus*)), Anseriformes (mallard (*Anas platyrhynchos*), mandarin duck (*Aix galericulata*)), *Falconiformes* (peregrine falcon (*Falco peregrinus*), kestrel (Falco tinnunculus)), and *Cuculiformes* (hawk cuckoo (*Hierococcyx varius*), Chinese hoel (*Eudynamys scolopaceus*)). Comparing the results of their corridor construction with the changes in the overall corridor index (Figure 7b), we can see that the corridors enhanced in the overall corridor index include most of the major corridors of the priority bird species, indicating that the corridors of the priority bird species can be effectively enhanced by the weighted model based on multiple degrees and phylogenetic data. Compared with corridors constructed using dominant species within cities (Ersoy et al., 2019; Grafius et al., 2017; Nor et al., 2017), the identification results of our model can help assess the differences in adaptation of different types of birds to urban resources, and take the effects of ecological corridors on bird species diversity and genetic diversity into account (Paker et al., 2014), which helps clarifying the conservation priorities of study birds and strengthening corridors for biodiversity conservation strategies.

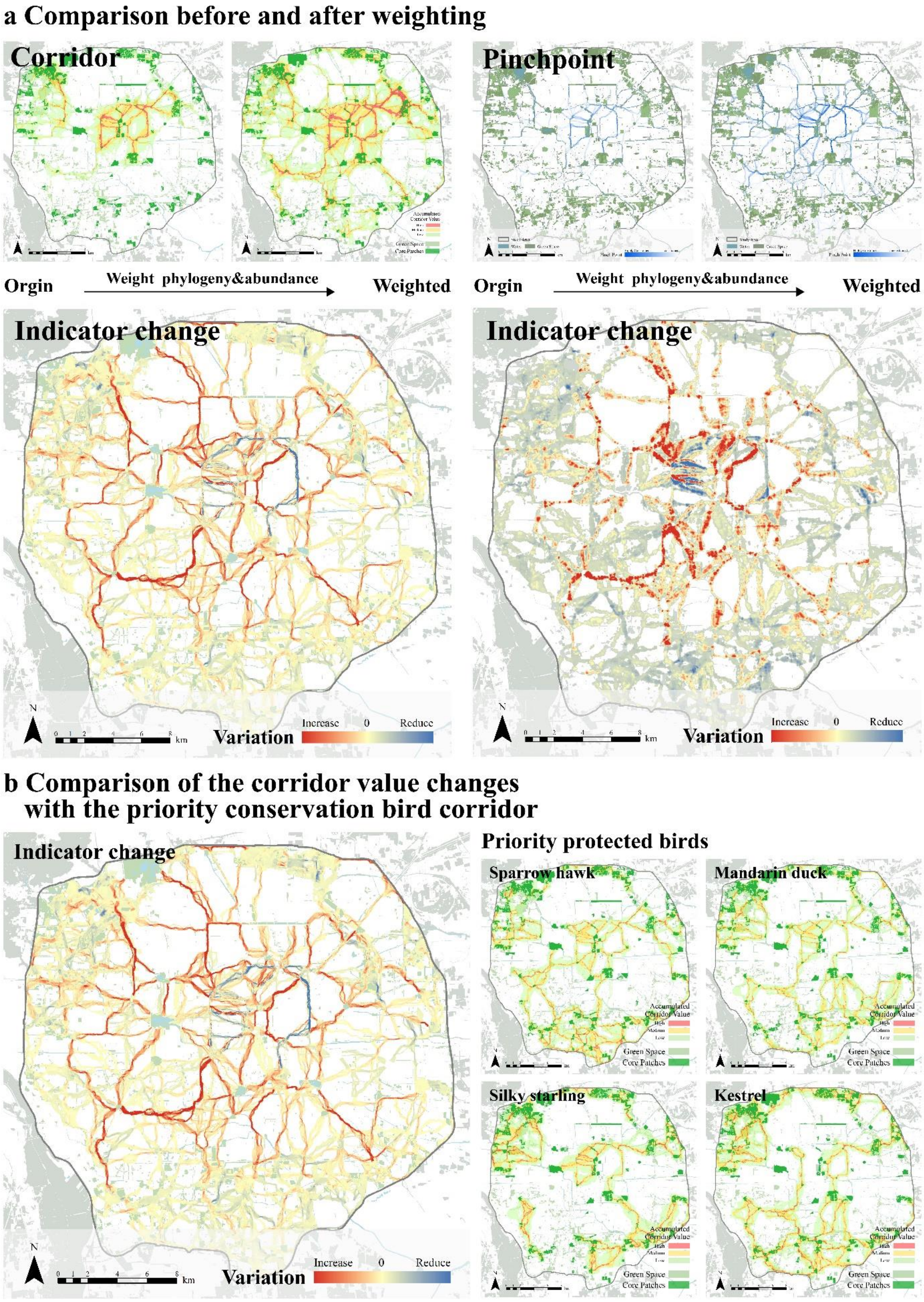

a Comparison before and after weighting
Corridor
Pinchpoint
Accumulated Corridor Value
High
Medium
Low
Green Space
Core Patches
Orgin
Weight phylogeny&abundance
Weighted
Orgin
Weight phylogeny&abundance
Weighted
Indicator change
Indicator change
N
0 1 2 4 6 8 km
Variation
Increase
0
Reduce
b Comparison of the corridor value changes with the priority conservation bird corridor
Indicator change
Variation
Increase
0
Reduce
Priority protected birds
Sparrow hawk
Mandarin duck
Silky starling
Kestrel
Accumulated Corridor Value
High
Medium
Low
Green Space
Core Patches

Figure 7. (a) Comparison of corridor cumulative values and pinch points before and after weighting, (b) Comparison of the corridor value changes with the priority conservation bird corridor

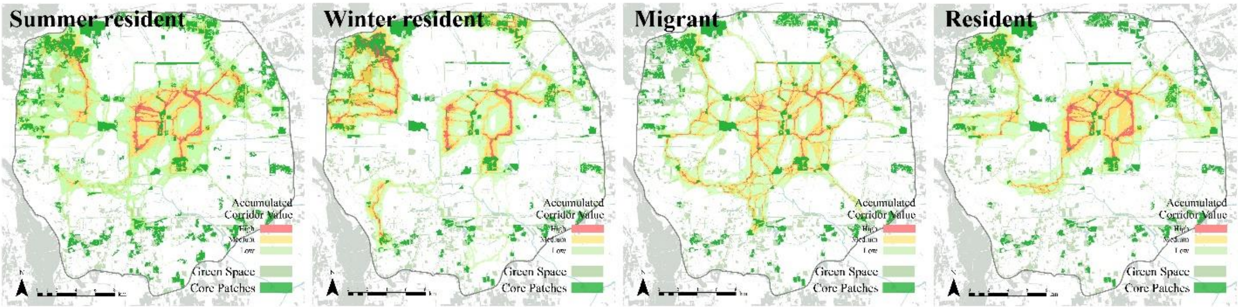
4.3 Application prospects

Our proposed corridor construction approach bridges local bird resources and ecological security pattern planning (Aronson et al., 2017), which can guide urban planners to manage urban biodiversity resources (Shwartz et al., 2008). Take the scenario of protecting migratory birds for example. In Figure 8a, we have reclassified the study birds into summer birds, winter birds, migratory birds and resident birds to guide the biological process of birds in the region according to different aspects of the problem. For light pollution and bird collisions, it is necessary to reduce nighttime light disturbance and the use of glass walls in high-rise buildings in the bird corridor area (Van Doren et al., 2017; Van Doren et al., 2021), and to plan alternative corridors outside the built-up areas (Cusa et al., 2015). For the distribution and characteristics of migratory birds' habitats, the vegetation structure (Tryjanowski et al., 2013) and coverage (Evans et al., 2011) of existing habitats can be enriched to provide sufficient resources for migratory birds, while suitable habitats for migratory birds can be set up in other green areas for alleviating the situation that some migratory birds compete intensively in the same area (Buron et al., 2022). By managing and regulating in the above ways, the entire urban landscape can be made to support existing migratory bird communities and increase the prevalence of native species of conservation concern or management interest (Shwartz et al., 2008), allowing the urban ecosystem to provide more services.

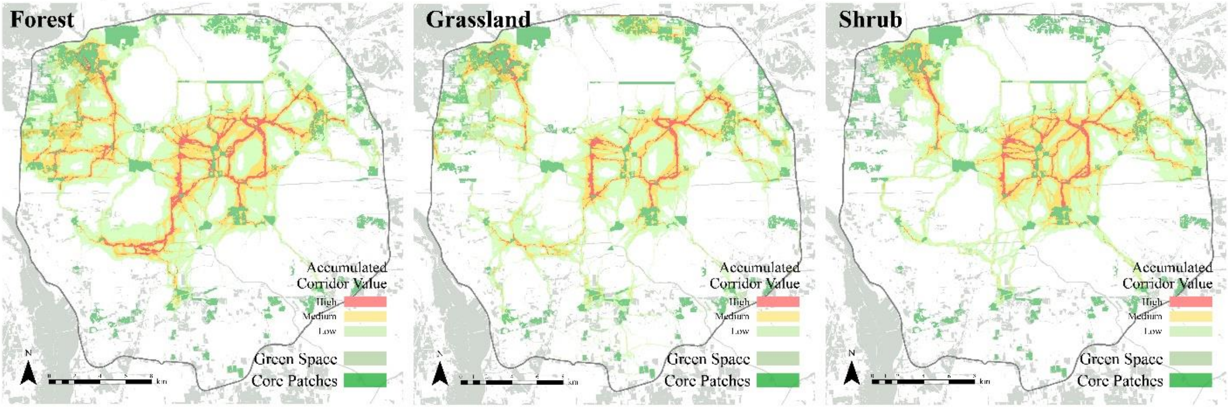
In our study, we classified birds based on their primary habitats and urban land cover, and we believe that this classification can similarly provide decision support in fine-grained biodiversity management (Figure 8b). This illustrates bird corridors where the primary habitats are forests, shrubs, and grasslands, and these species are broadly similar in terms of overall corridor structure, with localized areas of differences in the direction of bird flow. Differences in the direction of bird flow are found in localized areas. This places higher and richer demands on the configuration of plant structures in the management of major ecological corridors to facilitate the movement of various types of birds through corridor construction (Pinho et al., 2021).

In addition, the results of our study can be used to assess the effectiveness of green space policies in terms of ecological connectivity (Lambert & Donihue, 2020), especially when considering that large green spaces can serve more unique functions (Lenda et al., 2023). In the case of our study area, the construction of the first green belt policy in Beijing can be evaluated. The effect of Beijing's First Green Belt in constraining urban and landscape separation has been gradually confirmed by research after its completion (Han & Long, 2010; Lu et al., 2022), but its impact on urban ecological diversity as a green corridor has not yet been widely discussed as it continues to undergo a process of green space fragmentation (Li et al., 2005). After overlaying the results of the first green belt with our corridor construction (Figure 8c) we that the First Green Belt has an area of about 23,800 ha (8,691 ha of green space) within the study area, with 3,206 ha (13.5%) of core habitat and 6,077 ha (25.5%) of important corridors. Although the First Green Belt has a low percentage of green space and is fragmented and subject to strong edge effects (Baguette et al., 2013), most of the green space centers can support the majority of bird habitat needs, and there are high frequency corridors that interconnect, indicating high quality green space and strong connectivity between green spaces. For the whole study area, the first green belt supported 77.4% of the core habitat and 42.3% of the important corridors with 27.9% of the area, indicating that the first green belt plays an irreplaceable role in supporting bird diversity, especially in supplying food and housing resources for birds in the whole study area (Aronson et al., 2017). Also in the figure we can see that there is a mismatch between the corridor space and the existing green space patches in the first green belt: larger clusters of patches are not fully connected by the main corridors, and there are discontinuities of green space at key potential corridor nodes, which will greatly affect the ecological connectivity between the corridors and their surroundings, and will pose a certain obstacle to help birds overcome the high-density built-up environment. Planners can emphasize the enhancement of ecological connectivity in subsequent land planning adjustments.

a Study birds corridor construction results (migratory properties)



b Study birds corridor construction results (main habitats)



c Bird corridor network construction in the Beijing First Green Belt region

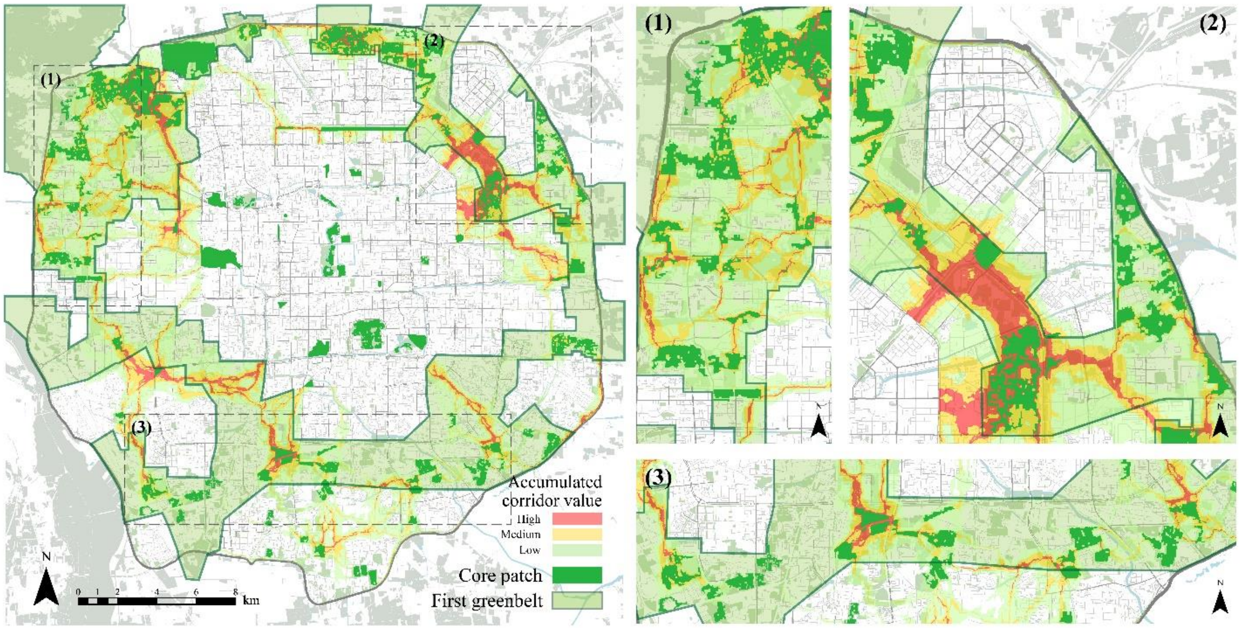


Figure 8. (a) Results of corridor construction for summer migratory birds, winter migratory birds, migratory birds and resident birds; (b) Results of bird corridor network construction in the

Beijing First Green Belt region: (1) Northwest region (2) Northeast region (3) South region

4.4 Limitations of the study

There are two principal limitations in this study: Firstly, some of the data for our local bird study came from citizen data science, and there were subjective biases in observation locations and species in the process of observation, resulting in a gap between the spatial distribution and population size of the obtained data and the real distribution of birds, which has some impact on the subsequent habitat prediction. Secondly, in terms of assessing the movement ability of birds, the assignment of different preferences for birds and the setting of corridor length mainly relies on evidence from existing literature, which without sufficient experimental data support cannot fully simulate the characteristics of birds' movement in the city. We believe that with the increase of open data sources and the advancement of bird behavior research, the urban bird ecological corridors we constructed will be more accurate and extensive, further contributing to the sustainable development of cities and the sustainable management and utilization of urban biodiversity.

5 Conclusion

Bird diversity enables birds to provide many key ecological services in cities, making them an important conservation target for urban ecological security pattern planning. Constructing urban bird ecological corridors is a major way to conserve urban bird diversity. Based on local bird observations and research results, this research uses circuit theory and least-cost path modelling to construct corridors for each bird species after assessing the flight ability and potential habitat of each species and distinguishes the conservation priorities of study birds based on abundance and phylogenetic data, with weighted corridor overlay to derive a comprehensive urban bird corridor network.

We propose a locally adapted bird ecological corridor construction model that can be diversified to assess individual birds. This approach enables differentiated modeling of each bird corridor and identification of important conservation species by combining bird studies with conservation importance assessment. This also avoids the generic pitfalls inherent in existing bird corridor construction models, allowing bird corridors to protect a broader range of biodiversity, and providing an accurate simulation of bird movement scenarios is further expanded.

This method can be applied to many large cities in the world, if the local birds are fully investigated, and accurate and timely land survey data are obtained. At the same time, the corridor construction process focuses on the clear identification of study bird movement patterns, which gives us the possibility to manage biodiversity and evaluate green space policies (Shwartz et al., 2008). We use the results of the corridor construction to discuss how bird migration is managed within Beijing's Fifth Ring Road and to identify the key role that Beijing's First Green Belt policy plays in biodiversity conservation. Through our ecological corridor construction model, large cities have the opportunity to identify unique biodiversity targets and protect threatened species that provide key ecological functions at the urban scale (Lambert & Donihue, 2020). The model we constructed is important for bird conservation and enhancing urban safety pattern planning, which can provide a reference for urban ecological conservation and restoration and urban planning, as well as for achieving the United Nations' sustainable development goals.

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