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Original Research

MaxEnt Modeling for Bird Habitat Preference and Ecological Restoration: A Case Study of Shanghai, China

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Abstract

With the acceleration of urbanization, urban space continues to expand, inevitably leading to the fragmentation of urban habitats and seriously damaging urban biodiversity. In this process, birds, as indicator species that are extremely sensitive to changes in the ecological environment, are experiencing shrinking habitats, and their survival conditions are precarious. Focusing on Shanghai as the study area, bird distribution data were integrated with environmental factors. Through the application of the ecological niche modeling approach, MaxEnt and Morphological Spatial Pattern Analysis (MSPA), precise identification and analysis of bird habitat distribution patterns were achieved using ArcGIS 10.8. Key findings indicate that precipitation in the wettest month, NDVI, and FVC were primary factors influencing bird habitat selection. Raptor and aquatic bird habitats clustered sparsely in northern Chongming and western Dianshan Lake, while songbird habitats were more homogeneous, concentrating within key ecological patches. MSPA-derived ecological sources in Shanghai showed macroscopic spatial alignment with bird habitats, but local correspondence was limited, revealing significant spatial heterogeneity in habitat distributions. This study represents an innovative departure from traditional single-habitat preference research by investigating habitat preferences across multiple bird species with diverse ecological habits. It provides a scientifically quantifiable basis for urban ecological planning and wildlife conservation.

Keywords: MaxEnt model, bird habitat, biodiversity, ecological sources

Introduction

Rapid urbanization and massive infrastructure construction have posed huge threats to the ecological environment and species diversity [1]. The Global Biodiversity and Ecosystem Services Assessment Report pointed out that the natural decline and species extinction are accelerating globally [2]. Wildlife habitats are vital areas for the survival, reproduction, and population development of organisms [3]. The distribution, areas, and quality of habitats can directly affect wildlife populations and survival rates.

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The degradation of ecological habitats is the most significant threat to endangered species. In high-density urban areas, the identification of suitable habitats and their characteristics is an essential target for biodiversity maintenance [4-6]. Birds, as habitat-sensitive groups, are threatened in terms of their habitat status and population size. A comprehensive assessment of net population changes in North America reveals across-the-board declines since 1970 [7]. Climate change has also been proven to contribute to the decline of bird habitats and reduce their suitability [8]. Loss of bird habitats can, in turn, have negative impacts on ecological functions and ecological services, further reducing the quality of urban ecological habitats [9].

Various countries and organizations have issued policies and guidelines for wild bird protection, especially for ecologically sensitive species. The European Union promulgated the Birds and Habitats Directives, covering birds, their eggs, nests, and habitats, aiming to conserve all wild birds by setting out rules for their protection, management, and control [10]. At the 15th Conference of the Parties to the UN Convention on Biological Diversity in 2022, the Kunming-Montreal Global Biodiversity Framework (GBF) was adopted as a guideline for sustaining biodiversity and nurturing a healthy relationship between people and nature [11]. Target 12 in the GBF aims to improve biodiversity through expanding and connecting urban green and blue spaces [12]. In addition to the "Wildlife Protection Act", the Chinese government has issued the "National Bird Migration Corridor Protection Action Plan (2021-2035)" and promised to place 90% of important habitats along bird migration routes under effective protection by 2030 [13].

The research field of urban bird ecology has increasingly employed multifaceted approaches to assess colonization patterns, population trends, and habitat preferences of birds within cities. The colonization of urban areas by wild species has become a widespread phenomenon. Grünwald et al. investigated bird populations in urban areas from ecological and evolutionary perspectives to detect the long-term population trends of organisms [14]. Cooper et al. predicted the wild bird communities in urban areas through a species-habitat model to guide the biodiversity-friendly urban design [15]. A total of 55 common bird species were included in the prediction and compared across five scenarios to find the best solution for bird diversity depending upon the biophysical context of each planned development. Zúñiga-Vega et al. used multiple-season occupancy models to find the habitat traits that promote migratory birds' presence in an urban reserve. They revealed that the heterogeneity of urban green areas could attract migrating birds [16]. Leveau has revealed that bird richness has a positive relationship with habitat diversity and primary productivity under the species-energy perspective. The variety of vegetation has been proven to increase bird richness in urban-rural gradients [17]. However, there is still a lack of research on the spatial distribution patterns of birds and habitat hotspots. The application of ecological niche models can effectively fill this research gap.

In recent years, methods for quantitatively assessing the ecological habitats of wild birds and the carrying capacity of ecosystems have also been widely used. Species distribution models (SDMs), Genetic Algorithm for Rule Sets (GARP), Boosted Regression Trees (BRT), and Maximum Entropy (MaxEnt) have gained great popularity due to their high suitability in mapping wildlife habitats [18-20]. Due to its high efficiency, even with insufficient sample data, the MaxEnt method stands out in the identification of bird habitats as one of the most vital tools for species habitat identification [21, 22]. The Maximum Entropy Model was first proposed by Wagensberg and Valls in 1987 and applied in the fields of ecological and environmental research and biodiversity conservation [23]. They revealed that biological adaptability could be analyzed using Maximum Entropy formalism in non-interacting systems, which was extended to the biomass statistical structures of populations exhibiting internal interactions. Then, Brierley et al. optimized the MaxEnt model to infer species density and map stock distribution from acoustic line-transect data [24]. To date, the MaxEnt model has been widely used in habitat management and habitat identification in increasingly urbanized environments [25], urban waterlogging indicators and risk assessment [26], suitable habitats under different climatic conditions [27], as well as cropland development potential [28].

Shanghai is located at the mouth of the Yangtze River Delta, an important migratory corridor for birds in the Asia-Pacific region. Meanwhile, it is also a high-density urban area with a population of 25 million. The construction of the Shanghai urban green space system has become a powerful guarantee for facilitating biodiversity conservation and meeting the recreational needs of citizens [29]. However, habitat fragmentation, high levels of human disturbance, and unsuitable vegetation communities result in low bird biodiversity in Shanghai. It is necessary to distinguish the relationship between bird populations and green space characteristics through habitat identification at the city scale. This research aims to explore the current distribution of bird habitats and the driving factors in Shanghai using the MaxEnt model, and then to optimize the structure, function, and vegetation community of urban green space for improving biodiversity.

Three vital issues are focused as follows: 1) Spatial characteristics of bird habitat distribution in Shanghai green space system; 2) Which factors affect bird habitat selection? 3) How can existing urban bird habitats be effectively repaired? This study can explain the rules of birds' responses to different urban green spaces and provide recommendations to conserve biodiversity through urban green space optimization.

Existing research has predominantly concentrated on the preservation of urban avian diversity and vegetation types. Nevertheless, there remains a dearth of research regarding the comprehensive habitat preferences of multiple ecological groups in megacities and the quantitative correspondence with structural ecological spaces. This study transcends the traditional research paradigm of ecological habitat studies, which typically center on single species or single methods. Instead, it contrasts the habitat preferences of diverse avian species (raptors, songbirds, and aquatic birds) and analyzes the spatial overlap between their habitats and ecological sources, thereby enhancing habitat diversity and stability in urban ecosystems.

Materials and Methods

The research framework for identifying bird habitat preferences and developing conservation strategies comprises the following steps (Fig. 1): The distribution

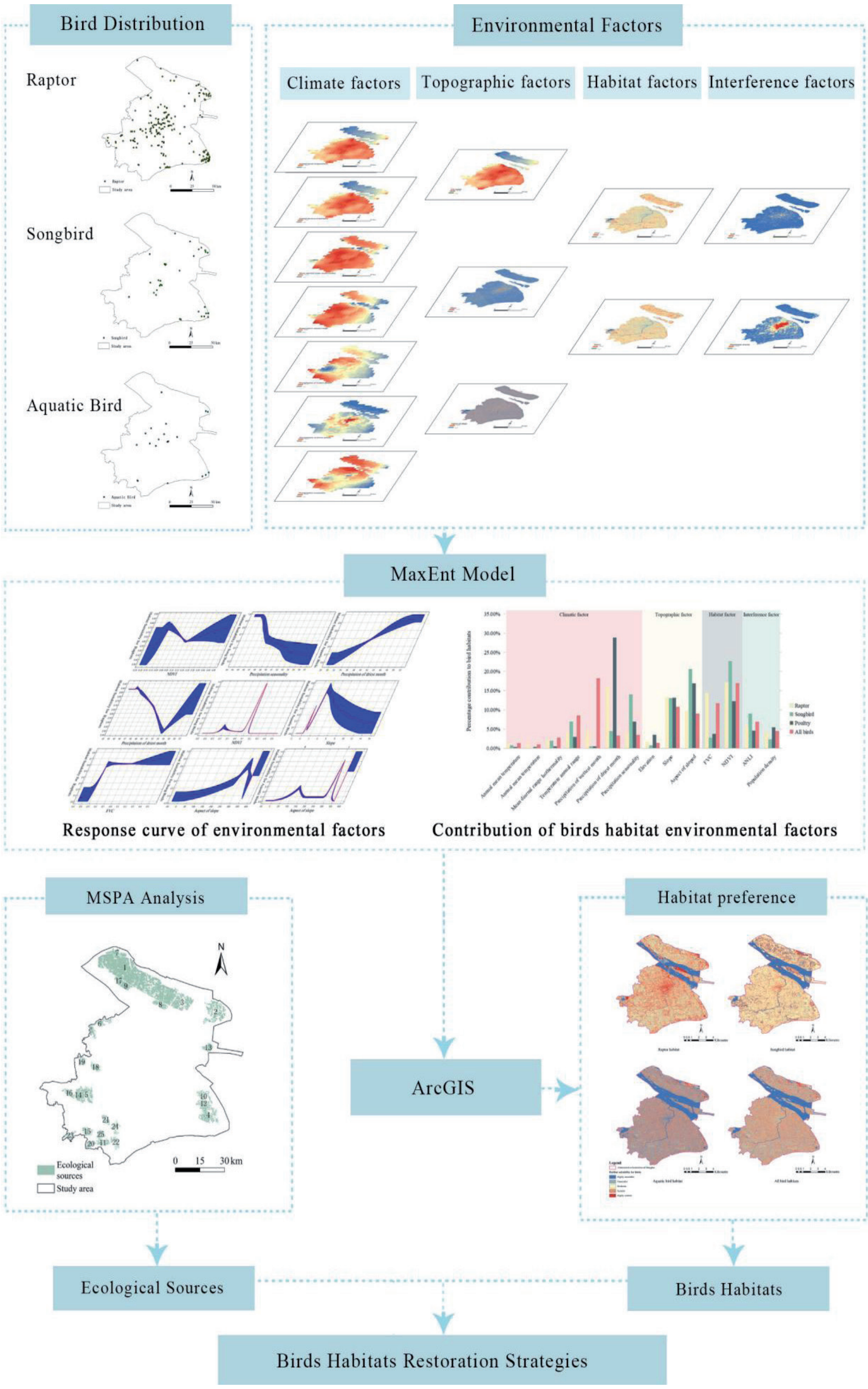

Fig. 1. Research framework.

points of 19 bird species in Shanghai were determined using data from China's National List of Wildlife Under Key Protection (KPSWL). Four categories encompassing 14 influencing factors of bird habitat preference were summarized, and habitat suitability was assessed using the MaxEnt model. In conjunction with Morphological Spatial Pattern Analysis (MSPA), a comprehensive analysis of Shanghai's ecological source areas and bird habitats was conducted, ultimately leading to the formulation of habitat restoration strategies.

Study Area

The research scope is defined within the administrative division of Shanghai. Shanghai is a major economic and cultural hub in eastern China, which sustains a population of 24 million and ranks among the highest in per capita GDP nationally. Its strategic location at the Yangtze River estuary confers unique ecological characteristics, positioning it as a critical stopover site for migratory birds within the East Asian-Australasian Flyway (EAAF). The stark ecological contrast between densely urbanized areas and vital bird habitats on Chongming Island presents significant conservation challenges (Fig. 2).

Data Source and Processing

Bird Data Collection

The study focused on bird species listed in China's National List of Wildlife Under Key Protection (KPSWL). Occurrence records were obtained from two complementary sources: (1) the China Bird Records Center (http://www.birdreport.cn/) for species identification and expert-verified records, and (2) the Global Biodiversity Information Facility (GBIF, https://www.gbif.org/) for spatial occurrence data. After quality control and deduplication, a total of 2,238 occurrence records from 2020 to 2024 were retained, covering 19 protected species in Shanghai (Table 1).

The bird distribution data were collected from the Global Biodiversity Information Facility (GBIF) website (https://www.gbif.org/), and 2,238 bird distribution recording stations in Shanghai between 2020 and 2024 were chosen. Birds are classified into three categories based on their habits: aquatic birds, raptors, and songbirds, with raptors accounting for the majority of the total. It should be noted that this study did not perform spatial dilution processing on the occurrence point data. Although spatial dilution is widely used to reduce sampling bias, the latest research [30, 31] indicates that for species with limited sample sizes, the data loss caused by spatial dilution may exceed the benefit of reducing bias. It has been found that for rare species, retaining all data is often superior to spatial dilution treatment [32]. Given that the number of records for some species in this study is relatively small, we chose to retain all high-quality occurrence records to maximize the availability of the data.

Furthermore, considering that the number of records for some species is relatively small (<30), we adopted a group-level modeling approach by jointly analyzing multiple species and utilizing the ecological similarities among species within the same group to improve the prediction accuracy for data-scarce species [33, 34]. Specifically, species with abundant data (≥30 records) were also modeled separately for comparison, whereas species with fewer records (<30 records) primarily relied on prediction results derived from the group-level models.

Environmental Factor Data

Combined with the climate and bird habitat characteristics of Shanghai, this study selects a total of 14 environmental factor indicators in the four categories

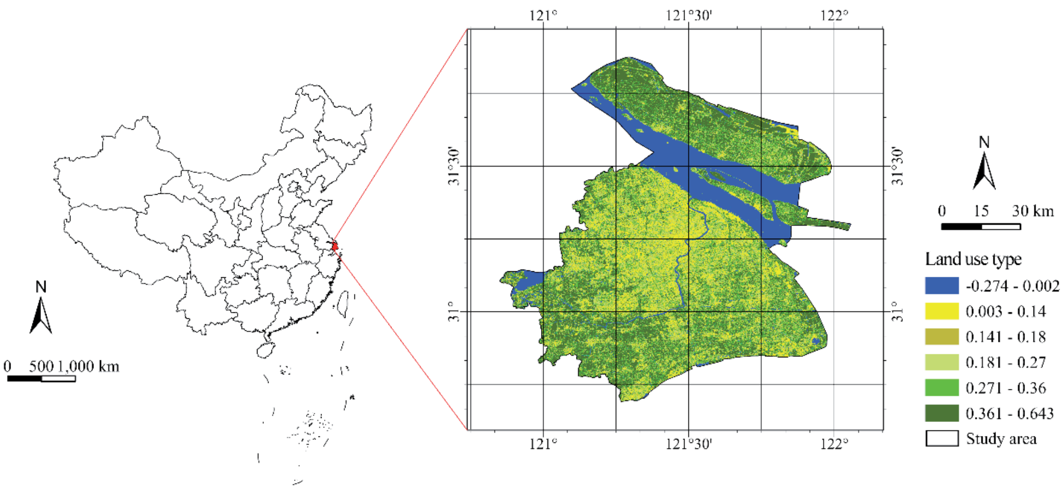

Fig. 2. Geographical location and land use of Shanghai.

Table 1. Experimental subject species of birds.

English name	Latin name	Classification	Record quantity
Mandarin Duck	*Aix galericulata*	Aquatic bird	88
Black-winged Kite	*Elanus caeruleus*	Raptor	51
Crested Honey Buzzard	*Pernis ptilorhynchus*	Raptor	78
Accipiter Trivirgatus	*Accipiter trivirgatus*	Raptor	204
Accipiter Soloensis	*Accipiter soloensis*	Raptor	26
Japanese Sparrowhawk	*Accipiter gularis*	Raptor	31
Besra	*Accipiter virgatus*	Raptor	1
Accipiter Nisu	*Accipiter nisus*	Raptor	62
Sparrowhawk	*Accipiter gentilis*	Raptor	28
Grey-faced Buzzard	*Butastur indicus*	Raptor	38
Eastern Buzzard	*Buteo japonicus*	Raptor	206
Short-eared Owl	*Asio flammeus*	Raptor	8
Common Kestrel	*Falco tinnunculus*	Raptor	861
European Hobby	*Falco subbuteo*	Raptor	37
Peregrine Falcon	*Falco peregrinus*	Raptor	264
Lark	*Alauda arvensis*	Songbird	230
Thrush	*Garrulax canorus*	Songbird	11
Siberian Rubythroat	*Calliope calliope*	Songbird	143
Yellow-breasted Bunting	*Emberiza aureola*	Songbird	23

of climate factor, topographic factor, habitat factor, and interference factor within the study scope of Shanghai (Table 2).

Although bird occurrence records span 2020-2024, while several environmental predictors (DEM, NDVI, FVC, nighttime lights) are derived from 2024 data, this temporal configuration is justified for two reasons. First, topographic variables (elevation, slope, aspect) remain essentially stable across the study period, making the 2024 DEM data representative of the entire timeframe.

Table 2. Environmental factor index for the Shanghai study scope.

Classification	Environmental factor	Data source
Climatic factor	Annual mean temperature Annual mean precipitation Mean diurnal range; Isothermality Temperature annual range Precipitation of the wettest month Precipitation of the driest month Precipitation seasonality	Downloaded a selection of historical climate data for 2020-2024 from the World Climate website (https://worldclim.org/)
Topographic factor	Elevation Slope Aspect of slope	Downloaded 2024 30 m DEM data from the Geospatial Data Cloud (https://www.gscloud.cn/). Conduct slope analysis and slope aspect analysis of downloaded DEM data using ArcGIS 10.8
Habitat factor	FVC NDVI	Downloaded the 2024 Landsat 8 data from the Geospatial Data Cloud (https://www.gscloud.cn/) and analyzed using ArcGIS 10.8
Interference factor	Average Nighttime Light Index (ANLI) Population density	Downloaded the night light data in March 2024 from NOAA (https://www.ngdc.noaa.gov/eog/viirs/download_ut_mos.html) Downloaded data from the WorldPop website (https://www.worldpop.org).

Second, habitat-related variables (vegetation indices and nighttime lights) from 2024 capture the current landscape configuration that has remained relatively consistent during 2020-2024 in Shanghai's established urban-rural gradient, with no major land use changes affecting bird habitat distribution patterns during this period. Climate variables appropriately span the full 2020-2024 period to match the temporal range of occurrence data.

Bird Habitat Analysis

Calculation of Normalized Difference Vegetation Index (NDVI)

The normalized difference vegetation index serves primarily as an environmental element in this investigation. The Raster Calculator in ArcGIS 10.8 is used to calculate Bands 4 and 5 of Landsat 8 images (Formula 1), yielding Shanghai's NDVI [35].

$$NDVI = \frac{NIR-RED}{NIR+RED} \quad (1)$$

Where NDVI is the normalized difference vegetation index; NIR is the reflectance of the infrared band, and in Landsat 8 images, it is the raster image of Band 5. RED is the red band, and in Landsat 8 images, it corresponds to the raster image of Band 4.

By reclassifying NDVI (Table 3), the land cover categories of Shanghai were determined. Simultaneously, to study water source distance and interference distance, which are environmental factors within the study scope of the green space system in Shanghai's Minhang District, the NDVI data were screened using the ArcGIS Raster Calculator, and Shanghai's water source and built-up area data were obtained.

Calculation of Fractional Vegetation Cover (FVC)

By leveraging the grid computation for calculating the normalized difference vegetation index (NDVI), the environmental factors of vegetation coverage can be estimated. The formula is presented as follows:

Table 3. NDVI reclassification boundary value [36].

Area type	Dividing value
Water	-0.19-0.015
Built-up area	0.015-0.14
Bare land	0.14-0.18
Grass	0.18-0.27
Sparse vegetation	0.27-0.36
Dense vegetation	0.36-0.44

$$FVC = \frac{NDVI-NDVI_{min}}{NDVI_{max}-NDVI_{min}} \quad (2)$$

Where FVC refers to vegetation coverage; *NDVI* represents the normalized difference vegetation index of the calculated pixel; $NDVI_{max}$ denotes the normalized difference vegetation index of pure plant elements; $NDVI_{min}$ indicates the normalized difference vegetation index of a completely unvegetated pixel.

Since the process of remote sensing data collection and transmission is inevitably disturbed by noise and there are certain quality errors, the maximum and minimum values of $NDVI_{max}$ and $NDVI_{min}$ are typically taken within a certain confidence range. The confidence level is mainly determined based on the actual situation of the image. Generally, the values of $NDVI_{max}$ and $NDVI_{min}$ are 95% and 5%, respectively [37]. Using ArcGIS, the NDVI value of Shanghai is reclassified into 20 divisions. $NDVI_{max}$ is 0.21, and $NDVI_{min}$ is -0.12. Thus, the vegetation coverage of Shanghai was obtained.

MaxEnt Model Construction

The maximum entropy model is capable of simulating species distribution when the system attains maximum entropy. In this research, MaxEnt 3.4.1 was employed to analyze the distribution points of birds and environmental factors, thereby obtaining the distribution of bird habitats and the contribution of each environmental factor. The random test percentage was set at 25%, and the number of repetitions was set to 10 in the MaxEnt software.

Model Integration Analysis

The results derived from the MaxEnt model were input into ArcGIS for reclassification. The natural breaks approach was employed to categorize the habitat grades of various types of birds into five classes based on habitat suitability: highly suitable, suitable, moderate, unsuitable, and highly unsuitable. The habitats of different bird groups were superimposed and analyzed, and the distribution pattern of bird habitats within Shanghai was obtained.

Results

Environmental Factor Analysis

The model results reveal that the average AUC value of the three ecological groups of birds is 0.873, signifying the high accuracy of the model predictions. In a complete analysis of all bird data (Fig. 3), we found that precipitation in the wettest month contributed most significantly to model prediction, accounting for 18.30%. It was followed by NDVI (16.99%) and FVC (11.71%). In contrast, average annual precipitation contributed the least to model prediction, at 0.97%.

Further examination of birds from other ecological groups reveals that the same environmental conditions have considerable variations in their impact on the habitats of different bird groups. For example, whereas precipitation in the wettest month has the biggest impact on the habitats of all birds, its contribution is lower for songbirds and aquatic birds than that of parameters such as annual mean temperature and slope. However, for raptors, NDVI is the most important environmental element, followed by precipitation of the driest month and FVC. Furthermore, the primary environmental elements that influence bird habitats in various ecological groups differ. Songbird habitat was similarly influenced by NDVI and slope direction. Unlike other groups, songbirds have less restricted habitats due to population aggregation. For aquatic birds, precipitation of the driest month had the greatest influence, followed by slope direction.

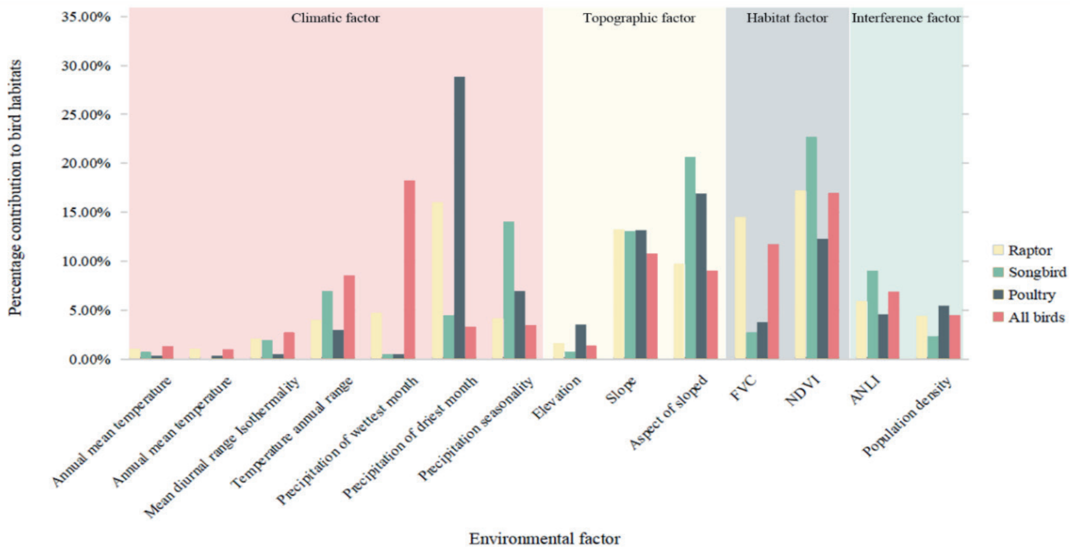

Fig. 3. Percentage contribution of bird habitat environmental factors in Shanghai.

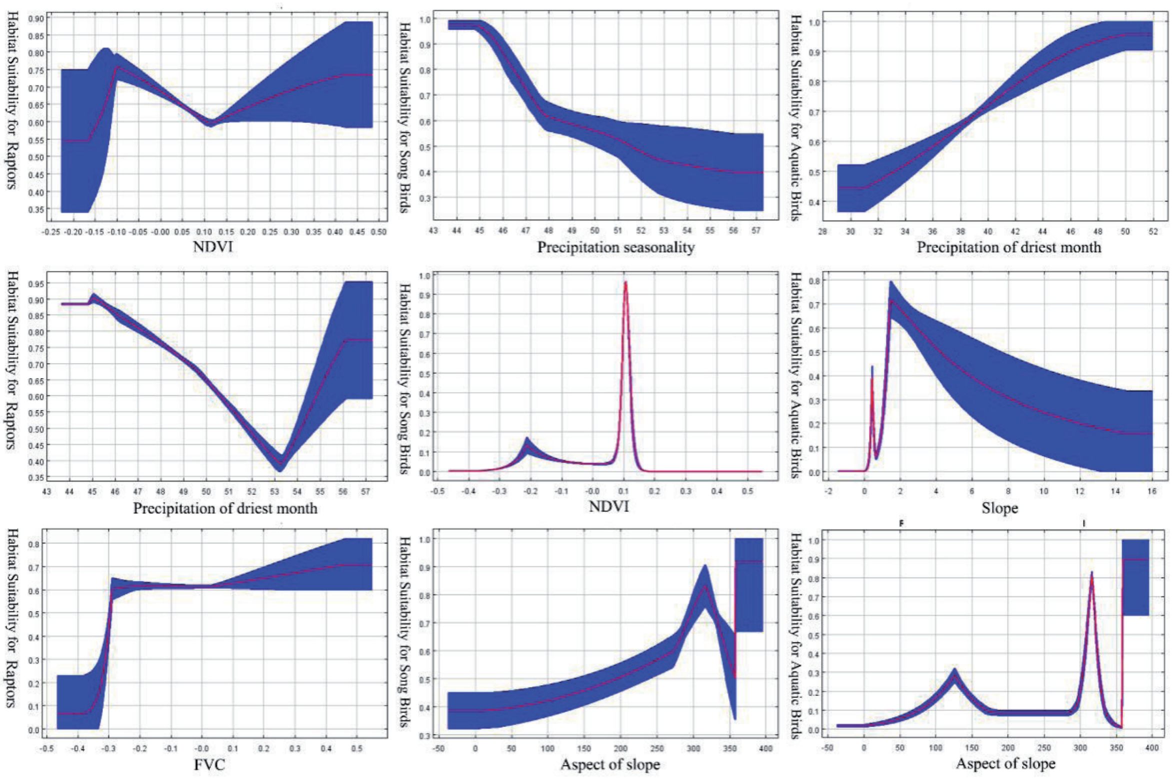

Fig. 4. Response curves of environmental factors to bird habitat distribution in Shanghai.

The three factors that have the greatest impact on the three types of birds were further analyzed with response curves (Fig. 4). According to the factor of NDVI, raptors had the highest habitat suitability at 0.45, while songbirds had the highest at 0.1, indicating that raptors have a stronger preference for vegetation than songbirds. It was also discovered that the slopes of the two curves differed, with songbird habitat being most susceptible to changes in NDVI. For raptors, habitat suitability related to precipitation in the driest month reached its highest value at 44 mm/month and decreased to its lowest value at 53 mm/month, whereas habitat suitability of aquatic birds showed a strong positive correlation with precipitation in the driest month. These findings suggest that aquatic bird habitats require a significant level of precipitation throughout the dry season. FVC peaked at 45% in terms of raptor habitat suitability. After reaching a peak value of 1.7° slope, the environmental factor slope was found to be negatively associated with habitat suitability for aquatic birds. For the factor of slope aspect, the habitat suitability of songbirds reached a turning point at 320°, whereas that of aquatic birds showed two turning points, one at 125° and the other at 320°. This indicates that aquatic birds are more sensitive to slope aspect and tend to face illuminated slopes from the southeast to the northwest, while songbirds have a higher tolerance for slope aspect and only avoid directions from the northwest to the north.

Spatial Distribution Analysis of Bird Habitat

The classification outcomes presented by ArcGIS indicate (Fig. 5) that the spatial distribution of bird habitats in Shanghai is predominantly concentrated in

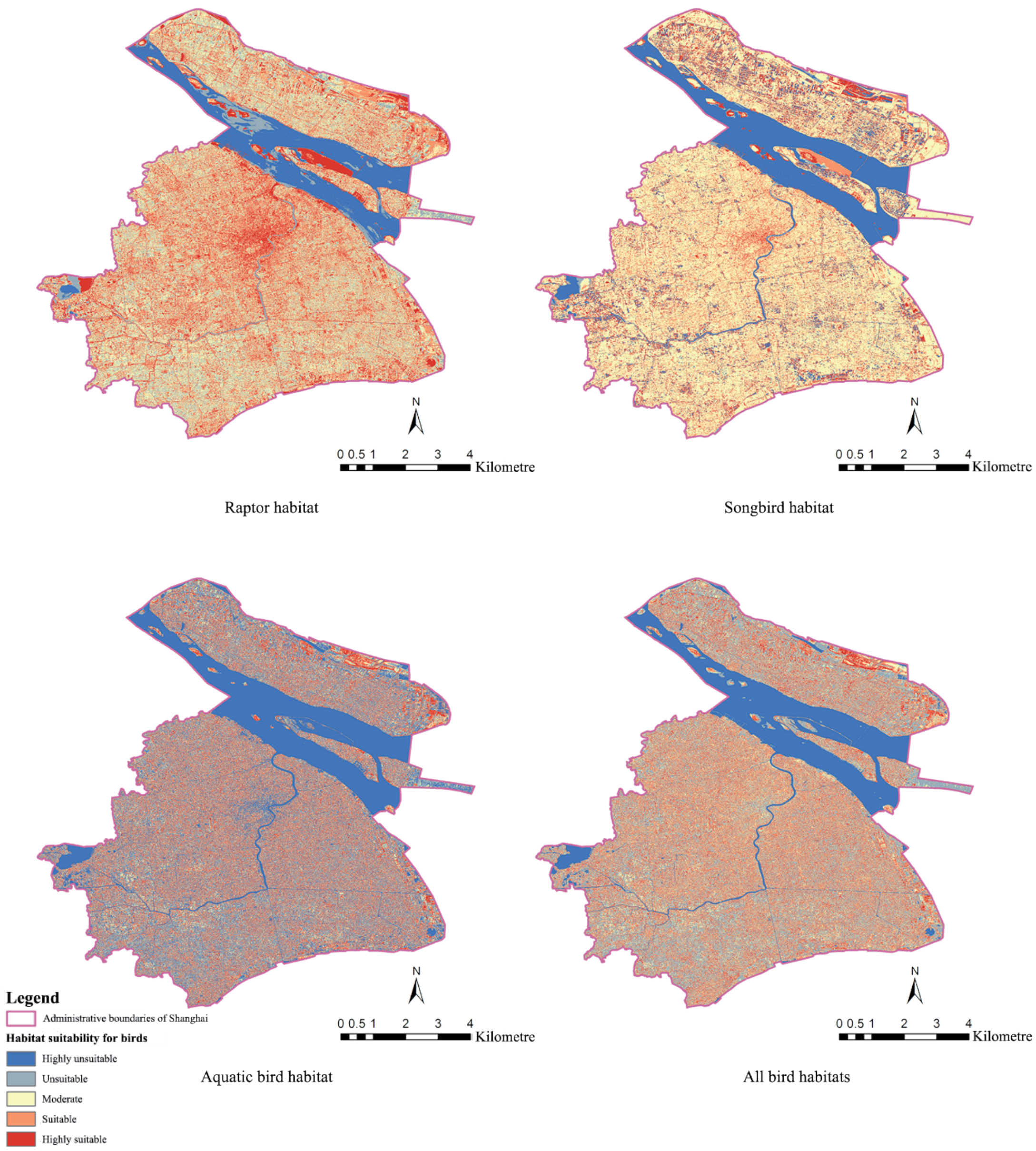

Fig. 5. Habitat distribution map of birds in the Shanghai study area.

the vicinity of Dongtan Wetland in the northeastern coastal area of Chongming District, around Bay Forest Park in the southern section of Fengxian District, and the eastern coastal area of Pudong New District. In contrast, the distribution of highly suitable habitats in inland regions is relatively limited. At the citywide scale, Table 4 provides additional information by showing the limited extent of optimal habitats: highly suitable habitats across all bird groups account for only 13.76% of the total study area, while suitable habitats comprise 19.13%. These results suggest that optimal habitat conditions are spatially limited and are primarily associated with coastal and estuarine environments.

When further divided based on the ecological groups of birds, the habitat range of aquatic birds is relatively fragmented, mainly concentrated in the eastern coastal area of Pudong District and the northeastern coastal area of Chongming Island, and seldom forms concentrated distributions in other regions. According to Table 4, aquatic bird habitats account for 15.53% of highly suitable habitats and 14.91% of suitable habitats, reflecting a strong dependence on coastal wetlands and water-dominated environments with specific hydrological and ecological conditions. However, raptor habitat is more extensive. From a quantitative perspective, raptors exhibit the largest proportion of suitable habitats among the three groups, with 28.07% classified as suitable and 13.98% as highly suitable, suggesting that while raptors can occupy a wide range of environments, optimal habitats remain unevenly distributed. In addition to the eastern part of Pudong District and the northeastern part of Chongming District, raptors are also prominently distributed from the confluence of the Huangpu River and the Yangtze River in Baoshan District to the Binjiang section of Yangpu District, and extend into inland areas. Additionally, concentrated distributions have emerged in the northern coastal area of Hengsha Island and the eastern part of Dianshan Lake, but no obvious diffusion tendency has been observed. Regarding songbird habitat, it comprises 14.14% highly suitable areas and 7.59% suitable areas (Table 4). This may be associated with the dependence of songbirds on fine-scale habitat features, such as vegetation structure and habitat connectivity, which are unevenly preserved within highly urbanized areas. There is a notable concentrated distribution in the Yangpu Binjiang section of the Huangpu River, which spreads westward to inland areas. Simultaneously, some distribution areas can also be observed in the northern part of Hengsha Island.

Discussion

Dominant Factors of Bird Habitat in Urban Areas

The rapid expansion of metropolitan areas, characterized by alterations in land surface properties and human settlement patterns, constitutes a significant factor contributing to ecological fragmentation [38, 39]. Particularly within high-density urban areas, these environmental modifications lead to the degradation of birds' habitats and subsequent population declines among bird species. This, in turn, negatively impacts urban biodiversity and ecosystem stability [40]. Conventional approaches, such as ecological network analysis and green system spatial structure analysis, often rely on single data sources and simplified models. These methods usually overlook the variations in habitat preferences among different species. Such oversight may hinder the effective identification of species-specific habitat ranges and spatial distribution patterns. Protecting bird habitats within cities has emerged as a common goal in ecological conservation [41]. However, current research exhibits a deficiency in the quantitative assessment of the habitat preferences of specific species. Consequently, site-specific conservation strategies at the local scale remain scarce.

This study integrates MaxEnt prediction of bird species spatial distribution to propose targeted research on species-specific habitat preferences and the contribution of associated environmental factors. Based on the identified preferences of different bird species, we developed a suite of precise conservation strategies. This approach effectively prevents the omission of biodiversity-suitable habitat patches resulting from

Table 4. Statistics of suitable habitat area and proportion for different bird groups.

Habitat Type	Suitability Level	Area (km²)	Proportion (%)
Raptor habitat	Highly suitable	1,126.22	13.98
	Suitable	2,260.89	28.07
Songbird habitat	Highly suitable	1,139.43	14.14
	Suitable	611.68	7.59
Aquatic bird habitat	Highly suitable	1,251.15	15.53
	Suitable	1,200.85	14.91
All bird habitats	Highly suitable	1,108.23	13.76
	Suitable	1,540.94	19.13

technical or methodological limitations, enhances identification accuracy, and better aligns with the practical demands of biodiversity conservation.

Habitat Differences Among Bird Species

As the core of the urban ecosystem, ecological sources provide stable and high-quality habitats for birds [42]. By applying the Morphological Spatial Pattern Analysis (MSPA) method, the ecological source areas in Shanghai were identified and extracted. In this study, a total of 25 ecological patches with an area greater than 10 km² were selected as ecological sources. These ecological sources are mainly distributed in the urban fringe areas, such as Chongming Island. The total area of the ecological sources is 725.76 km², accounting for 11.45% of Shanghai's total area. Among all the ecological sources, the largest one is distributed on Chongming Island, covering an area of 424.60 km², which accounts for 6.70% of Shanghai's total area.

The kernel density map of suitable habitats for the three bird groups was superimposed on the ecological source areas in Shanghai. Comparing the current distribution of birds and protected areas, we find that the suitable areas and ecological sources do not match very well. As shown in Fig. 6 and quantified in Table 5, there are different spatial overlap characteristics between ecological sources and different bird habitats. Among the three bird groups, the habitat distribution of raptors is highly negatively correlated with human population density, and raptors are more dependent on water systems than aquatic birds. Only 6.27% of highly suitable raptor habitats and 11.22% of suitable raptor habitats fall within ecological source areas, indicating a relatively low level of spatial overlap. Their habitat is highly concentrated in the Yangtze River Estuary in northern Shanghai and Dianshan Lake in western Shanghai. In addition, sparsely populated green areas in southwestern Shanghai are also preferred habitats for raptors. Surprisingly, the habitat distribution of songbirds is highly concentrated on Changxing Island and in the city center area. Table 5 shows that 17.05% of highly suitable songbird habitats are located within ecological source areas, whereas only 5.42% of suitable habitats overlap with these areas. However, Adams et al. have found that songbird habitat is not related to whether it is located in the urban center, but is closely related to vegetation characteristics such as species turnover, shrub density, canopy height, and tree basal area [43]. The preferred habitats of aquatic birds are located at the mouth of the Yangtze River, along the northern coast of Chongming Island, and in the Dianshan Lake area. Unlike raptors, aquatic birds are distributed in smaller numbers in urban areas and have no obvious regional preference. 12.61% of highly suitable aquatic bird habitats and 12.81% of suitable habitats are located within ecological source areas. This pattern reflects the strong dependence of aquatic birds on water bodies and wetlands, which partially coincide with, but are not fully encompassed by, existing ecological source delineations. Overall, the distribution of the three bird groups in Shanghai is relatively scattered, reflecting the obvious niche differentiation in the habitat selection of different birds, forming a unique response mechanism to Shanghai's diverse ecological environment.

According to the studies of Cai et al. and Xu et al., birds tend to avoid urban centers affected by the heat island effect and instead choose suburban areas with lower temperatures, which echo the conclusions drawn in this study [44, 45]. The above conclusions also confirm that bird habitat selection tends to occur in suburban areas with larger patches and greater continuity.

Implications for Bird Protection in Shanghai

As a critical node along the East Asian-Australasian Flyway, Shanghai has integrated wild bird conservation into the core agenda of its urban ecological development. At the policy level, Shanghai strictly implements the Wildlife Protection Law of the People's Republic of China and the Shanghai Municipal Regulations on Wildlife Protection. These regulations designate 198 bird species, including the Chinese Merganser and Black-faced

Table 5. Area and proportion of suitable habitat for different bird groups within ecological source areas.

Bird Type	Suitability Level	Area (km²)	Area within Ecological Source Areas (km²)	Proportion within Ecological Source Areas (%)
Raptors	Highly suitable	1,126.22	70.59	6.27
	Suitable	2,260.89	253.66	11.22
Songbirds	Highly suitable	1,139.43	194.32	17.05
	Suitable	611.68	33.13	5.42
Aquatic birds	Highly suitable	1,251.15	157.78	12.61
	Suitable	1,200.85	153.85	12.81
All birds	Highly suitable	1,108.23	166.27	15.00
	Suitable	1,540.94	151.52	9.83

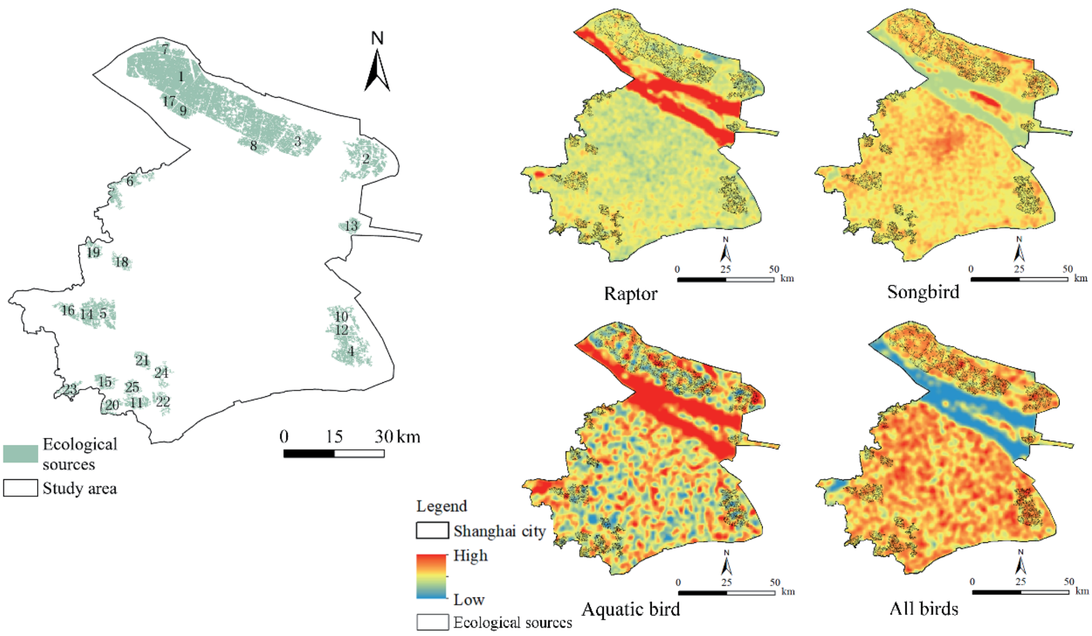

Fig. 6. Spatial overlap of birds' preferred habitats and ecological sources.

Spoonbill, on the municipal-level key protection list. Furthermore, internationally significant wetlands such as Chongming Dongtan and Nanhui Dongtan have been legally designated as no-hunting zones. Shanghai has systematically restored bird habitats through "ecological corridors" and "wetland restoration" projects. However, the diverse array of protected area types established by different jurisdictional authorities for specific objectives, coupled with an unclear delineation of responsibilities among relevant agencies, creates significant challenges for government accountability mechanisms.

At the spatial level, protected areas and birds' preferred habitats exhibit a mismatch. By comparing the current distribution of birds' preferred habitats and ecological sources, we can observe that there is macroscopic spatial consistency between bird habitats and the distribution of ecological sources, but local matching is not very high. The distribution of ecological sources is very uneven, with large areas located in suburban regions, especially in the northern, eastern, and western parts of Shanghai, but birds' preferred habitats are affected by multiple factors, and there are differences among various bird groups. Raptors tend to choose areas with high vegetation coverage and sparse human habitation in order to avoid predators and facilitate hunting. Their habitats and ecological sources have a certain spatial correlation but do not completely overlap.

Strategy for Bird Protection

Our results provide new recommendations regarding the impact of environmental factors on bird habitats. In high-density urban areas, protecting core habitats should be prioritized. These areas provide essential natural resources, including vegetation, water sources, food, and shelter critical for bird habitats, and serve as key nodes in maintaining urban ecological stability [46]. Furthermore, high-frequency human activities in central urban zones exacerbate ecological network fragmentation. Rigorous assessment is required to evaluate whether large-scale development projects compromise regional ecological security.

To counter severe fragmentation in central urban districts, establishing ecological buffer zones around isolated ecological patches is essential [47]. Connectivity within the ecological network should be enhanced through flexible approaches such as community renewal projects, pocket parks, and street green spaces, thereby broadening ecological corridors and improving the overall quality of bird habitats [48].

For large green spaces in suburban areas, ecological value must be elevated by safeguarding existing resources while strengthening plant community structure and native biodiversity. The strategy involves restoring ecological functions and refining management practices. In severely degraded bird habitat patches, restoration should focus on introducing native bird-foraging plant species [49]. Selecting stress-tolerant, complementary niche native trees enhances carbon sequestration and soil-water conservation, accelerating the transition toward stable climax communities [50].

Additionally, sensitive areas should be seasonally closed during critical bird breeding periods (e.g., in spring) to ensure reproductive security. For endangered species, population dynamics must be monitored using infrared camera traps and soil sensors, enabling data-driven adjustments to conservation management plans [50].

Research Limitations

While this study provides insights into urban bird habitat preferences, several limitations must be acknowledged, which also indicate directions for future research. First, guild-level modeling may obscure interspecific differences; future species-level analyses would offer more precise conservation insights [51]. Second, constrained by data availability, key urban variables such as noise pollution and building morphology were not incorporated, potentially affecting model interpretation in structurally heterogeneous urban environments [52]. Third, the limited temporal scope (2020-2024) may not fully capture long-term distribution dynamics. Future research should integrate higher-resolution urban data, longer time series, and cross-species comparisons to better elucidate the mechanisms driving avian habitat selection within cities.

Conclusions

Exploring the habitat preference characteristics of birds in urban areas is of great significance for protecting wild birds and improving the quality of ecosystem services. This study used the MaxEnt model to analyze 19 specially protected bird species recorded in Shanghai on the official website of the China Bird Records Center. By quantitatively analyzing the habitat preference factors of three major types of birds – raptors, songbirds, and aquatic birds – this study has revealed the following results: 1) Among the 14 factors encompassing climate, topography, habitat, and interference, precipitation during the wettest month, the Normalized Difference Vegetation Index (NDVI), and the Fractional Vegetation Cover (FVC) emerged as the most crucial influencing factors for bird habitat selection. 2) The distribution of the three types of bird habitats exhibits significant spatial heterogeneity. Raptors and aquatic birds tend to inhabit the less-populated northern regions of Chongming Island and the western areas of Dianshan Lake, whereas the spatial distribution of songbird habitats is more uniform, gravitating towards several key ecological patches. 3) Using the Morphological Spatial Pattern Analysis (MSPA) method, ecological sources in Shanghai were extracted. A comprehensive analysis of these ecological sources in conjunction with bird habitats indicated that while there is macroscopic spatial consistency between bird habitats and ecological sources, local matching is still restricted. The novelty of this research lies in its integrated analytical framework encompassing multiple species and groups, which spatially corresponds to the structural ecological space identified by MSPA. This approach offers a quantitative spatial matching strategy that directly supports ecological restoration planning in megacities, enhancing the specificity and applicability of conservation strategies. Based on the aforementioned conclusions, this paper proposes bird habitat protection strategies for diverse scenarios, including urban areas, suburban areas, ecologically degraded areas, and important ecological patches. This study proposes more precise bird habitat preference indicators and corresponding parameters, which provide an important scientific foundation for bird protection and planning in urban areas, ensuring urban biodiversity and ecological stability.

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Conflict of Interest

The authors declare no conflict of interest.

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