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The role of urban waterbodies in maintaining bird species diversity within built area of Beijing

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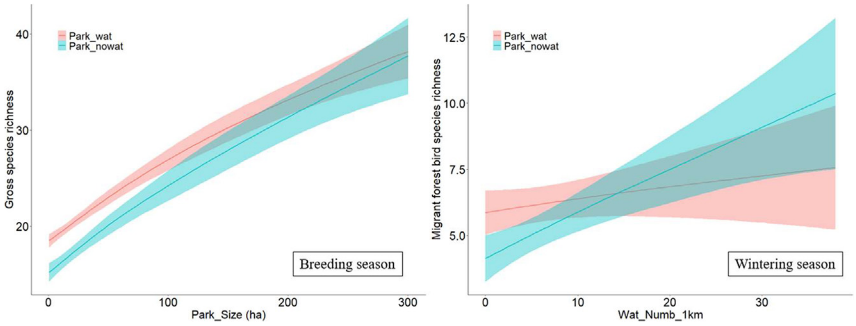
HIGHLIGHTS

- Urban parks with waterbodies are more efficient in maintaining avian diversity.
- Waterbodies have similar importance for forest birds of different physical statuses.
- Waterbodies within and outside a given park are competitive in attracting birds.
- Urban forest birds prefer habitats near waterbody patches.

GRAPHICAL ABSTRACT



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ABSTRACT

This study aims to provide a comprehensive understanding of the role of urban waterbodies in avian ecology, which is instructive for both biodiversity conservation and urban planning. Based on bird surveys conducted in 41 urban parks in Beijing during the breeding and wintering seasons of 2018–2019, and using standardized regression analyses, we identified the specific effects of waterbody attributes on the full avian community and forest bird guilds. We assessed this at multiple spatial scales, first within the focal parks, and then within buffer zones with radius of 200 m and 1000 m. We found that waterbodies can serve as avian diversity “hotspots” in the urban landscape. More specifically, they support avian diversity in the following ways: (1) Parks with waterbodies maintain a higher number of bird species than parks without waterbodies during the breeding season and attract resident forest birds during the wintering season. (2) When not frozen, waterbodies inside and outside parks contribute equally to resident forest bird species richness, while more individuals were attracted by waterbodies within neighborhoods. (3) In parks without waterbodies, the number of forest bird species significantly increases with the number of waterbody patches within neighborhoods, while the corresponding relationship for parks with waterbodies is insignificant. These findings suggest a preference for habitats nearby waterbodies among forest birds residing highly urbanized areas. This study provides new insights into avian ecology in urban landscapes and scientific support for the idea that creating and maintaining urban waterbodies can conserve biodiversity.

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1. Introduction

Today, over 55% of the world's population resides in urban areas, and the majority of future growth will occur in developing countries (UN, 2018). Urbanization is inevitably accompanied by land cover changes from natural/agriculture to artificial surfaces, making urbanization one of the major drivers of global biodiversity loss (Frishkoff et al., 2016; Maxwell et al., 2016). Wetlands have been among the most vulnerable and widely-impacted natural habitats with respect to urbanization-induced land cover change (Dewan and Yamaguchi, 2009; Pauchard et al., 2006). For instance, the Pearl River Delta, an urban agglomeration of over 70 million people in southern China, suffered a 25.79% loss (covering 1518 km^2) of natural habitats between 1992 and 2012, with 41.99% or 760 km^2 being wetlands (He et al., 2014). The loss of wetlands and related waterbodies due to urbanization endangers water-related biodiversity and causes significant loss of regional ecosystem service value (Li et al., 2010). Indeed, according to comprehensive assessments, wetlands can be 75% more valuable than lakes and rivers, 15-times more valuable than forests, and 64-times more valuable than grasslands and rangelands in terms of the ecosystem services they provide (Costanza et al., 1997). Although the value of wetlands/waterbodies has been well-established, half of these ecosystems have disappeared in the past century (Davidson, 2014).

In the context of global land use change, urban wetlands are crucial to the maintenance of avian diversity (Hassall, 2014), and their restoration in urban areas is key for the maintenance of urban biodiversity (Marzluff and Ewing, 2001). There is consistent evidence that waterbody occurrence and patch configuration are key drivers of both the forest and water bird diversity (Canedoli et al., 2018; Hsu et al., 2019; Imai and Nakashizuka, 2010), while significant differences have been found between forest and water birds' respective responses to land use/landcover (LULC) changes caused by urbanization (Xie et al., 2020). However, the underlying ecological mechanisms of the multi-scale bird-wetland relationship within highly urbanized areas are still insufficiently understood, especially with respect to the influence of urban wetlands/waterbodies on forest birds.

According to existing studies, there are other key drivers for the residence of avian communities in urban environments. Among which the species-area relationship is unarguably the most well-established (Belcik et al., 2020), which has been found to be consistent across different habitat types and multiple spatial scales for all major biodiversity clusters (Gaston, 2000). Larger habitat patches include more habitat types, thus meeting the needs of different bird ecotypes; moreover, the edge effect is lower because of a lower boundary-area ratio compared to smaller habitat patches (Evans et al., 2009).

Based on island biogeography and metapopulation theory (Fernandez-Juricic and Jokimaki, 2001; Marzluff, 2005), the urban matrix acts as the physical barrier between the source and sink patches and therefore has a negative effect on bird diversity (Prevedello and Vieira, 2010). By contrast, forest cover within neighborhoods can mitigate the isolating effects of the urban matrix, thereby exercising a positive effect on bird occurrence (Melles et al., 2003). An increase in vegetation species/cover generally provides more food resources and ecological niches, enabling a given habitat patch to sustain a more diverse avian community (Carbo-Ramirez and Zuria, 2011; Chong et al., 2014; Taylor et al., 2016). However, in temperate forests, the mixture of built area and native forest characteristic of suburban development is associated with higher bird diversity than either urban or reserved natural habitats (Marzluff, 2005; Marzluff et al., 2016b). In addition, human visitation to avian habitats is regarded as a threat by most bird species, while environmental noise tends to disturb intra-species vocal communication; therefore, many urban studies have found a negative effect on avian diversity (Leveau and Leveau, 2016; Proppe et al., 2013).

In terms of habitat exploitation and the avoidance of interspecies competition, avian community structure varies according to the spatial scale adopted; in another words, avian assemblages are the product of regional and local processes (Ricklefs, 2008). According to existing results, the most plausible driver for avian community assemblages are combinations of habitat diversity and functional and phylogenetic traits (Sobral and Cianciaruso, 2016). These drivers lead to diverse bird assemblages at local and biogeographical scales (Brooker et al., 2009; Pavoine and Bonsall, 2011), while avian communities are more functionally clustered at the regional scale (Pausas and Verdu, 2010). Therefore, it is necessary to conduct multi-scale bird-environment analysis to demonstrate the importance of diverse landscape patterns.

Beijing, the location of this study, has a large number of wetlands and waterbodies, including rivers, lakes, and ponds in urban parks, which usually occur as isolated waterbody patches embedded in the urban matrix. It has been found that Beijing is home to at least 161 water bird species, which as a whole account for 54.55%, 32.43%, and 36.59% of the gross number of orders, families, and species, sequentially (Zheng, 2017). However, according to a recent ecological risk assessment, most urban wetlands in Beijing, especially wetland parks, were at a moderate to high level of risk from disturbance (Li et al., 2020), which could weaken their role as bird habitats, thereby endangering biodiversity.

To understand the role played by Beijing's urban waterbodies in avian ecology to avian diversity, we test the hypothesis that, along with increasing park size, bird species richness in parks with waterbodies will reach a higher level than that in parks without waterbodies due to the function of wetlands in sustaining water bird populations; since ocular utilization of urban waterbody would inevitably beyond the park boundary, we further hypothesize that a deficiency of waterbodies in a given park can be mitigated by waterbody patches within the surrounding landscape.

2. Methods

2.1. Study sites

We conducted our study in Beijing, China's capital city, which is located in the northernmost end of the North China Plain (39°54′ N, 116°23′ E). The human population in 2019 was 21.54 million (Beijing Municipal Bureau of Statistics, 2019). The average elevation within the city boundary is 43.5 m. The regional climate is a typical temperate monsoon climate characterized by hot-wet summers and cold-dry winters. Specifically, the annual average temperature is 10–12 °C, and the average temperature in January (the coldest month) within the last five years has been −7.2 °C. Most of the persistent waterbody surfaces were covered by thick ice in the absence of human intervention. The 1085 distinguishable rivers in Beijing belong to tributaries of the Haihe River Basin, which sustains five large river systems: the Yongding River, North Canal, Chaobai River, Daqing River, and Ji Canal. The complicated river system connects a large number of urban wetland patches scattered across the urban landscape.

We selected 41 urban parks as our sample sites, with the area ranging from 0.79 ha to 300.31 ha. Among the selected parks, 19 have at least one visible waterbody partially or fully surrounded by natural or semi-natural soft edges available for forest and water birds, while water surfaces are absent in the remaining 22 sites. Our sample sites were evenly distributed within the sixth ring road of Beijing (within which almost the entire urban population lives), with the minimum distance between each two sites exceeding 1 km (Fig. 1). Basic information on our sampled parks, and information on the comparison between parks with and without waterbodies, are provided in Appendix 1.

2.2. Bird survey and disturbance data

Bird surveys were carried out using the line-transect method (Bibby et al., 1998), with survey lines covering all major microhabitat types (including forests, grass, shrubs, gardenscapes, and artificial structures) within our sample sites and the minimum distance between each two

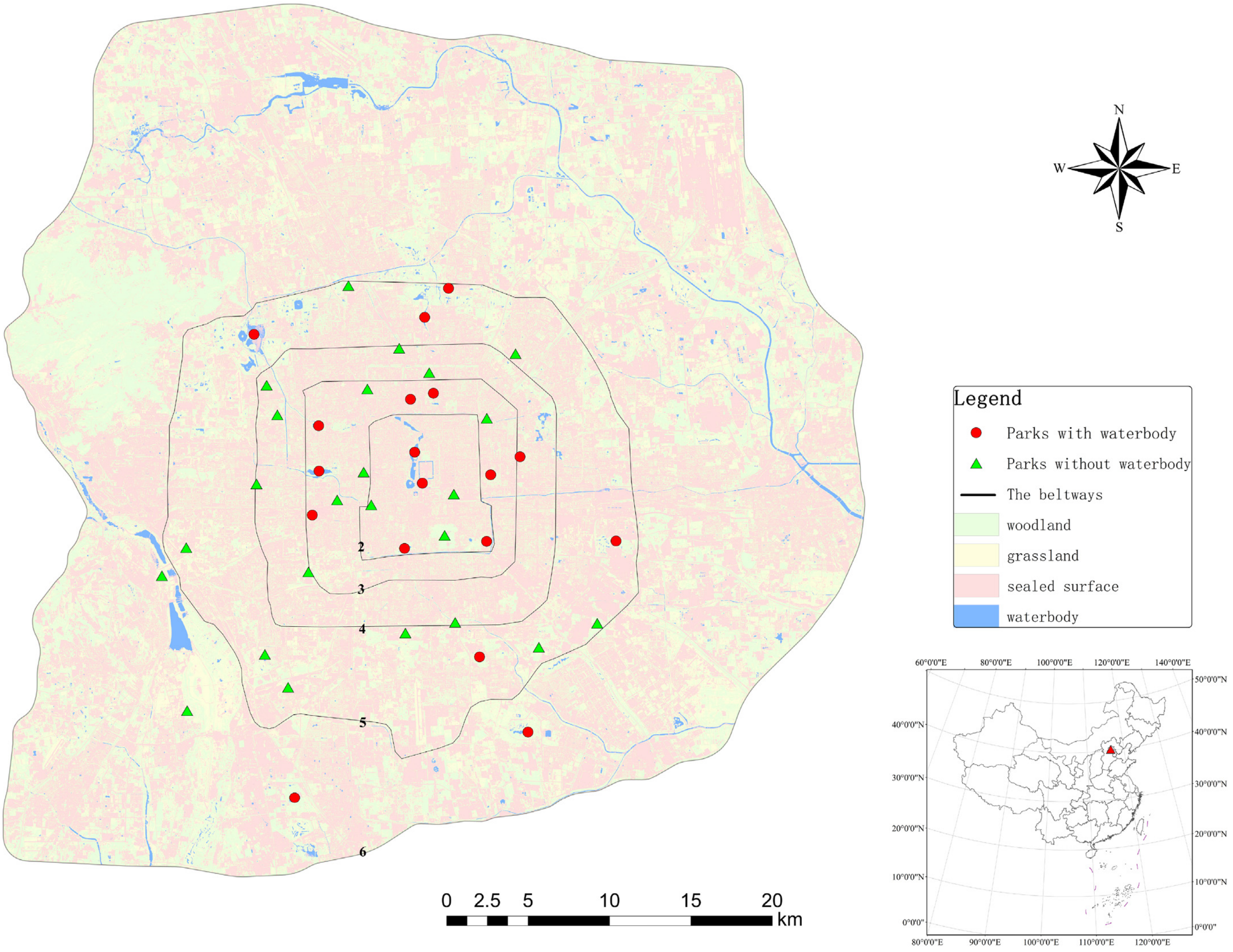

Fig. 1. Geographic distribution of sampled park sites with/without waterbodies. The beltways are numbered sequentially (2nd–6th) from the inner ring to the outer ring, which are official names identifying them.

lines exceeding 200 m. Surveys were conducted during both the wintering (December 2017 to February 2018) and breeding (May 2018 to July 2018) seasons, within the 4 h after sunrise when birds are most active. We did not conduct bird surveys during rainy days or days with strong wind (>30 km/h). We recorded both species and the number of individuals that appeared or were heard within a 25 m range of both sides, by a speed of about 2 km/h. Birds that flew through the transects at high speeds or hovered in the sky were recorded but were excluded from bird-environment relationship analyses. At the time of the bird surveys we also counted the tourist numbers in the transects, and visitor density was calculated as the ratio of tourists to the survey area. Environmental noise was measured at 100 m intervals by holding the noise meter (SNDWAY, SW-524) above the surveyor's head. We recorded the minimum and maximum noise levels across 30 s. We adopted the average noise value for each site as the final noise level. For sites with waterbody patches, we walked around each waterbody to take a census of the water birds after the line-transect survey.

2.3. Vegetation survey

Vegetation surveys were conducted in random quadrats. One to six 20 m × 20 m quadrats were randomly placed within each park site, the number of vegetation quadrats depended on park size (i.e., 0–2 ha: 1 quadrat; 2.01–5 ha: 2 quadrats; 5.01–10 ha: 3 quadrats; 10.01–20 ha: 4 quadrats; 20.01–40 ha: 5 quadrats, >40.01 ha: 6 quadrats). Furthermore, two to three herbaceous quadrats (1 m × 1 m) were placed in each vegetation quadrat to detect rare herb species. In vegetation quadrats, we recorded species and coverage of trees and shrubs; in herbaceous quadrats, we recorded the species, coverage of each herb species, and the gross coverage of the herb layer. Tree height and the coverage of each layer [herb (0–0.5 m), shrub (0.6–2 m), tree (>2.1 m)] were estimated visually. To reduce bias due to differences among observers, all estimates were made by an experienced surveyor.

2.4. Classification of land cover and acquisition of landscape indices

The border of each sample site was delineated in Google Earth. Land cover classification was based on high-resolution GF-2 satellite imagery (1 m resolution, acquired in July 2017), using ArcGIS 10.3.1. A supervised classification method (the maximum likelihood classifier) was adopted to classify land cover as woodland, grassland, waterbody, sealed surface, or bare land.

Using ArcGIS 10.3.1 and Fragstats 3.3, landscape analyses were conducted at three spatial scales (the focal sites and the 200 m and 1000 m buffer regions of the given sample sites, which is commonly used to investigate multi-scale bird-environment relationships (Huste and Boulinier, 2011; Matsuba et al., 2016)), with special attention paid to waterbody patches within and nearby selected sites. The measured landscape indices including those describing the basic characteristics of greenspaces (e.g., green area and green ration), waterbody patches within sites (e.g., waterbody occurrence, area, and ration), waterbody patches within the neighborhood of sites (e.g., waterbody size, patch number), and surrounding matrix (e.g., the percentage of woodland and sealed surface) (detailed information and data sources are listed in Table 1).

2.5. Data analysis

Forest birds were bound to terrestrial habitats while water birds could only occupy aquatic habitats. Based on this rule, we first classified bird species as water birds (including *Grallatore*, *Natatores*, and *Alcedinidae*) and forest birds (all other species) (Zheng, 2012). We further classified forest bird species as residents (R), through migrants (P), summer breeders (S), and winter visitors (W) based on residence types (Zheng, 2017). To distinguish the difference between the effects of waterbodies on bird guilds with different residence status, we classified all birds as migrants except for residents.

To eliminate the bias of special habitat preferences from hydrophilous forest bird species, we excluded forest bird species exhibiting obvious preference for aquatic habitats, including Oriental Reed Warbler (*Acrocephalus orientalis*), Black-Browed Reed Warbler (*Acrocephalus bistrigiceps*), and Water Pipit (*Anthus spinoletta*), which were all migrants in our study area.

In the bird-environment relationship analyses, a total of 22 predictive environmental variables were classified as eight variable types, that is: park size (Park_Size), waterbody geomorphic indices (Inner_Water), surrounding waterbody indices (Nearby_Water), interaction between indices of waterbody inside and surrounding each site (Interact_Water), greenspace indices (Green_Indices), plant structure indices (Plant_Structure), matrix indices (Matrix), and disturbance indices (Disturbances) (the detailed variables included in each variable type are listed in Table 1).

Aimed at comparing the relative importance of each explanatory variable type in describing the variation in species richness and abundance of gross avian community, and that of residents and migrants within the breeding and wintering seasons, we first conducted a standardization process for all explanatory variables. Here we note that the interactions between waterbodies within and outside park sites, and the quadratic term of area-related indices, were adopted as new explanatory variables. Then, we determined the key influencing factors responsible for species richness, abundance of forest birds, and the gross avian community based on AICc criterion. We calculated the VIF value for each environmental variable and deleted explanatory variables whose VIF >2 before we conducted parameter permutation (Burnham and Anderson, 2004); we drew the residual plot to ensure that initial models met the basic assumptions for linear regression. In order to

Table 1
Definitions of selected environmental variables and descriptive statistics followed by data ranges.

Types	Abbreviation	Description	Data source	Mean (range)
Park size (Park_Size)	Park_Size (ha)	Gross area surrounded by the border of each park site	Calculated from the park border shape files	35.26 (0.79–300.31)
Waterbody geomorphic indices (Inner_Water)	Wat_Occur	The occurrence of persistent water surface within each site	Parks with waterbodies was defined as 1, parks without waterbodies was 0	0.46 (0.00–1.00)
	Wat_Area (ha)	Gross area of waterbodies within each park site	Calculated from the water border shape files	17.51 (0.04–173.15)
	Wat_Edge (km)	Total length of shoreline within each site		6.31 (0.17–61.38)
	Wat_Ratio (%)	% cover of water surface in each park site	Area_wat/Size_park	16.88% (0.02%–57.66%)
Surronding waterbody indices (Nearby_Water)	Wat_Area_200m (ha)	Waterbody area within 200 m buffer region of the site boundary	Obtained from the classified GF-2 image	1.65 (0.02–9.65)
	Wat_Numb_200m	Number of waterbody patches within 200 m buffer region of the site boundary	Counted visually in Google Earth	3.23 (1.00–16.00)
	Wat_Area_1km (ha)	Waterbody area within 1000 m buffer region of the site boundary	Obtained from the classified GF-2 image	8.37 (0.00–54.91)
	Wat_Numb_1km	Number of waterbody patches within 1000 m buffer region of the site boundary	Counted visually in Google Earth	6.93 (0.00–38.00)
	Dist_to_Wat (m)	Nearest linear distance to waterbody patch exceeded 1 ha or rivers	Measured in Google Earth	498.93 (0.00–3014.00)
Greenspace indices (Green_Indices)	Green_Area (ha)	Gross greenspace area in each site	Obtained from the classified GF-2 image	22.70 (0.75–104.56)
	Green_Ratio (%)	% cover of greenspace in each site		78.60% (30.56%–97.46%)
Plant structure indices (Plant_Structure)	Tree/Shrub/Herb_Spe	Species richness of trees, shrubs, and herbs	Number of tree/shrub/herb species	12.39 (3.00–19.00) 5.88 (1.00–11.00) 48.05 (24.00–75.00)
	Tree/Shrub/Herb_Cov	% cover of tree, shrub, and herb layers	Visually estimated by a specific surveyor	65.36% (17.00%–95.00%) 20.65% (1.00%–54.00%) 68.95% (25.00%–94.00%)
Food resources (Food_Resources)	Food_Plant_Breed	Number of plant species berring edible fruits	Counted in field survey by the same time with bird survey	8.54 (2.00–18.00)
	Food_Plant_Wint	Number of plant species produce edible seeds that can survive into the winter		18.24 (6.00–33.00)
Matrix indices (Matrix)	Perc_Wood_1kmb	% cover of woodland cover within 1000-m radius buffer region of the sample boundary	Obtained from the classified GF-2 image	30.50% (19.50%–47.17%)
	Perc_Seal_1kmb	% cover of artificial land within 1000-m radius buffer region of the sample boundary		57.87% (29.09%–72.98%)
Disturbance indices (Disturbances)	Visitors (/ha)	Number of contemporaneous visitors counted during bird survey within the same distance range	Number of visitors/survey area, averaged by season for each site	Breeding: 23.11 (1.21–84.76); Wintering: 22.92 (0.74–79.52)
	Noise	Environmental noise level measured concurrently with bird survey	Averaged all values by season for each site	Breeding: 52.33 (43.74–62.63); Wintering: 50.52 (40.58–61.43)

predict avian community structure under specific circumstances, we further used the model with the lowest AIC value containing variable interactions to conduct Bayesian estimation using the brms package in R. We predicted the responding avian community indexes under different variable levels in the interactions. All statistical analyses were conducted using the package "MuMIn" (Bartoń, 2016) and "brms" (Buerkner, 2017) implemented in R version 3.5.1 (R Development Core Team, 2018).

3. Results

A total of 104 bird species were recorded in our field survey, among which 81 species (66 forest birds; 15 water birds) were recorded in the breeding season, while 65 species (52 forest birds; 13 water birds) were recorded in the wintering season. Residence type clusters for forest bird species in the breeding season were evenly distributed, with residents, summer visitors, and passage migrants each accounting for approximately one third of total forest bird species; this was different to the proportion during the wintering season, when residents accounted for more than half of the whole, followed by passage migrants (18 species, 35%) and winter visitors (3 species, 6%).

In the breeding season, with increasing size, parks with waterbodies reach a higher plateau in the species-area curve than those without waterbodies, and the confidence intervals rarely overlap. The threshold value for the species richness plateau of parks with waterbodies is higher than that of parks without waterbodies (Fig. 2(A)). In contrast, during the wintering season, when waterbodies turned into solid ice, the occurrence of waterbodies made only negligible contributions to the growth of gross bird species richness along with increasing park size (Fig. 2(B)).

Water-related environmental indices show strong explanatory capacity for both gross avian community and forest bird guilds (which have no direct ecological relationship with aquatic habitats) (Figs. 3–5). The effects of all significant water-related variables are positive, while the interactions between waterbodies within and outside the sites are negative (Figs. 3–5).

The variation in forest bird community structure described by water-related indices is largely consistent through the liquid and solid condition of water surfaces (about 40%–50% of gross variance), except that the value during the wintering season (59.65%) is larger than that during the breeding season (23.86%) for the majority of resident forest bird individuals (Figs. 4–5); in the breeding season, when liquid water is more available within parks (all of them have available edges) than in neighborhoods, forest bird species richness is equally driven by waterbodies within and outside the given parks (about 30% of gross variance), with the latter having a higher explanatory capacity (residents: 30.84% vs. 1.98%; migrants: 40.46% vs. 10.52%) for most forest bird populations (Figs. 4(A, B) and 5(A, B)). This relationship could be further strengthened by the fact that the effect on resident forest bird species abundance from the inner waterbody patches (waterbody occurrence) is not significant (Fig. 5(A)).

Water-related variables explain a higher proportion of the variance in the species richness of migrant forest birds than in that of residents, which was consistent through the two studied seasons (breeding season: 52.18% vs. 41.76%; wintering season: 46.48% vs. 30.92%). The result for species abundance is similar in the breeding season (52.95% vs. 23.86%), but we found a converse result for the wintering season (42.02% vs. 59.65%) (Figs. 4–5). In addition, the influence exerted by disturbance indices and plant structure were repeatedly recorded for both the gross and forest bird communities (Figs. 3–5).

In our model selection results, the averaged results of the best model subsets for each response variable only produced two models with significant effects from the interaction between waterbody patches within and outside the given sites. These are the model for species richness of breeding gross bird species richness (the interaction between waterbody occurrence within sites and waterbody area within 1 km radius buffer region; Fig. 6(A)) and wintering migrant forest bird species richness (the interaction between waterbody occurrence within sites and number of waterbody patches within 1 km radius buffer region; Fig. 6(B)).

Based on Bayesian estimation, we predicted the distribution pattern of bird species among park sites under the manually settled condition - the occurrence or absence of waterbodies. The prediction for gross species richness showed that, under the influence of waterbody area within the 1 km radius buffer region, bird species richness in parks with or without waterbodies is asymptotic within the breeding season. The prediction for migrant forest bird species richness showed that, under different conditions of waterbody occurrence, the number of waterbody patches within the 1 km radius buffer region has a linear effect on the species richness of migrant forest bird during the wintering season. Migrant forest bird species in the all-park-without-waterbody condition significantly increases with increasing waterbody patch number within the neighborhood, while neighborhood waterbody patches only showed a marginal effect on the given species richness in the all-park-with-waterbody condition.

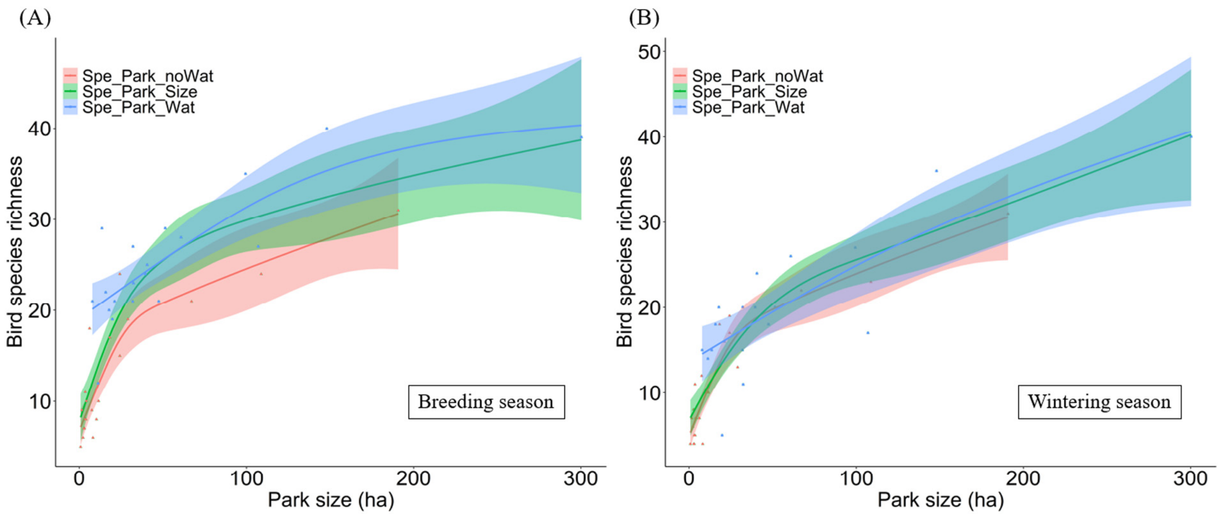

Fig. 2. Species-area curves in breeding (A) and wintering (B) seasons. "Park_wat" represents for parks with waterbody patches, "Park_nowat" represents for parks without waterbody patches.

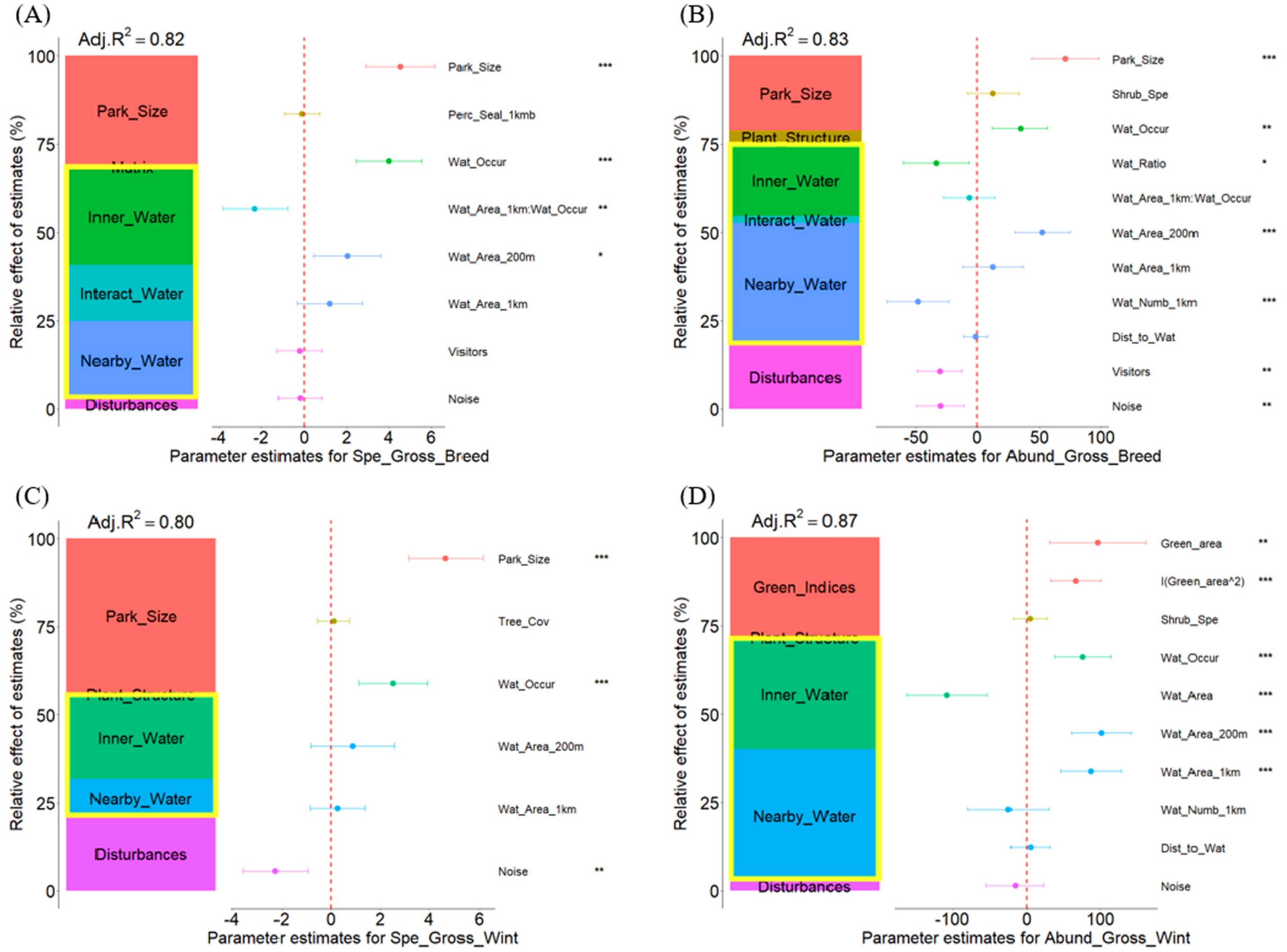

Fig. 3. Relative effects of multiple predictors on gross species richness (breeding season: A; wintering season: C) and abundance (breeding season: B; wintering season: D). The amount of variance explained by a water-related indices were enclosed by yellow squares. Averaged parameter estimates (standardized regression coefficients) of model predictors are shown with their associated 95% confidence intervals following the relative importance of each predictor type, expressed as the percentage of explained variance. The description of the abbreviations can be found in Table 1. The adjusted (adj.) R^2 of the averaged model and the P-value of each predictor are given as: $^{*}P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$.

4. Discussion

There has been consistent evidence suggesting that local/focal factors are more important for avian diversity than landscape-level ones (Beninde et al., 2015; Melles et al., 2003). However, the effects of landscape waterbody patches within and outside urban parks have seldomly been explored in studies of avian ecology in cities. A comprehensive understanding of the key elements of landscape configuration and vegetation composition could greatly aid in the design and management of urban parks for avian diversity. For instance, the consistent negative influence we found from the interaction between waterbody occurrence (inside park sites) and waterbody patches in the neighborhood indicates a potential competitive relationship for resident forest birds between them, which provide valuable information for future gross urban planning.

Wetlands/waterbodies directly improve gross avian species diversity through the maintenance of water-related species. Additionally, they influence avian community structure by providing safe drinking and bathing resources (Zivanovic and Luck, 2016), which is one of the key drivers of the urban-rural distribution pattern of some forest bird species (Cleary et al., 2016). In this study, we sought to answer the questions regarding ‘when’, ‘where’, and ‘how’ urban waterbodies exert their influence on urban birds. For water birds and the small guilds of forest birds living on aquatic habitats, urban waterbodies provided necessary habitats in the breeding season when water was in liquid status, which resulted in a higher plateau of gross species richness than during the wintering season when waterbodies exist as the solid ice. This result was consistent with previous studies suggesting that parks with waterbodies have a significantly higher level of avian species diversity (Chamberlain et al., 2007; Shih, 2018). This does not mean that there are no water birds in the wintering season. In fact, even at this time they could reach large clusters of about one thousand individuals in large waterbodies. However, since the confidence intervals for species-area curves of bird communities in parks with or without waterbodies overlapped with each other, our findings suggest that the presence of water bird species in the wintering season can compensate for the loss of forest bird species sustained by the same greenspace area. On the other hand, the replacement of green area by water surface within a given park reached a net growth in avian species richness. For forest birds without a direct ecological relationship with waterbodies, water-related indices account for a similar proportion of the variance in species richness and abundance both in the breeding and wintering seasons, with the exception of residents' abundance in the wintering season; this indicates that the contribution of waterbodies is generally consistent for this bird guild across timescales. Therefore, the answer to the question of when urban waterbodies play a

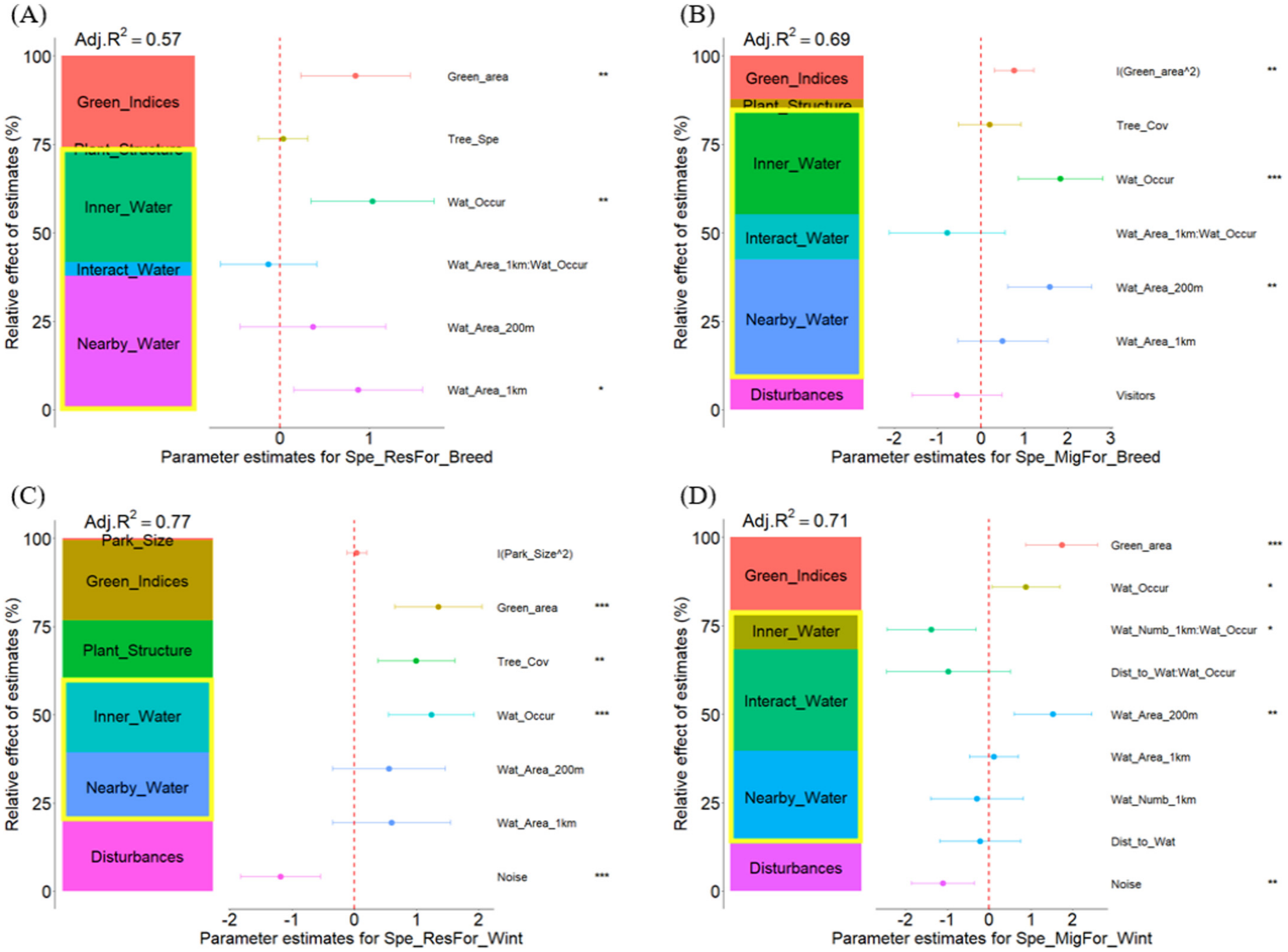

Fig. 4. Relative effects of multiple predictors on species richness of resident (breeding season: A; wintering season: C) and migrant (breeding season: B; wintering season: D) forest birds.

major role in avian community structure is that they maintain an additional proportion of bird species compared to parks without waterbodies during the breeding season, while also attracting resident forest bird individuals during the wintering season.

As to the question concerning the spatial scale in which urban waterbodies exert their effects on avian communities, our results showed that, in the breeding season, waterbodies inside parks and those within the neighborhood contribute equally to resident forest bird species richness, while more individuals of the same guild residing in urban parks were attracted by waterbody patches within the neighborhood, especially in the near neighborhood (200 m radius buffer region).

It is also noteworthy that the confidence intervals for predicted breeding total bird species richness in parks with and without waterbodies overlapped. However, it should be noticed that the predicted increase of bird species richness in parks without waterbodies consisted of forest bird species (especially the migrants) attracted by waterbody patches in the neighborhood. The predicted bird species richness lends further support to their potential untested reliance on waterbody, since just a small waterbody could satisfy the direct needs (drinking, aqueous bath) of forest bird guilds, and the species richness increased along with both the size and patch number of nearby waterbodies. The asymptotic curve of the relationship between predicted gross species richness in parks with/without waterbody under the background of the interaction between waterbodies within and outside park sites is likely explained by the fact that, increasing water surface size within a given park makes its greenspace more fragmented, which usually accompanied by the loss of forest dependent species from those sites (Pell and Jones, 2015). These results offer further support for forest birds' preference for terrestrial habitat patches near waterbody patches, though the specific ecological mechanism still needs more definite evidence from study designs such as satellite tracking and trajectory modeling.

Nonetheless, we do not deny the importance of local characteristics for urban bird diversity, which have been well-examined in existing studies, including the plant structure, human disturbance, and environmental noise (Belaire et al., 2014; Imai and Nakashizuka, 2010; Melles et al., 2003). Given global trends in urban greenspace homogenization in their structure and management (Aronson et al., 2017), it is of great significance to create/maintain urban wetlands/waterbodies based on our results, both within and nearby green patches, for the purposes of avian ecology and biodiversity conservation (Marzluff and Ewing, 2001). This management implication is consistent with existing research suggesting that the focus of wetland conservation planning needs to expand from the site scale to the landscape scale, so to ensure that connections within the regional wetland pattern is accounted for (Whited et al., 2000). Additionally, our results showed that the contribution of food-providing plants is negligible for both species richness (appearance) and abundance (occupancy) of forest birds, indicating that food resource availability is not a limiting factor for current avian communities.

The current study found results consistent with those in Callaghan et al. (2021) on the continental scale, which, based on a meta-analysis

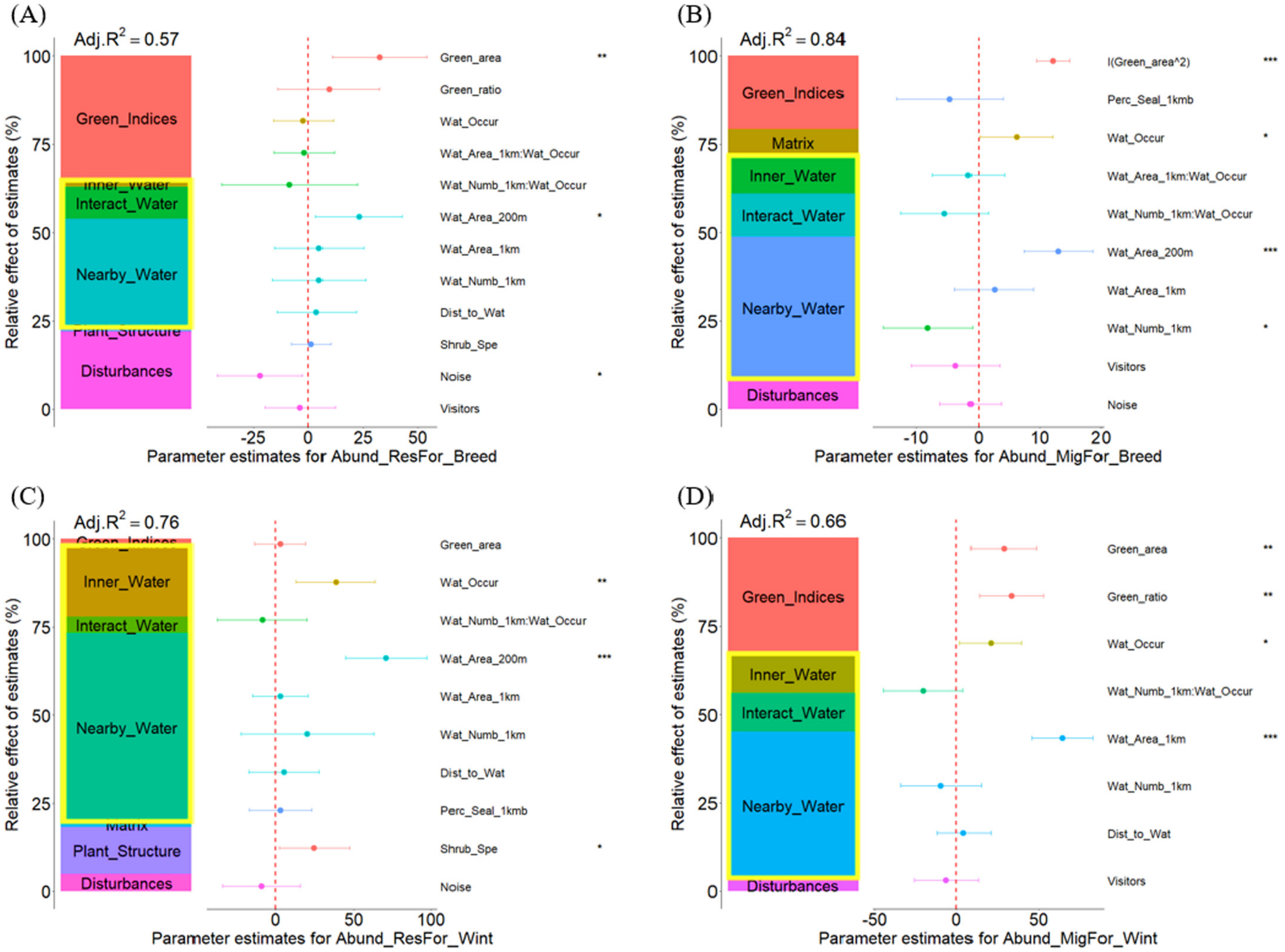

Fig. 5. Relative effects of multiple predictors on species abundance of resident (breeding season: A; wintering season: C) and migrant (breeding season: B; wintering season: D) forest birds.

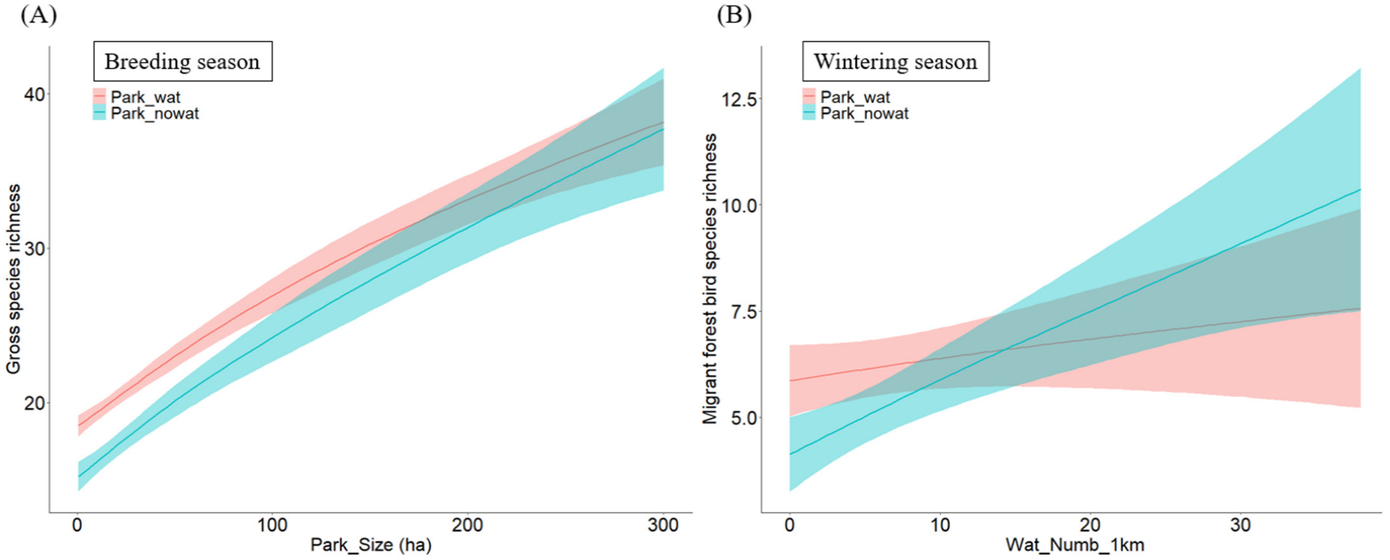

Fig. 6. Predicted changes in gross species richness (A) and migrant forest bird species richness (B) with increasing park size or number of waterbody patches within the 1 km radius buffer region under different situations (characterized by the occurrence of waterbodies in parks). The shaded areas show the 95% confidence interval for each trend line fixed with the "gam" method. "Park_wat" represents for the situation that waterbody patches occurred within all parks, "Park_nowat" represents for the situation that none of the studied parks was with waterbody.

with 1581 cities, found a significant relationship between the proportion of water-cover within a city and the residual species richness (Callaghan et al., 2021). We thus suggest that avian diversity within highly urbanized areas could be conserved more efficiently if greater attention to the size and distribution of waterbodies in parks and surrounding neighborhoods were paid by stake-holders and policy makers.

5. Conclusion

We found that water-related indices own a significant explanatory ability for the variances in different bird guilds' community structure, especially for forest birds which do not show obvious dependence on aquatic habitats. Additionally, it's noteworthy that landscape-level water-related indices had generally stronger effects than local habitat characteristics. This study offers a new understanding on the factors influencing avian communities residing urban habitats, with valuable implications for gross urban planning.

CRediT authorship contribution statement

SX, JM, YS, YW, FL, and ZO contributed to study design, SX, YS, YW, and NM contributed to field data collection, SX and CG contributed to statistical analyses. All authors together wrote the first draft of the manuscript, which TW, FL, CX, YZ, and ZO critically and substantially edited. All authors checked and approved the final manuscript.

Declaration of competing interest

The authors of this study declare no competing interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.150430.

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