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Analysis on the hotspot characteristics of bird diversity distribution along the continental coastline of China

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Global climate change and disturbances from human activities lead to habitat loss and changes in habitat quality, resulting in a reduction in biodiversity. The continental coastline of China distributes some cities with highly developed economies and coastal wetlands with rich biodiversity, and both economic development and biodiversity conservation are important topics. In order to clarify the spatial distribution of bird biodiversity in coastal areas, based on the MaxEnt model and GIS spatial analysis, the distribution data of 488 species of birds and 15 environmental variables were used to simulate the suitable distribution areas of birds, and to analyze the spatial distribution and hotspots of bird biodiversity in coastal areas. The main findings of this study are as follows. (1) A total of 488 species in 249 genera of 21 orders and 81 families of birds were involved in the modeling of coastal areas. The main environmental factors affecting the potential distribution of birds in general are: land use, monthly mean diurnal temperature range, and precipitation of the driest month. (2) High value areas of bird richness are distributed in different locations in the four sea areas: In the Bohai Rim region, they are mainly distributed in the Liaohe Estuary Wetland in Liaoning Province, the vicinity of the Yongdingxin River and Haihe River in Tianjin, the eastern part of Tianjin, and the Yellow River and Yellow River Delta Wetland in Shandong Province; In the coastal area of the Yellow Sea, they are primarily found in Kunyu Mountain National Nature Reserve, Laoshan Provincial Nature Reserve in Shandong Province, and Yancheng Wetland Rare Birds National Nature Reserve in Jiangsu Province; In the coastal areas of the East China Sea, they are mainly found at the mouth of the Yangtze River, at the national nature reserve of Dongtan birds on Chongming Island, along the southeastern coast of Zhejiang Province, near the Min River and along the coast of Quanzhou in Fujian Province; In the coastal areas of the South China Sea, they are mainly distributed in the Pearl River Delta wetlands of Guangdong Province, the southeastern coastal areas of the Guangdong-Hong Kong-Macao Greater Bay Area, and the Shiwanda Mountain National Nature Reserve in Guangxi Province. (3) The spatial trends in the distribution of hotspots of birds of

national priority protection in coastal areas are generally consistent, but more concentrated than the distribution of all birds. (4) After the high-value areas of bird richness were superimposed with protected areas, it was found that the intersecting area accounted for a small proportion of the protected area, and many areas near the inland had low bird richness. Finally, the findings provide references for bird biodiversity conservation and planning in coastal areas.

KEYWORDS

coastal areas of mainland China, bird biodiversity, MaxEnt model, suitable distribution area, nature reserve, species protection

Introduction

The coastal zone is the transitional zone between ocean and land, with complex and diverse geographical environment. It is pregnant with rich biodiversity and is also the region with the most developed social economy. In particular, the intensity of human interference is increasing and coastal wetlands are decreasing (Murray et al., 2022), the impact of climate change is more obvious, so the important habitat of birds in the coastal zone is more seriously threatened in recent years (Debue et al., 2022). Then, biodiversity conservation in coastal areas has attracted more attention from international biodiversity conservation and scientific research. China's coastal areas have many types of coastal zones, estuaries, bays, wetland ecosystems, etc., which are important parts of the flyway of East Asia and Australasia, and also key areas for global biodiversity protection.

The preservation of species habitats is essential for biodiversity conservation. A series of studies on species habitat assessment and suitable habitat identification, including identifying conservation gaps in suitable habitat, adopting conservation measures in suitable habitat areas, limiting human activities and avoiding excessive disturbance, are the main ways to achieve biodiversity conservation goals. Using the habitat suitability model to evaluate the habitat suitability of species, identify the potential distribution areas of species and reveal the possible influencing factors of species changes are the scientific basis of biodiversity conservation (Guisan & Zimmermann, 2000; Gurnell et al., 2002; Peterson, 2006; Peterson et al., 2011; Araújo et al., 2019). According to whether the sample data of species distribution is needed when the model is established, the habitat suitability model can be divided into three types: mechanism model, statistical model and ecological niche model. Ecological niche models are popular, because that they can be modeled by combining environmental variable data with species occurrence point data only, and have good evaluation effect (Phillips et al., 2006; Merow et al., 2013; Radosavljevic & Anderson, 2014; Bai et al., 2022b). Among them, MaxEnt model is easy to operate and has good applicability. Even if he distribution sample data and environmental variable data are insufficient, MaxEnt model has a good prediction effect, too (Elith et al., 2006; Hernandez et al., 2006; Bai et al., 2022a).

As an important part of the East Asian-Australasian flyway, more than 20 species of waterfowl are globally threatened in China's coastal wetlands, and the population of about 100 species of waterfowl exceeds 1% of the population of the world or the East Asian-Australasian flyway (Zhang, 2017). Globally, 60% of the population is concentrated in the coastal zone, and 2/3 of the cities with a population of more than 1.6 million are located in the coastal zone (Xu et al., 2006), the coastal zone is also the most concentrated area of human activities in China. This poses a serious challenge to the protection of biodiversity and suitable habitats. Before 2014, the length of the artificial shoreline increased from 0.33×10^4 km in the early 1940s to 1.32×10^4 km in 2014, the proportion increased from 18.30% to 67.08%, and the length of natural shoreline decreased from 1.48×10^4 km in the early 1940s down to 0.65×10^4 km in 2014, the proportion decreased from 81.70% to 32.92% (Chen et al., 2021). In recent years, with the Chinese government paying more attention to wetland protection, the protection of coastal wetlands in China has achieved good results (Hou et al., 2016). As of 2018, there are 18 International Important Wetlands, more than 80 Wetland Nature Reserves and more than 160 National Wetland Parks in coastal provinces, and the area of coastal wetlands included in the reserve system is 1.395 million hm^2 (Zhang et al., 2018). By consulting literatures, it is found that there are few biodiversity assessment cases for China's coastal areas. Therefore, taking the prefecture-level cities involved in the coastline of Chinese Mainland as the research scope, this paper carries out biodiversity distribution, identification of suitable habitats, and analysis of conservation preliminary gaps, which is of great significance to the biodiversity conservation in China's coastal areas and even the global coastal areas.

Materials and methods

Study area

The study area is located in the coastal area of mainland China (107°28′E, 20°13′N—125°42′E, 42°7′N), Starting from the Yalu River estuary in the north and the Beicang River estuary in the south, including four administrative levels: 48 prefecture-level cities, 2 municipalities (Tianjin and Shanghai), and 1 special administrative region (Hong Kong), with a total area of about 470,000 km^2, as shown in Figure 1. The study area belongs to temperate monsoon climate and subtropical monsoon climate, including multiple climate zones such as mid-temperate, warm temperate, northern subtropical, central subtropical, southern subtropical and tropical (Zheng et al., 2013). The continental coastline belongs to four sea areas: Bohai Sea, Yellow Sea, East China Sea and South China Sea.

Species occurrence records

Download all birds recorded in the study area since 2000 from http://www.gbif.org (GBIF, 2022). The species distribution data of GBIF are provided by several institutions, so the data often contain some problems. Therefore, it is necessary to remove duplicate data and missing data of longitude and latitude, and check the species scientific names according to the third edition of the Chinese Bird Taxonomy and Distribution List. Ideally, the study area should have undergone systematic or random unbiased sampling, but in practice, limited by the terrain of the study area, some places are not covered, resulting in different degrees of sampling bias (Kramer-Schadt et al., 2013). Thus, to avoid overfitting the model and eliminate spatial autocorrelation, this study selected birds with more than 10 occurrence records as the research object, and the SDMtoolbox tool of ArcGIS10.8 software was used to spatially filter the data, so that only one distribution record was retained in each 1 km×1 km raster (Brown et al., 2017). Finally, 488 bird species with a total of 61,153 points were used in this study.

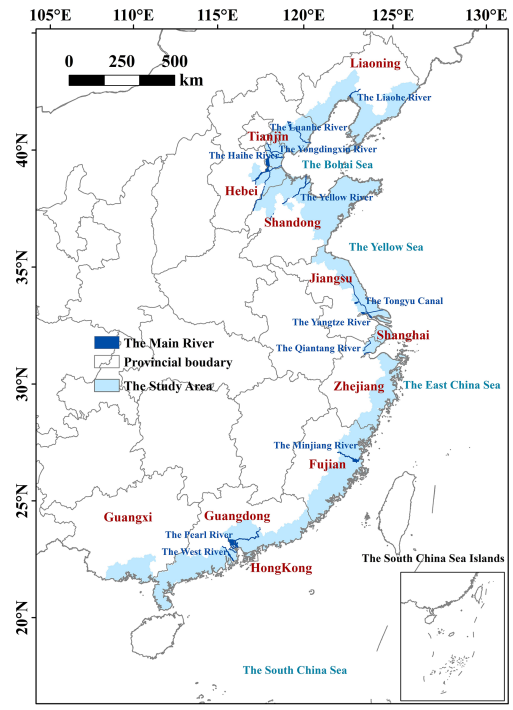

FIGURE 1
Location of study area. Based on the standard map with the approval number GS (2020) 4619 downloaded from the Standard Map Service Website of the National Bureau of Surveying, Mapping and Geographic Information of China, with no modification to the base map.

Environmental data

On the basis of previous studies (Dong et al., 2014; Wu et al., 2016; Luo et al., 2021), combined with the comprehensive impact of climate change, terrain, habitat type and human disturbance on the distribution of birds, this paper selects a total of 26 environmental variables that affect the distribution of bird species to construct the model, including 19 climate variables, NDVI, altitude, slope, aspect, land use type, distance to water sources, distance from human activities. There might be relationships between some environmental variables, and applying all environmental factors to modeling can lead to overfitting. Therefore, this study used the R package of ENMTools 1.0.6 developed by Warren et al. for the correlation analysis of various environmental factors, independent of distribution data, and able to obtain reliable results (Warren et al., 2021). The secondary environmental variables with $|R|\geq 0.9$ were eliminated, and the following 15 environmental factors affecting the distribution of birds were screened (Table 1). The climate factor data comes from the bioclimatic data of the World Climate Database (http://www.worldclim.org) version 2.1 with a resolution of 1km, and the NDVI comes from were obtained from the 2000–2020 NASA MODIS product data MODIS09A1 (http://ladsweb.nascom.nasa.gov/), Topographic variables and land use types were downloaded from the Resource and Environment Science and Data Center (https://www.resdc.cn/). Distances to water sources and distances to human activities were obtained by calculating Euclidean distances after extracting data based on land use types. The above data is uniformly resampled to a resolution of 1km × 1km.

MaxEnt Model Construction and Analysis of Hotspots Area

This study uses the SDMtoolbox tool to call the MaxEnt model to predict the potential distribution areas of 488 bird species in coastal areas. Due to the spatial deviation of species sampling, this study first used the SDMtoolbox tool to create a Gaussian kernel density deviation file for each species, so that more background

TABLE 1 Variables used for modeling.

Code	Environmental Variable	Source
Bio1	Annual mean temperature (°C)	
Bio2	Monthly mean diurnal temperature range (°C)	
Bio3	Isothermality %	
Bio4	Standard deviation of temperature seasonal change	
Bio5	Max temperature of the warmest Month (°C)	
Bio6	Min temperature of the coldest month (°C)	
Bio7	Range of annual temperature (°C)	
Bio8	Mean temperature of the wettest quarter (°C)	
Bio9	Mean temperature of the driest quarter (°C)	
Bio10	Mean temperature of the warmest quarter (°C)	
Bio11	Mean temperature of the coldest quarter (°C)	
Bio12	Annual average precipitation (mm)	
Bio13	Precipitation of the wettest month (mm)	
Bio14	Precipitation of the driest month (mm)	
Bio15	Coefficient of variation of precipitation %	
Bio16	Precipitation of the wettest quarter (mm)	
Bio17	Precipitation of the driest quarter (mm)	
Bio18	Precipitation of the warmest quarter (mm)	
Bio19	Precipitation of the coldest quarter (mm)	http://www.worldclim.org (Bio1-Bio19)
Bio20	Aspect (°)	
Bio21	Altitude (m)	
Bio22	Slope (°)	
Bio23	Distance to water sources (m)	
Bio24	Distance to human activity (m)	
Bio25	Land use	https://www.resdc.cn/(Bio20-Bio25)
Bio26	Normalized difference vegetation index	http://ladsweb.nascom.nasa.gov/

points were selected in the area with large sampling deviation (Brown, 2014). Five cross-validations were performed on each bird, and the output type of the result was a Clogclog model, and the rest of the parameters were default. The Jackknife method was chosen to test the importance of each environmental factor. The model prediction results were tested by the area enclosed by the receiver operating characteristic curve (ROC) and the abscissa, that is, the AUC value, to evaluate the model prediction accuracy (Phillips et al., 2006; Phillips & Dudík, 2008; Merow et al., 2013; Radosavljevic & Anderson, 2014). The AUC value ranged from 0.5 to 1. The closer the value was to 1, the higher the model prediction accuracy. The AUC values are 0.5–0.6, unqualified; 0.6–0.7, poor; 0.7–0.8, fair; 0.8–0.9, good; and 0.9–1.0, excellent. Select Maximum training sensitivity plus specificity (MTSS) Cloglog threshold as the threshold (Phillips et al., 2017), and convert the model prediction results into binomial values of 0 and 1. If the distribution probability of a species in a grid is greater than this threshold, the species is considered to be distributed in this grid, otherwise it is not distributed.

Based on the prediction results of MaxEnt model, the raster calculator of ArcGIS was used to superimpose the binarized prediction results of all birds to obtain the spatial distribution pattern of the abundance of all birds in the coastal area. Then, according to the "List of National Key Protected Wild Animals in China" (China Forestry and Grass Bureau website, 2022.2.9), 97 key protected bird species were screened, and the predicted results of national key protected birds were superimposed to obtain their distribution pattern. The results were divided into 5 categories using the natural discontinuity method, including: cold spot areas, sub-cold spot areas, moderate hot areas, sub-hot spot areas and hot spot areas. Further, the high biodiversity value areas of all birds and national key protected birds were overlaid with national protected areas and provincial protected areas respectively to identify the conservation vacant areas. The technical roadmap of the paper is shown in Appendix Figure S1.

Results and analysis

Species composition

The birds involved in the MaxEnt modeling were 488 species in 249 genera of 21 orders and 81 families, Passeriformes,250 species, Ploverformes Charadriiformes, 68 species, Anseriformes,

30 species, and Accipitriformes, 27 species are the orders with the most species, making up 51.23%, 13.93%, 6.15%, and 5.53% of all the birds in the study area, respectively (Table 2), indicating that songbirds, wetland waterbirds, and raptors were predominant in the study area. The most common families are Muscicapidae with 39 species, Scolopacidae with 36 species and Anatidae with 30 species. There are 18 national key protected wild animals and 79 national key protected wild animals.

MaxEnt model results

The results showed that the average AUC of the MaxEnt model for 488 bird species was 0.923 ± 0.069 (for details, see Table S1), indicating that the vast majority of models had good prediction accuracy. The results showed that the average AUC of the MaxEnt model for 488 bird species was 0.923 ± 0.069, indicating that the vast majority of models had good prediction accuracy. As shown in Figure 2, the environmental variables with high contribution to the model are mainly land use (19.70%), monthly mean diurnal temperature range (15.48%), and precipitation of the driest month (11.35%). For 97 species of national key protected birds, the environmental variables with high contribution to the model are mainly land use (18.31%) and monthly mean diurnal temperature range (16.19%). The impact of different environmental variables on the birds distribution is also different. It may have a greater impact on some birds, but less on others. For instance, land use had a greater effect on the distribution of birds such as *Limnodromus scolopaceus* and *Turnix tanki*, and a lesser effect on birds such as *Emberiza aureolah* and *Corvus pectoralis*. The selection of land use types of birds is mostly concentrated in areas where they are lakes, rivers and wetlands. The complete ecosystem and good ecological environment of wetlands can provide suitable habitats for birds.

Bird biodiversity distribution pattern

The distribution pattern of bird biodiversity in Figure 3A shows that all bird diversity hotspots are mainly concentrated in: 1) Near the Liaohe estuary wetlands in the Bohai Sea, northwest of Yingkou City, south of Jinzhou City, and southwest of Dalian City in Liaoning Province; 2) Near the Yongdingxin River and Haihe River in Tianjin, the eastern coastal area of Tianjin; 3) Near the Yellow River Delta, the northwestern coastal areas of Shandong Province, Weihai City, and the southeastern coastal areas of Qingdao City; 4) East of Lianyungang, North of Yancheng and South of Nantong, Jiangsu Province; 5) At the mouth of the Yangtze River in the East China Sea, northwest of Shanghai, Chongming Island, Zhoushan City; 6) The southern coastal areas of Taizhou City and the northeastern coastal areas of Wenzhou City in Zhejiang Province; 7) the cities near the Minjiang River and the coastal areas of Quanzhou City in Fujian

TABLE 2 Number of bird orders, families, genera, species and percentage of total number of species in the study area.

	Number of families	Number of genura	Number of species	Percentage of total number of species (%)
Accipitriformes	2	16	27	5.53
Anseriformes	1	12	30	6.15
Bucerotiformes	1	1	1	0.20
Caprimulgiformes	2	4	8	1.64
Charadriiformes	9	31	68	13.93
Ciconiiformes	1	1	2	0.41
Columbiformes	1	4	8	1.64
Coraciiformes	3	6	8	1.64
Cuculiformes	1	7	13	2.66
Falconiformes	1	7	5	1.02
Galliformes	1	6	6	1.23
Gruiformes	2	9	13	2.66
Otidiformes	1	1	1	0.20
Passeriformes	45	120	250	51.23
Pelecaniformes	2	10	19	3.89
Piciformes	2	6	9	1.84
Podicipediformes	1	2	3	0.61
Psittaciformes	1	1	2	0.41
Strigiformes	2	9	13	2.66
Suliformes	1	1	1	0.20
Trogoniformes	1	1	1	0.20

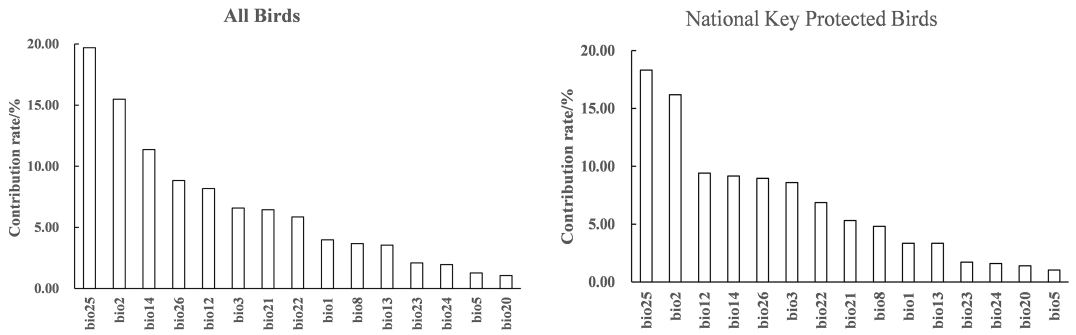

FIGURE 2
Average contribution of environmental variables.

Province; 8) Cities near the Xijiang and Pearl Rivers in Guangdong Province, and the southeastern coastal areas of the Guangdong-Hong Kong-Macao Greater Bay Area, mainly Zhuhai, Shenzhen, and Zhongshan; 9) Fangchenggang City and Beihai City in Guangxi Province. The distribution of birds is mainly concentrated near the coastline and near the estuary, and in coastal cities near the East China Sea and the South China Sea all birds are concentrated and distributed over a larger area than in the Bohai Sea and the Yellow Sea, with sub-hot spots and medium areas gradually extending outward in the hot spots. Figure 3B shows that the distribution hotspots of national key protected birds are essentially the same in terms of spatial distribution as all bird diversity hotspots, but that the distribution is more concentrated, with hotspots concentrated in the Bohai Rim and close to the Pearl River Delta, the Guangdong-Hong Kong-Macao Greater Bay Area, as well as sub-hotspots and moderate hot areas close to the hotspots. However, the biodiversity of national key protected birds in coastal areas of Fujian Province and Zhejiang Province was significantly lower than all birds.

Spatial distribution of hotspots and protected areas

The sub-hotspot areas and hotspot areas of the spatial distribution of bird richness are collectively referred to as high biodiversity areas (HBA). The next step is to analyze the spatial

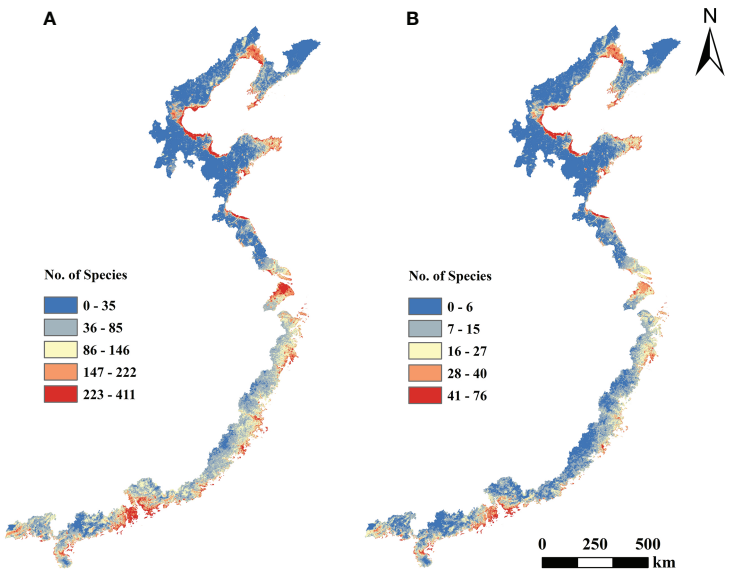

FIGURE 3
Biodiversity distribution pattern of All birds in coastal areas **(A)** and national key protected birds **(B)**.

superposition of HBA of all birds and national key protected birds with national nature reserves (NNRs) and provincial nature reserves (PNRs), respectively, and the intersection of HBA and NNRs/PNRs in terms of area and proportion. There are a total of 53 NRRs around the study area, with an area of about 17740.34 km^2, and 94 PNRs with an area of about 10516.65 km^2. The HBA area of all birds is about 84572.55 km^2, and the HBA of national key protected birds is about 58908.26 km^2. The next step is to analyze the spatial superposition of HBA of all birds and national key protected birds with national nature reserves (NRRs) and provincial nature reserves (PNRs), respectively, and the intersection of HBA and NNR/PNR in terms of area and proportion. As shown in Table 3, the area of the intersection of HBA and NNRs of all birds is 2078.96km2, accounting for 11.72% of the area of all NNRs, and the area of the intersection of HBA and PNRs of all birds is 1605.67km2, accounting for the area of all PNRs of 15.27%. The area of the intersection of HBA and NNRs of national key protected birds is 1737.36km2, accounting for 9.79% of the area of all NNRs, and the area of the intersection of HBA and PNRs of national key protected birds is 1175.07km2, accounting for 11.17% of all PNRs. The overlap between HBA and protected areas for all birds is primarily distributed in the coastal regions of China's four major seas, as shown in Figure 4. It can be seen that the proportion of suitable distribution areas for birds belonging to HBA and in protected areas in the coastal areas of mainland China is not high, and there are protection gaps in non-HBA areas and areas close to inland areas.

From the analysis in Figure 4, it can be concluded that for the Bohai Rim area of HBA where birds are distributed, the degree of biodiversity of birds is relatively high, and the spatial distribution of national key protected birds is also relatively concentrated, mainly in the Liaohe estuary National Nature Reserve and Panjin Liaohe estuary Provincial Nature Reserve in Liaoning Province; Beidagang Wetland Provincial Nature Reserve in Tianjin; Caofeidian Wetland and Birds Provincial Nature Reserve, Nandagang Wetland Provincial Nature Reserve and Haixing Wetland Provincial Nature Reserve in Hebei Province; Binzhou Shell Embankment Island and Wetland National Nature Reserve and Yellow River Delta National Nature Reserve in Shandong Province. The Liaohe estuary National Nature Reserve and the Yellow River Delta Nature Reserve are strictly controlled, and the existence of nature reserves can effectively improve the habitat quality of the area. The Liaohe Estuary National Nature Reserve is located at the downstream of Liaohe River and Hun River, at the estuary of Liaohe River in Liaodong Bay. Upstream fresh water carries a lot of nutrients and is deposited near the downstream coastal zone, forming a wetland environment suitable for birds with reed marshes and coastal intertidal zone (Shi, 2020). It is situated in the crucial area along the flyway of migratory birds from East Asia to Australia, and is the wintering and breeding site of many national key protected birds, and the national protected wild animal *Larus saundersi* breeds here. The HBA area in Tianjin and Hebei Province is mainly in the southwestern part of Bohai Bay and the northwestern part of Laizhou Bay, and the main sea-entering rivers are Luan River, Hai River, Yongdingxin River and Yellow River. The annual sediment accumulation at the mouth of the Yellow River, which merges with oceanic rivers to form the Yellow River delta wetland, is the most complete and extensive wetland ecosystem preserved in the warm temperate zone in China, with vegetation communities dominated by the *Phragmites australis* community and the *Suaeda heteroptera* community and a rich variety of aquatic organisms (Chen et al., 2017). The good wetland habitat conditions provide sufficient food and good habitat for birds to breed and overwinter.

For the distribution of HBA of birds around the Yellow Sea, the HBA of birds is mainly in the coastal area of Weihai City, Shandong Province, Kunyushan National Nature Reserve, Laoshan Provincial Nature Reserve and Yancheng Wetland Rare Bird National Nature Reserve in Jiangsu Province. In the past decade, ecological restoration projects have been implemented in Yancheng Wetland Rare Bird National Nature Reserve, and large artificial wetlands have been established. The upstream water system of Yancheng Wetland has Guanhe rivers and Huaihe River converging into the ocean, with sufficient water resources and vigorous growth of mudflat organisms and *Phragmites australis* communities and *Spartina anglica Hubb.* communities. The Yancheng Wetland Rare Bird National Nature Reserve is the largest wintering habitat for the internationally endangered species of cranes (Ma et al., 2009).

For the coastal areas of the East China Sea where HBAs of birds are distributed, they are mainly near the mouth of the Yangtze River, Chongming Island Dongtan Bird National Nature Reserve, Jiuduansha Wetland National Nature Reserve, cities near the Minjiang River and Quanzhou City coastal areas in Fujian Province. The sediment deposition at the estuary of the Yangtze River promotes the formation of wetlands at the estuary of the Yangtze River. It is a typical estuarine wetland in China. The main wetland types are paddy fields and tidal flats. The vegetation community is dominated by the *Phragmites australis* community

TABLE 3 Spatial relationships of all birds and national key protected birds with NRRs and PNRs.

	NRR	PNR
Intersection area of all birds (km^2)	2078.96	1605.67
The proportion of HBA of all birds (%)	11.72	15.27
The intersection area of national key protected birds (km^2)	1737.36	1175.07
The proportion of HBA of national key protected birds (%)	9.79	11.17

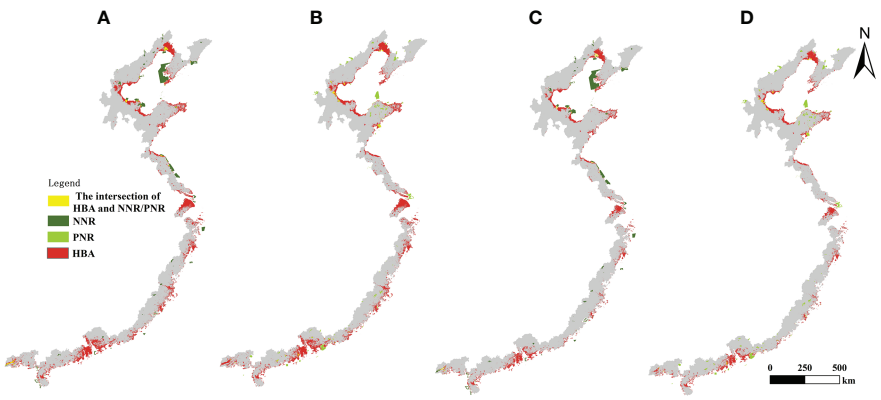

FIGURE 4
Spatial distribution of all birds **(A, B)**, national key protected birds **(C, D)** with NRR and PNR.

and the *Spartina alterniflora* community. The Chongming Island Dongtan Bird National Nature Reserve, located in the wetlands at the mouth of the Yangtze River, is rich in benthic fauna and vegetation resources, and is a resting place for many migratory birds on their way, as well as a wintering ground for some waterfowl. In the highly urbanized city of Shanghai, where citizen science provides more abundant data (Xu et al., 2022), more bird distribution data are obtained at this location, and thus bird hotspots are concentrated in the MaxEnt model prediction results. The Minjiang River in Fujian Province is one of the major rivers that feeds into the East China Sea, and its estuary has a warm, hot and humid climate with typical semi-diurnal tides, salty grass marsh wetlands, reed marsh wetlands and invaded areas of flowering rice grass (Tong et al., 2011), flat mudflats and abundant food. Ardeidae and Scolopacidae birds mostly inhabit this area (Chen et al., 2001).

For the coastal areas of the South China Sea where the HBAs of birds are distributed, they are mainly near the Pearl River system and the southeastern part of the Guangdong-Hong Kong-Macao Greater Bay Area, Gudoushan Provincial Nature Reserve in Guangdong Province, and Shiwanda Mountain National Nature Reserve in Guangxi Province. The distribution of HBA of birds in the coastal areas of the South China Sea is consistent with the spatial distribution of local water resources. The Dongjiang, Xijiang, Beijiang and other rivers flow into the Pearl River Delta, and the entire water system is fan-shaped. The region has a subtropical monsoon climate, which is warm and humid all year round, and the habitat is suitable for birds to overwinter. The Guangdong-Hong Kong-Macao Greater Bay Area is an important resting and wintering ground for migratory waterbirds from the north to the south and many rare and endangered waterbirds. There are a lot of mangrove trees, which can prevent wind and waves, store carbon, maintain biodiversity, and shelter a lot of marine benthic creatures (Zhang & Sui, 2001). There are also lots of coastal wetlands and water network wetlands, which distributes a large number of water birds.

Discussion

The hotspot areas of bird diversity in coastal areas are mainly concentrated in the Liaohe estuary wetlands in the Bohai Sea waters, near the Yongdingxin River and Haihe River basin in Tianjin, at the estuary of the Yellow River and in the Yellow River Delta Nature Reserve, in the urban coastal areas of northwestern Shandong Province, in the Yancheng Wetland Rare Bird National Nature Reserve in northern Yancheng City, Jiangsu Province, at the estuary of the Yangtze River, Chongming Island Dongtan Bird National Nature Reserve, in the southeastern Zhejiang coastal areas, near the Min River and coastal areas of Quanzhou City in Fujian Province, the Pearl River system in Guangdong Province, and the southeastern coastal areas of the Guangdong-Hong Kong-Macao Greater Bay Area, Fangchenggang City in Guangxi Province, and Beihai City. Large wetlands are distributed near the coastline, with rich biodiversity. Many coastal cities in mainland China are economically developed areas, and some important coastal wetlands located in these cities are also an important part of the East Asian-Australasian flyway and are critical habitat for many migratory birds. Most of these places are close to the mouths of rivers, and lakes, swamps, and wetlands can provide good habitats for birds.

Problems and suggestions for habitat conservation of birds in coastal areas

The coastal wetlands are the weak link of wetland protection in China, and there are obvious protection gaps. In recent years, the loss of migratory bird habitat caused by the reclamation and exploitation of coastal wetlands has led to a reduction in the biodiversity of birds along the migration routes. The degree of bird biodiversity in the coastal areas of the Bohai Sea is high, and the spatial distribution of the national key protected birds is also more concentrated. The development of urbanization in the central

Liaodong Bay and southern Bohai Bay over the past fifteen years has led to a gradual decrease in the ecological quality of coastal wetlands and a trend of biodiversity degradation (Xiao et al., 2018). Therefore, in the areas with intense human activities, it is recommended to implement restoration and management countermeasures by expanding the scope of protection. The hotspot of bird biodiversity in the Yellow Sea waters is in Weihai City and Yancheng Wetland Rare Bird National Nature Reserve in Shandong Province, where bird populations forage and overwinter in the wetlands around the Yellow Sea and Bohai Sea. In recent years, affected by the invasive species Spartina alterniflora and the reclamation and aquaculture of sea tidal flats, some wetlands have been degraded and food resources have been reduced. It is necessary to pay attention to the habitat quality of these wintering waterbirds to ensure sufficient food resources and a good ecological environment (Wang et al., 2022). The bird biodiversity area in the East China Sea region is near the estuary of the Yangtze River, near Chongming Island Dongtan Bird National Nature Reserve and Jiuduansha Wetland National Nature Reserve. Focusing on the ecological protection of the whole Yangtze River basin is not only related to people's production and life, but also to the quality of the habitat of birds in the estuary. The bird biodiversity hotspots in the coastal areas of the South China Sea are near the Pearl River system and the southeastern part of the Guangdong-Hong Kong-Macao Greater Bay Area, which is consistent with the spatial distribution of local water resources. With the development of urbanization and industrialization, the coastal wetlands are seriously degraded and biodiversity is lost, and it is necessary to pay attention to the vacant areas of bird protection in this region (Ma et al., 2021).

In general, for areas where bird biodiversity hotspots overlap with protected areas, it is recommended to continue to deepen control measures in hotspots, improve management and assessment mechanisms, establish or expand the area of protected areas on the basis of the original hotspots with large wetland marsh distribution areas as core areas, fill protection gaps, and actively carry out monitoring and assessment of coastal wetland ecosystems. Hotspot areas that do not overlap with protected areas and have small wetland areas should be combined with local land use planning, make rational use, give full play to the advantages of ecological resources, and lead to the realization of a new trend of economic development and conservation synergy. In the hot spots of coastal cities with highly developed urbanization and industrialization, considering the local development status and land use types, optimizing the urban ecological spatial structure and realizing the development goals of urban characteristics, not only establishing protected areas, but also focusing on coordinating the relationship between nature and economic and social development. In the Yangtze River Delta, Pearl River Delta and other regions, it is possible to consider establishing waterbird ecological corridors (Luo et al., 2021), constructing and improving biodiversity protection networks, restoring waterbird habitats, promoting popular science, developing bird watching activities and wetland tourism.

In bird surveys, citizen science generally has a long survey cycle and sufficient time, which can solve the problems of manpower and funding, and also allow the public to understand ornithological research and increase environmental awareness (Tulloch et al., 2013). The data and related research provided by citizen science are widely recognized (Devictor et al., 2010), and these data have been corrected by database professionals with a high degree of quality assurance, so they are widely used in the estimation and assessment of bird biodiversity (Sullivan et al., 2014). It is recommended to continue to carry out bird distribution surveys in coastal areas to obtain comprehensive and continuous bird distribution data, and regularly hold bird population surveys and identification activities, and carry out coastal wetland habitat assessment work. Strengthen the public's awareness of wetland protection and bird biodiversity protection, and improve the policy system and protection measures for coastal wetland protection.

Effects of key environmental factors on bird habitats in coastal areas

Studying the relationship between bird communities and environmental factors is important for the conservation and restoration of bird habitats. Influenced by global climate change and human activities, the behavior pattern, population dynamics and distribution range of birds have also been greatly affected. Coastal wetlands are distributed along the coast of mainland China, which is a transition zone between terrestrial and marine ecosystems and plays an important role in maintaining national security and biodiversity security. For a long time, the waters and wetlands near the coast have maintained the development of marine fisheries and are key areas for fish breeding sites. Marine fish, mangroves, and seagrass beds also provide abundant food sources and habitats for birds. In the results of this study, the main driving factors affecting the suitable distribution of birds are land use, monthly mean diurnal temperature range, precipitation of the driest month. Rapid changes in land use patterns and extreme changes in climate may lead to habitat loss for birds, and economic and social development over time has led to degradation of natural wetland areas in coastal areas and incomplete ecosystems in artificial wetlands, all of which dynamically affect changes in the core distribution areas of birds. We need to focus on the response of individual species to future land use patterns and climate change, model the extent and degree to which these factors alter core areas, and dynamically adjust the boundaries of protected area design (Soultan et al., 2022). The urbanization process of coastal areas will change the pattern of land use. Urban bird habitats mainly include wetlands, woodlands, agricultural lands and public green spaces, and studies have shown that the area of urban public green spaces is the main factor affecting bird richness, and in cities with non-hotspot areas of bird distribution, it is recommended that maintaining vegetated areas, reducing the use of pesticides, and it is an effective measure to improve the quality of urban bird habitats

(Huang et al., 2015). Studies have shown that larger, structurally complex and resource-rich habitats can provide a diversity of microhabitats and maintain greater bird biodiversity (Honkanen et al., 2010). In coastal areas, the unique mangrove resources are one of the environments that birds rely on, and follow-up research also needs to pay attention to this environmental factor. The habitat structure of mangroves is mainly determined by the species of mangroves and the density of the river network. For mangrove plants in the East China Sea and the South China Sea, priority should be given to protection and restoration, assessing the ecological status of mangroves, and understanding the impact of mangroves on bird protection in order to maintain bird biodiversity (Mohd-Azlan et al., 2015). In this manuscript, we only distinguish the national key protected birds that need urgent attention, and discuss the distribution areas of all the birds and the national key protected birds in the coastal area. These birds are also of great conservation significance. As an important part of wetland ecosystems, waterbirds play a key role in maintaining wetland ecological balance, material and energy flow, and wetlands also provide waterbirds with rich food sources and good habitats. The study of wetland birds has always been one of the important contents of wetland science. In follow-up studies, we will consider more specific studies of the breeding and wintering sites of wetland waterbirds to explore their interactions with wetland habitats.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding authors.

Author contributions

PH, JH, JuZ, and JB analyzed the data. PH and JB wrote the manuscript. PH conceived the study, directed work and supervision. YM, JiZ and YC assisted with collect and check the data, and provided valuable comments in the paper writing. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.1007442/full#supplementary-material

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