Study on suitability assessment of waterbird habitats along the Bohai Rim

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A B S T R A C T

In recent years, due to rapid economic development, the Bohai Rim has become a focus of attention. The area has abundant waterbird resources, however, the coastal wetlands in the Bohai Rim are currently under serious threat and waterbird conservation needs to be addressed urgently. Exploring the changes and main driving factors of waterbirds and conducting habitat suitability assessments for waterbirds are of great significance to regional ecology and environmental protection efforts. In this study, during the period of 2002–2021, we recorded the waterbird numbers and species in the Bohai Rim region of China. Then, we quantified the potential suitable habitats and analyzed the driving factors for waterbirds using the MaxEnt model. The results showed that the waterbird richness around the Bohai Rim increased gradually over a 20-year period, and more waterbird species were detected in wetland habitats than in other habitats. Five waterbird hotspot regions require special attention, including the Yellow River Delta Nature Reserve, Beidagang Wetland, Beidaihe National Wetland Park, Liaohe Estuary wetland and Caofeidian Wetland Park. The main driving factors of waterbird changes are the NDVI, land cover and maximum temperature in the warmest month. This study provides a reference and theoretical support for waterbird conservation and rational habitat use.

1. Introduction

Waterbirds are the most important component of wetland biomes. Their presence and activities have multiple positive impacts on wetland biodiversity, and their composition directly affects the structure and function of wetland ecosystems (Green and Elmberg, 2014; Whelan et al., 2008). At the same time, waterbird communities can quickly sense changes in wetland ecosystems, which can be used as an important indicator to assess the quality of coastal wetland ecosystems (Zhou et al., 2020; Xu et al., 2022; Chatterjee et al., 2020). In addition, waterbird conservation is gradually gaining importance in China (Cui et al., 2014). According to the Ramsar Convention, more than 60 wetlands have been included in the List of Wetlands of International Importance since 1992, and 260 species of waterbirds have been identified. However, for the past few years, the degradation of environmental quality and ecological functions of global coastal wetlands has become increasingly serious due to anthropogenic influences, including resource overexploitation, tideland reclamation, urbanization and environmental pollution (Song et al., 2021; Bai et al., 2019; Ekumah et al., 2020). Undoubtedly, the intensification of the abovementioned human activities and degradation

of natural wetlands will lead to poorer quality waterbird habitats, which will give rise to a multitude of negative effects on the sustainable development of waterbird populations (Grand et al., 2020; Hansen et al., 2021; Jackson et al., 2020). Liu et al. (2004) found that the loss and fragmentation of wetlands as a result of agricultural development over 50 years has impacted the waterbird population in China's Sanjiang Plain wetland. Therefore, based on observations of waterbird communities, the causes of waterbird changes should be discussed.

Moreover, many scholars have analyzed the changes in waterbird diversity and waterbird driving factors at small spatial scales using time scales shorter than 5 years (Dauda et al., 2017; Wang et al., 2020). For instance, Arizaga et al. (2014) assessed the use of an artificial lagoon by waterbirds in Urdaibai, Spain in 2012 and its contribution to waterbird communities and richness. Wang and Yang. (2021) evaluated the community structures of waterbirds in artificial wetlands at Lake Dianchi using nestedness theory from March 2013 to February 2014. Consequently, when studying birds in a particular habitat, attention is generally focused on surveying bird diversity in a short period of time and on examining indicator species, bird community structures and gradient changes of birds in different disturbed habitats (Liao et al.,

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2020). Most previous studies have only emphasized bird diversity at a single habitat or at small spatial scales as a study area, with less information on waterbirds along entire migration routes due to the limitations of data, workload and time (Sun et al., 2021). To date, however, a major problem is that bird guilds have different adaptations to different habitats and are unlikely to reside in the same habitat year round (Crowe et al., 2009). In other words, the response of bird guilds to multiple habitats at large spatial scales has been overlooked (Tu et al., 2020; De Coster et al., 2015). Therefore, using multiyear field survey data to examine the spatial variations in waterbird communities at different scales and under different conditions will compensate for the current study area being too independent (Graves et al., 2013). In addition, waterbird observations over extended periods of time provide a more comprehensive understanding of their spatial and temporal variations along their migratory routes. In addition, this study helps to explore the specific reasons why waterbirds choose different habitats and their driving factors, which will accordingly lead to more rational conservation measures.

The Bohai Rim is a vast area located in the northern part of China along the western coast of the Pacific Ocean and surrounds the entire Bohai Sea and part of the coastal area of the Yellow Sea. It is also the largest industrial zone in China. Inevitably, the population concentration and rapid development of coastal industries have led to sharp increases in the amounts of land-based pollutants entering the sea (Gao et al., 2014). In addition, for waterbirds, the coastal wetlands around the Bohai Rim are an important station on the north–south and East Asian-Australasian Flyway (EAAF) (Yang et al., 2011). More specifically, the coastal mudflats represented by the Beidaihe Wetland, Shuangtaihekou Wetland and the coast of the Tianjin Binhai New Area provide breeding, resting and wintering sites for migrating waterbirds (Calder et al., 2019; Heo et al., 2019). Currently, the coastal wetlands in the Bohai Rim have become one of the most threatened sites along the entire migration route, and waterbird conservation needs to be urgently addressed because of the unpromising habitat suitability (Chen et al., 2018; Duan et al., 2020). However, there are currently few studies on the diversity of waterbirds around the Bohai Rim as a whole. Therefore, to fill the gaps in the current research, there is an urgent need to conduct large-scale waterbird surveys in the Bohai Rim and to continuously collect bird data for many years. These data can be used to clarify the compositions of waterbird communities and seek to explain the spatial and temporal variations in waterbird diversity in the region and their driving factors.

As a result of our work, the following aspects have been significantly enriched. (1) We investigated and recorded the species and numbers of waterbirds along China's Bohai Rim from 2002 to 2021. (2) We ascertained the spatial distributions and hotspot regions of waterbirds in Bohai Rim region of China and analyzed the habitat preferences of various waterbird guilds. (3) We revealed the driving factors of waterbird changes and conducted a study on the distribution of potentially suitable habitats using the MaxEnt Model. The major objectives of this study are to develop an understanding of the main causes that affect waterbird distributions and to reveal the mechanisms of spatial and temporal changes in waterbird guilds along the Bohai Rim. Exploring these issues will help increase the awareness of the important value of waterbirds along the Bohai Rim among national and local governments and in the public. The current findings provide fundamental data and objectives for the effective conservation of waterbird diversity.

2. Materials and methods

2.1. Study area

Located in the northern part of China along the western coast of the Pacific Ocean, the Bohai Rim is called the "gold coast" of China's northern coast and plays an important role in China's coastal development strategy of opening up to the outside world. According to the CEIC database for the China Economic Zone theme report (2019), in 2019, the

region had a population of 257 million and GDP exceeding $2.6 trillion. The total length of the coastline around the Bohai Rim reaches 3,628.1 km, which is the area with the most concentrated distribution of coastal wetlands in China (Wei et al., 2019). This study was conducted between latitudes 35°41′N and 42°08′N and longitudes 115°42′E and 123°31′E. The survey area covered estuaries, protected areas, wetland parks, and intertidal mudflats (Fig. 1).

The study area was defined as those coastal wetlands located within 10 km of the coastline; however, some wetlands outside of this range were included because of their important roles in providing habitat for waterbirds (Xia et al., 2016). The majority of the survey area consists of silt-muddy coastal tidal flats, with relatively intact ecosystems and rich wetland biological resources, providing a variety of waterbirds with places to stay, feed and breed. Meanwhile, it is a key area along the East Asian-Australasian Flyway (EAAF), which is the largest wintering site for the red-crowned crane and an important breeding site for Saunders's gull, whose populations have increased nearly fivefold in 20 years due to a series of ecological protection measures (Wen et al., 2020).

2.2. Waterbird data

The waterbird data in the Bohai Rim region from 2002 to 2021 were obtained from field surveys in Tianjin and the Chinese bird report records website, http://www.birdreport.cn/. A total of 7094 records related to waterbirds with clear latitude and longitude information were collected from 14 cities, including Dalian, Qinhuangdao, Tianjin and Binzhou. To ensure model accuracy and decrease the risk of spatial autocorrelation by avoiding bias, only waterbird data with ten or more occurrences were selected as the research object in this study, and each 300 m × 300 m grid was merged into one research point. Finally, 176 waterbird species with 47 research points were used in this study, and we split the waterbird location information into four periods as shown in Appendix Fig A1.

Due to the large number of research points used in this study and the fact that most were obtained from the website, the number of observations per study area per year is not uniform. Therefore, to ensure the scientific accuracy of the subsequent statistics and calculations, we also counted the number of observations per year for each waterbird species at each research point. The metric, number of waterbird observations, was used, and the acronym, NWO, was used in this dissertation. The NWO was defined as the waterbird population divided by the number of observation times.

2.3. Driving factors

2.3.1. Environmental variables and human disturbances

Different habitat distributions and conditions lead to significant differences in waterbird diversity among different habitats (Gawlik, 2002). With rapid socioeconomic development, the spatial distribution patterns of waterbirds can be severely altered by land-cover changes (Steen et al., 2014). Furthermore, human disturbances may affect not only the migratory status of waterbirds but may also directly threaten the survival of populations (Pocewicz et al., 2013; Ronconi et al., 2015). The impact of climate change on habitat distributions and frequent extreme weather events can also affect the early nesting activities of waterbirds, as well as habitat selection and food replenishment (Ismail and Rahman, 2013). Therefore, based on the above considerations and studies of other scholars (Wang et al., 2021; Duan et al., 2022), to avoid the potential influence of spatial correlations of variables on model accuracy, the following approach was used. The raster correlation and summary statistics tool in the SDM tool was first used to remove variables with Pearson correlation coefficients $|r| > 0.8$. Finally, we reserved 14 variables from three aspects, habitat factors, human disturbance factors and climate factors, which were used to model the ecological niches of waterbirds around China's Bohai Rim (Table 1).
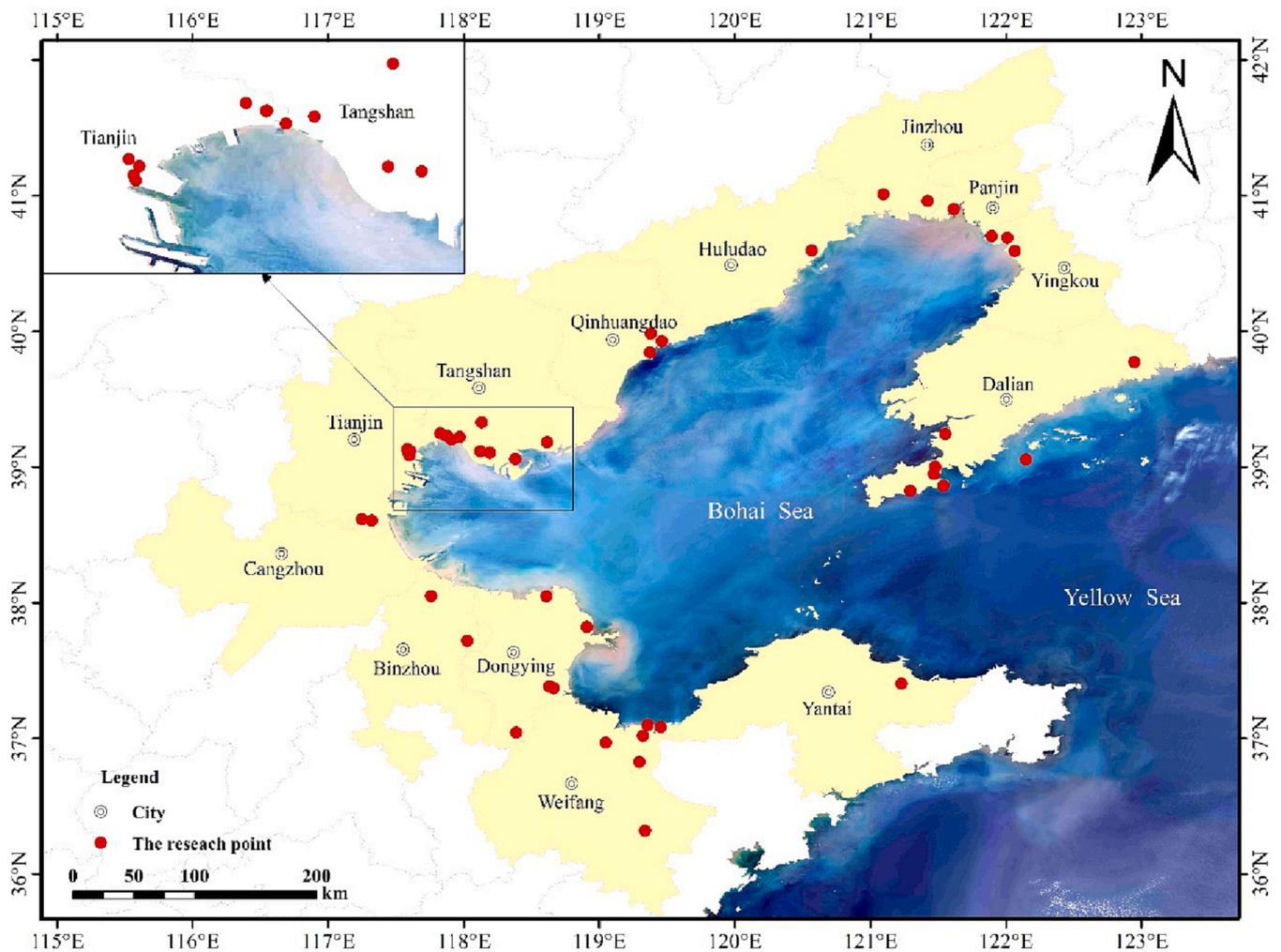
Fig. 1. The location of the study area and research point distribution.

2.3.2. Sources of driving factor data

In the habitat data, land cover data were obtained from Chinese land-use remote-sensing monitoring data that were released by the Resource and Environment Science and Data Center of the Chinese Academy of Sciences with a spatial resolution of 1 km. Normalized difference vegetation index (NDVI) information was downloaded from the above-mentioned data center to obtain the annual vegetation index spatial distribution dataset from 2001 to 2018. Distances to the nearest surface water were calculated as the Euclidean distances from each grid to the nearest water source (e.g., rivers, lakes, and reservoirs) and were converted into a raster file using Euclidean distance analysis.

Among the human disturbance data, population density data and GDP per capita data were obtained from the above-mentioned data center. Distance data to the nearest settlement, nearest road and nearest surface water were obtained from the National Catalog Service for Geographic Information. Among them, the distances to the nearest settlement, nearest road and nearest surface water data were calculated by using Euclidean distances in ArcGIS 10.2 to obtain the raster layers of each pixel from roads, settlements and rivers in the study area, respectively.

Climate data were extracted from contemporary climate data from the WorldClim Global Climate Data.

WGS-1984-UTM-Zone-51 N was used as the projection coordinate system, while D_WGS_1984 was used as the geographic coordinate system. The raster layer sizes were uniformly resampled to 1 km × 1 km. The vector boundary of the Bohai Rim region was used as a mask to clip the raster layer data to produce uniform boundaries of 14 driving factors. Finally, the raster data of the 14 driving factors were converted and saved as ASCII files by using the Raster to ASCII tool in ArcGIS, which is required by the MaxEnt model.

2.4. Statistical analysis

The MaxEnt model used in this investigation is a prediction model based on maximum entropy theory (Elith et al., 2011; Phillips et al., 2006). By training the actual geographical distribution point data of species, combined with the characteristics of various drivers (e.g., climate and human disturbances) at the distribution sites, the model can predict the habitat suitability of each point in the entire region (Phillips and Dudík, 2008; Wen et al., 2016). The MaxEnt model showed improved results compared to other prediction models in ENMs. It provides more accurate results for cases of incomplete information and avoids errors caused by subjective human judgments when weighting driving factors (Elith et al., 2006; Harte and Newman, 2014). It has been widely used in recent years to explore the suitable and potential spatial distributions of biodiversity habitats, biological invasions, potential impacts of climate change on species distributions and in other studies (Hernandez et al., 2006; Kufa et al., 2022).

Therefore, in this paper, we used MaxEnt software version 3.4.1 k to evaluate the habitat potential suitability of the Bohai Rim region in 2005, 2010, 2015 and 2020. First, the waterbird research points (in CSV format) and the above-mentioned 14 driving factors in the Bohai Rim region were imported into MaxEnt. Seventy-five percent of the water-bird distribution data were randomly selected to train the model, and

Table 1

Index system of the driving factors for waterbird change in coastal wetlands around the Bohai Rim.

Categories	Indicator layer	Abbreviation	Data sources
Habitat	Normalized difference vegetation index	NDVI	https://www.resdc.cn
factors	Land cover	LC	https://www.resdc.cn
Human	Population density	PD	https://www.resdc.cn
disturbance	GDP per capita	GDP	https://www.resdc.cn
factors	Distance to the nearest settlement (m)	DS	https://www.webmap.cn
	Distance to the nearest road (m)	DR	https://www.webmap.cn
	Distance to the nearest surface water (m)	DW	https://www.webmap.cn
Climate	Annual mean temperature (°C)	AMT	https://www.worldclim.org
factors	Temperature annual range (°C)	TAR	https://www.worldclim.org
	Maximum temperature of the warmest month (°C)	MTWM	https://www.worldclim.org
	Minimum temperature of the coldest month (°C)	MTCM	https://www.worldclim.org
	Precipitation seasonality (mm)	PS	https://www.worldclim.org
	Precipitation of the wettest month (mm)	PWM	https://www.worldclim.org
	Precipitation of the driest month (mm)	PDM	https://www.worldclim.org

the remaining 25% of the data were used for validation. The bootstrap method was chosen as the repetition category with 10 replications, 10,000 random background points, and maximum number of iterations set to 500. The relative importances of their driving factors and their impacts on the habitat suitability of waterbirds around the Bohai Rim were analyzed by the jackknife test, and the influences of the driving factors were analyzed by the response curves. The output of the MaxEnt model consists of continuous raster data in logistic format (0–1), each raster value represents the habitat suitability index (HSI) of the raster, and the other model parameters were maintained as the defaults.

The prediction effect of the model was evaluated by using the area under the curve (AUC) of the receiver operating characteristic (ROC) curve to evaluate the merit of the model results, and the evaluation criteria were as follows: the AUC was 0.5–0.6 for failure, 0.6–0.7 for poor, 0.7–0.8 for fair, 0.8–0.9 for good and 0.9–1 for excellent.

Finally, the output of the MaxEnt model was reclassified to classify the potential suitable habitat qualities for waterbirds around the Bohai Rim into four grades: high, medium, low and non-suitable areas, and the habitat suitability reclassification and mapping were conducted in ArcGIS 10.2 software.

3. Result

3.1. Population composition

Over a period of 20 years, 176 species, 22 families and 10 orders of waterbirds were recorded across the research points, and the NWO was 459,230. The waterbird species and NWO collected over a duration of 20 years are represented in Table A1.

The numbers of waterbird species and populations were unevenly distributed among 10 identified orders. The results showed that Charadriiformes contributed a total of 82 species and 196,861 NWO, accounting for 46.59% of the registered species data and 42.87% of the NWO data. A total of 43 species and 208,845 NWO belonging to Anseriformes accounted for 45.48% of the NWO data, mainly the bean goose and common pochard. Pelecaniformes were detected as 20 species

in the study area, with 5,936 NWO. There were 16 species and 36,602 NWO of Gruiformes.

Among the 176 waterbird species recorded, 23 species are listed as threatened under the IUCN Red List, including Anseriformes (8 species), Charadriiformes (6 species), Gruiformes (5 species), Pelecaniformes (2 species), Ciconiiformes (1 species), and Podicipediformes (1 species) (IUCN 2018). Of these, 3 species of waterbirds were listed as critically rare (CR), which account for 50% of CR species in China, 8 species were identified as endangered (EN), and 12 species were classified as vulnerable (VU) (Wang et al., 2018). Another 16 species were listed as near threatened (NT), and 134 species were listed as of least concern (LC). There were 3 species that met the Ramsar 1% criterion, namely, the bean goose, great knot and black-headed gull. Additionally, according to the "List of Protected Animals in China", there were 7 species that are first-grade conservation birds in China and 21 species are second-grade conservation birds in China. Among them, black-headed gull and Eurasian spoonbill had a significant increase in numbers in 2021 compared to other years. The black-headed gull mainly feeds in wetlands such as reservoirs and fish ponds. The Eurasian spoonbill inhabits reed swamp wetlands and coastal marshes, and can be seen migrating through groups in the Bohai Rim every spring and fall.

3.2. Spatial distributions and critical zones of waterbirds on China's Bohai Rim

Overall, the total data collected covered 47 research points, and the distribution results of waterbird species and individuals from 2002 to 2021 are shown in Figure (Fig. 2 and Fig. 3). It is easy to see that the locations at which we observed the greatest number of individuals were concentrated along the northern half of China's Bohai Rim coast.

During 2002–2021, a total of 173 waterbird species (98.30%) and 366,724 NWO (79.86%) were found in wetland habitats. This means that the number of waterbirds identified in wetland habitats was significantly higher than in other habitat types. All waterbird orders counted in this study were present in wetland habitats, and only four bird species, long-billed dowitcher, red-faced cormorant, black-throated diver and white-faced egret, were not found in wetland habitats, and they belong to the order Charadriiformes, Suliformes, Gaviiformes, and Pelecaniformes, respectively. This shows that waterbirds prefer wetland habitats.

In the present study, 126 waterbird species were detected in non-wetland habitats, and Charadriiformes was the most abundant, with 62 species, such as the Kentish plover, black-tailed gull and black-headed gull. Most Charadriiformes tend to be found in habitats such as bridge bottoms, mudflat beaches, estuaries and inlets because these habitats provide both habitat and security and tend to fall into wilderness categories.

In addition, the waterbird numbers have gradually increased over the past 20 years (Table 2). The highest NWO was found in the Beidagang Wetland (BW) in Tianjin, with 173,680, and there were 125 species here. The NWO in the BW was at relatively high levels during all 20 years, among which the average annual NWOs from 2013 to 2018 were greater than 10,000. Our findings also showed that the maximum counts for the single recorded relict gull and oriental white stork in the BW were 6000 and 264, respectively, which were greater than 30% (IUCN, 2017) and 10.56% (IUCN, 2018), respectively, of the total numbers of mature individuals worldwide. Therefore, according to the international wetland evaluation criteria (https://rsis.ramsar.org/), the BW can be regarded as one of the most important habitats for waterbirds.

In addition, the Yellow River Delta Nature Reserve (YRDNR) in Shandong Province had a large number of NWO, over 80,000, and the species and individuals in the YRDNR have changed little over two decades. The Liaohe Estuary Wetland (LEW) in Liaoning had 61,907 NWOs from 102 species. The NWO in the LNNR was just under 2,500 in the first 10 years and was over 26,000 in the second 10 years. The greatest diversity of waterbirds in the Beidaihe National Wetland Park (BNWP)
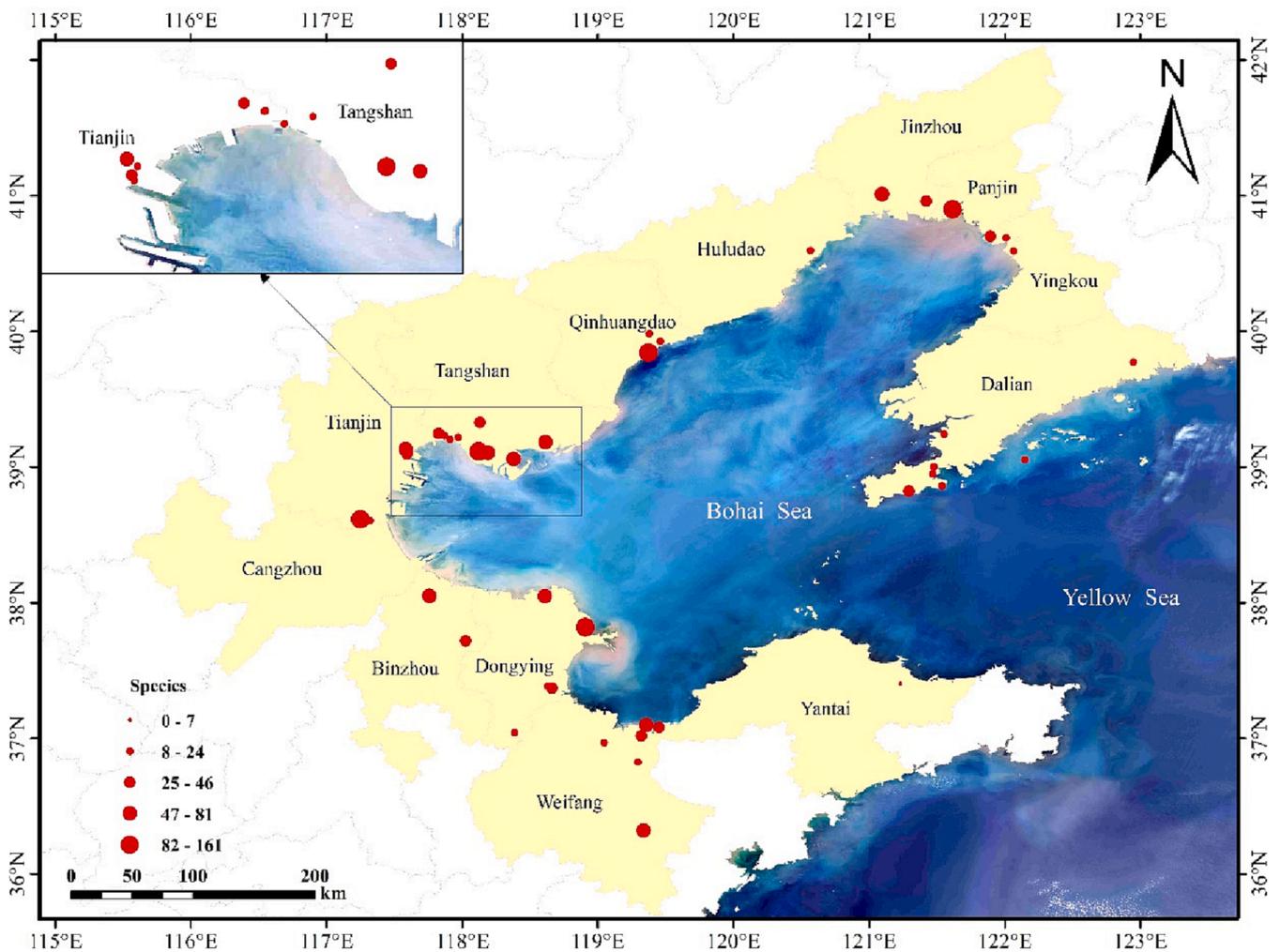
Fig. 2. Spatial distribution pattern of species along the Bohai Rim of China from 2002 to 2021.

region reached 161 species. The NWOs in the BNWP in 2002, 2012 and 2017 were lower than those in other years, and in general, the NWOs in 2003–2010 were higher than those in recent years. The NWO in the Caofeidian Wetland Park (CWP) peaked in 2018 and had continued to decline in recent years. The above five study areas were identified as waterbird hotspot regions.

3.3. Driving factors of waterbird change

The results showed that the AUC (area under the curve) values were greater than 0.94 in 2005, 2010, 2015 and 2020, indicating that the model has high accuracy and is valid for habitat suitability assessments and predictions of waterbird occurrences. The driving factor with the highest predicted contribution rate from the model in these four years was the NDVI, with a contribution of over 46%. The second highest contribution was from LC in 2005, 2015 and 2020, with a contribution of over 16%. The second highest contribution in 2010 came from the MTWM, which ranked as the third highest contribution in 2015 and 2020, with contributions of over 9.5%. The above three drivers were considered to be the main drivers affecting the habitat suitability of waterbirds along China's Bohai Rim in these four years and all contributed cumulatively to more than 74% of the influence effect (Fig. 4A). Driving factors with contributions ranging from 1.0 to 8.0% were considered as secondary variables affecting waterbird changes. In contrast, the contributions of PWM, MTCM, and AMT were less than 1% in all four years, which indicated that their impacts on waterbird habitat suitability were minimal.

The jackknife test results for the AUC values demonstrated that the NDVI, LC and TAR had the greatest impacts on the model prediction results in 2005 and 2010, while the NDVI, LC and GDP had the strongest effects on the model prediction results in 2015 and 2020. The driving factor with the large increase was the NDVI (Fig. 4B,C,D,E), so it appears to contain the most information that is not present in the other variables, indicating that it has the greatest impact on waterbird changes. This result was in good agreement with the contributions of environmental variables to the maximum entropy model.

3.4. Distribution of potentially suitable habitats for waterbirds

We combined the actual situation of waterbirds in the Bohai Rim and reclassified the model output using the natural breaks (*Jenks*) method to obtain a map of potentially suitable habitats for waterbirds in the Bohai Rim (Fig. 5). The distribution value levels and the corresponding distribution ranges are divided and indicated by different colors, 0.48 to 1.0 is high suitability area, while 0.23–0.48 is medium suitability area, 0.07 to 0.23 is low suitability area, and 0–0.07 is unsuitable area. The results of the hotspot analysis showed that the high suitability areas were mainly distributed in the coastal areas of Tianjin, Tangshan, Dongying and Dalian. Subsequently, the proportion of the total surface of each area that was covered by suitable habitat was determined (Table 3). In general, from 2005 to 2010, high suitability areas increased in the southern part of the Bohai Rim and decreased in the northern regions. The areas of high-, medium- and low-suitability habitats increased, with increases of 143 km² (0.12%), 125 km² (0.12%) and
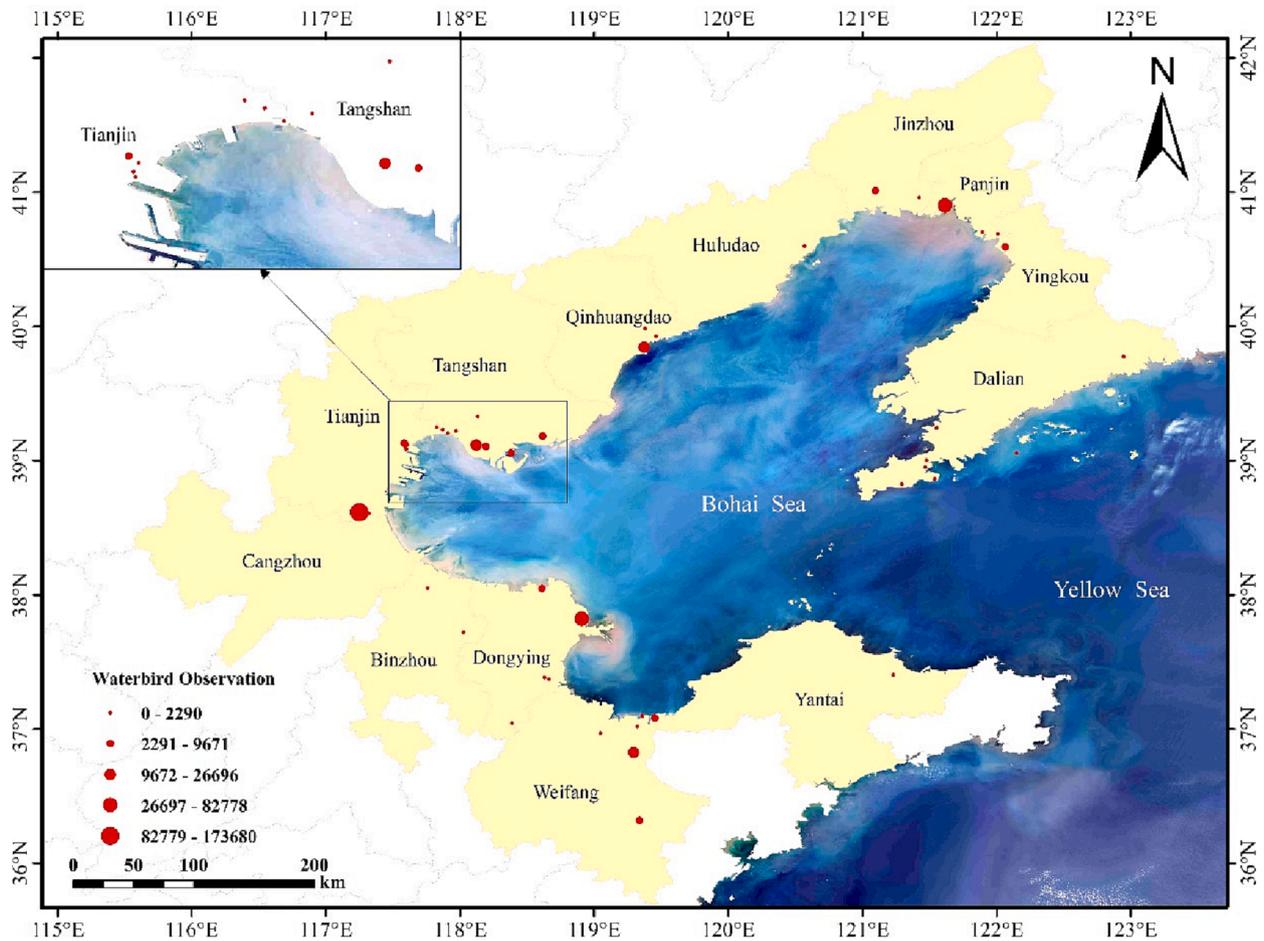
Fig. 3. Spatial distribution pattern of individuals along the Bohai Rim of China from 2002 to 2021.

Table 2
Changes in waterbird species and NWOs from 2002 to 2021.

Year	Number of species	NWO
2002–2006	160	28,651
2007–2011	119	68,471
2012–2016	127	96,935
2017–2021	145	265,172

2006 km^2 (1.61%), respectively, during this period. The area of low-suitability habitat decreased from 19,636 km^2 (15.17%) in 2010 to 13,896 km^2 (10.64%) in 2015, while the highly suitable area decreased by 743 km^2 (0.59%). Some regions changed from non-suitable areas to suitable areas between 2015 and 2020. The total area of highly suitable habitats expanded to 3,784 km^2 in 2020 (an increase of approximately 0.81% over the highly suitable area in 2015).

Specifically, for the BW, a waterbird hotspot, the area of low suitability regions accounted for more in 2005, and the area of high suitability regions then gradually increased. The CWP has always been in the high suitability area, and the total highly suitable area has increased rapidly between 2015 and 2020. The areas of high-suitability regions in the LEW and BNWP have increased significantly in the past 20 years. The area of high suitability habitat in the YRDNR showed a large-scale decline from 2010 to 2015 and a slight recovery after 2015.

Our data were subjected to extensive field observations and web collections, and finally we found a high degree of consistency between the simulated results and realistic waterbird data. Due to the limitation of article length, we do not show more pictures, and we give an example here to verify and re-evaluate the reliability of the method. As shown in

Fig. 6, the vast majority of waterbirds observed on site in the CWP area are located in high suitability area. And the negative effects of pedestrians on roads and overly deep ponds on waterbirds can also be shown on the map.

4. Discussion

4.1. Waterbird colony

The most investigated regions of waterbird communities in the past are located in the United States and northern Europe, and the most studied area in China is the Yellow Sea (Ogden, 2014; Pöysä and Linkola, 2021; Jackson et al., 2019). However, in China's Bohai Rim region, there is a paucity of relevant studies, which have mainly been concentrated in several important wetlands, such as the LEW and BW (Lin et al., 2022). In conclusion, this study presents the first comprehensive survey and statistics of waterbirds located in the coastal wetlands around the Bohai Rim over a 20-year period and analyzes the changes in spatial distributions and temporal distributions of waterbird populations.

The coastal areas around China's Bohai Rim are important locations for migratory birds along the East Asian-Australasian Flyway, as well as the main overwintering areas and habitats for birds (Barter, 2002; Hu et al., 2017). Additionally, waders were the most researched waterbird type within the region, as they are important waterbirds along the EAAF and are highly dependent on coastal mudflats (Amano et al., 2010). Field surveys have shown that we can also see some rare waterbirds in wetlands with stronger ecological environmental protections, including the Oriental stork, red-crowned crane, Siberian crane, and relict gull (Duan et al., 2020). Among them, we believe that some special species
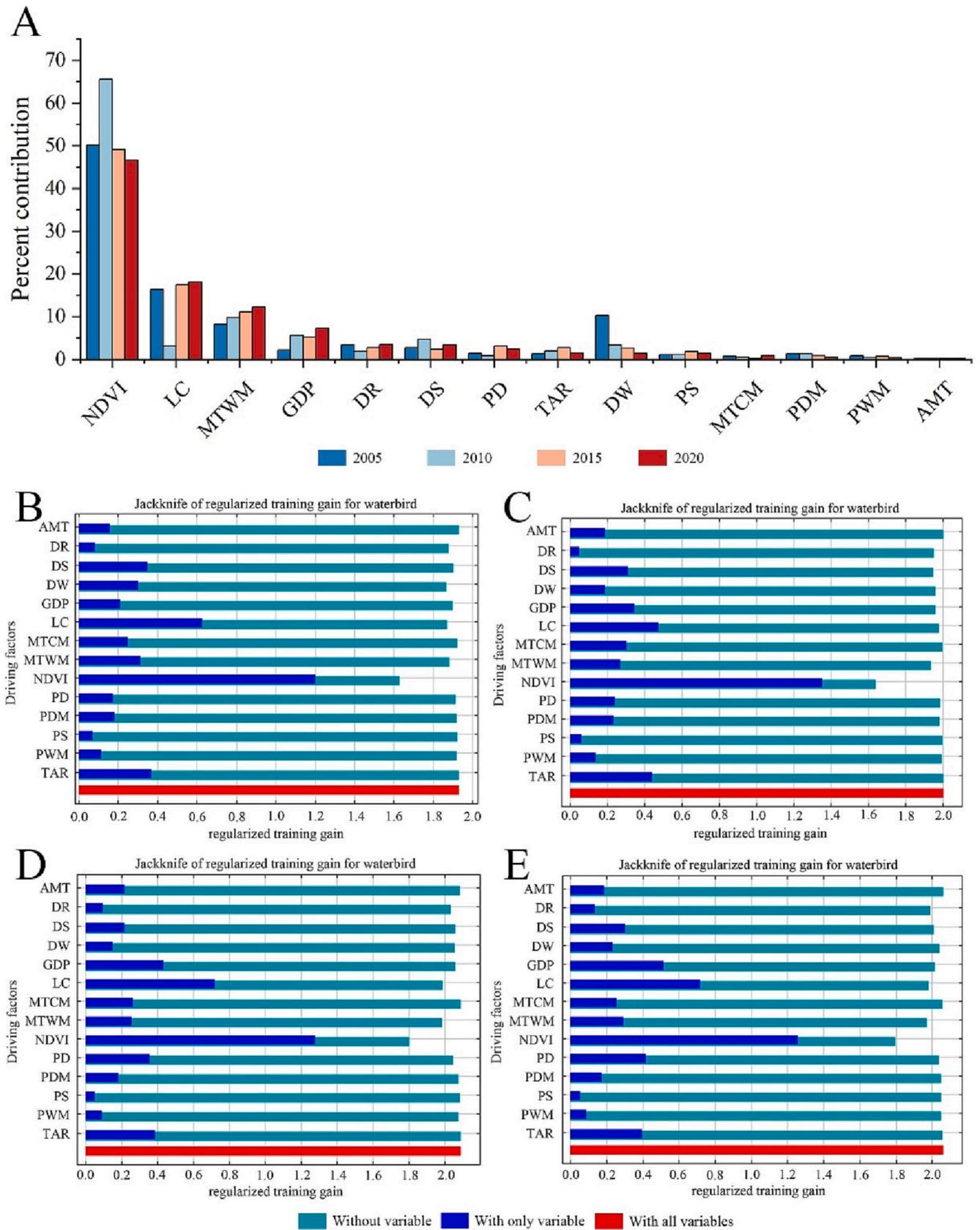
Fig. 4. MaxEnt model results of driving factors in 2005, 2010, 2015 and 2020. (A) Estimates of relative contributions of the driving factors to the MaxEnt model, contribution of the AMT is too low to be quantified. (B-E) The results of the jackknife test of variable importance.
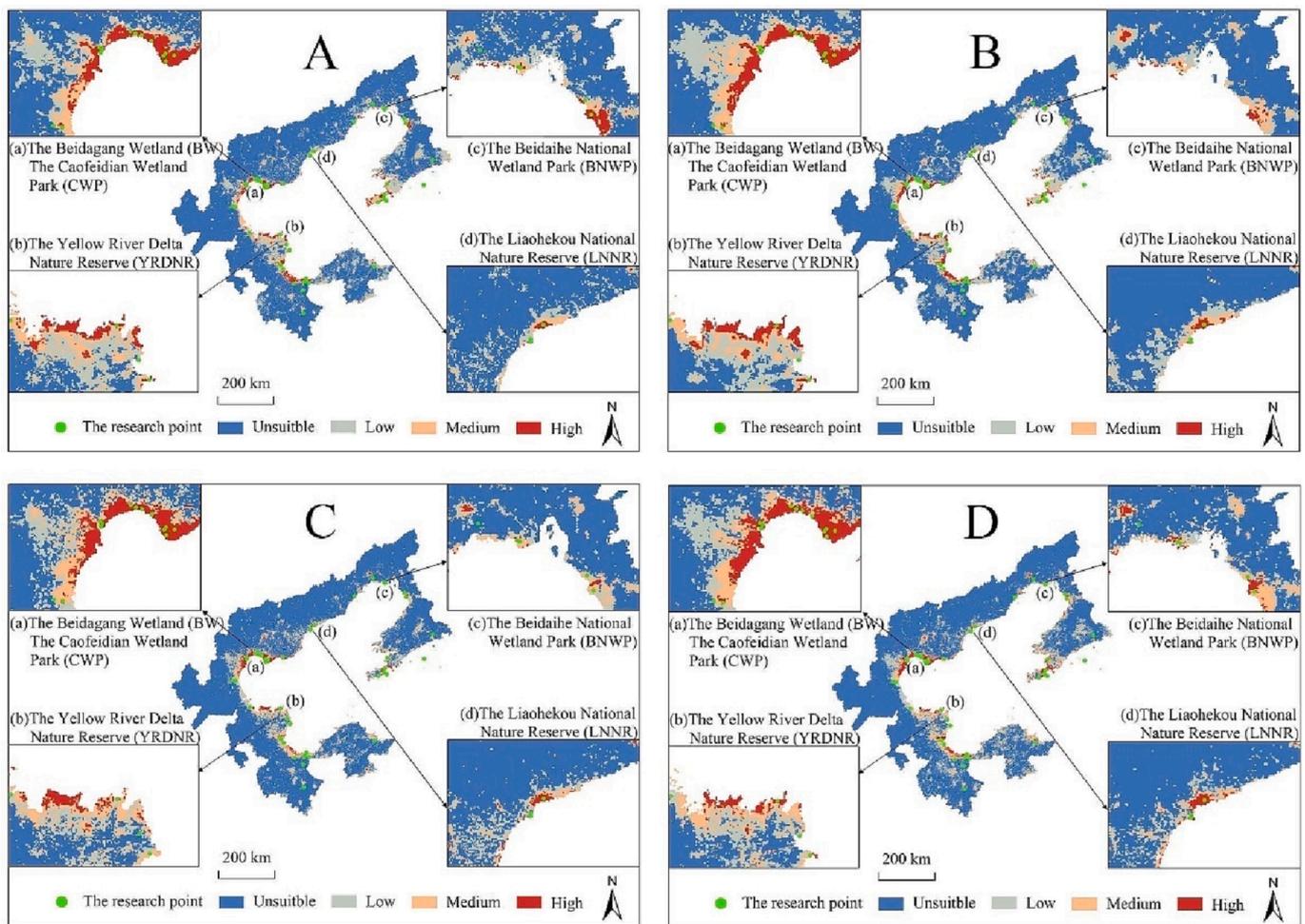
Fig. 5. Distribution areas of potential suitable habitats for waterbirds around the Bohai Rim in (A) 2005, (B) 2010, (C) 2015, and (D) 2020.

Table 3
The area and proportions of each suitability class of potential distributions for waterbirds around the Bohai Rim in 2005, 2010, 2015 and 2020.

Year	High		Medium		Low		Unsuitble		Total area
	Area /km^2	Proportion /%	Area /km^2	Proportion /%	Area /km^2	Proportion /%	Area /km^2	Proportion /%	Area /km^2
2020	3784	2.89	6905	5.28	17,213	13.16	102,921	78.67	130,823
2015	2724	2.09	6152	4.71	13,896	10.64	107,842	82.57	130,614
2010	3467	2.68	5756	4.45	19,636	15.17	100,609	77.71	129,468
2005	3324	2.56	5631	4.33	17,630	13.55	103,507	79.56	130,092

should be listed as flagship species and umbrella species in the region, and they should be listed as key conservation targets to guide the planning, construction and management of the wetlands around China's Bohai Rim according to the overwintering habits and ecological environment requirements of the flagship species and umbrella species.

Flagship species are species that attract public attention to their conservation actions on a regional or worldwide scale. Flagship species not only enable these species to be better protected, but also protect those species that are less influential by association. From all perspectives, both the Oriental stork and and relict gull certainly fit the meaning of flagship species. And, the umbrella species means that the habitat needs of this target species can cover the habitat needs of other species, and the habitat needs of such target species should combine the information of the habitat needs of other species. The habitat type, habits and food habits of the relict gull are highly representative, and such survival conditions are shared by other gull species and waders. If the survival conditions of the relict gull are ensured, the survival of other close

species will also be guaranteed. On the contrary, if the survival conditions of the relict gull are missing, more than just the relict gull will be lost. In recent years, relict gulls have gathered in the study area, they are numerous, dense, stay long, and highly dependent on the silty intertidal zone of coastal wetlands. We should seize this opportunity to create a suitable living environment for the flagship and umbrella species led by the relict gull through scientific planning, reasonable construction and effective management. On the one hand, it is to contribute to the wildlife conservation in China and even in the world. On the other hand, it is also a natural ecological business card for China's Bohai Rim.

4.2. Habitat preferences and drivers

Previous studies in the region have focused on reserves or local scales, and the populations and waterbird abundances have not been assessed at the same level as that of the Bohai Rim region. Therefore, it is not possible to know the dynamic changes in the waterbird community

Fig. 6. Distribution of waterbird research points in the CWP in 2020.

over a 20-year period. However, what types of habitats waterbird communities choose is precisely what is important to assess the state of the ecological environment (Gregory and van Strien, 2010; Eglington et al., 2012). Gabel et al. (2021) showed that colony site selection by long-legged wading birds is influenced by amphibians. A study in Taoyuan, Taiwan by Hsu et al. (2019) showed that waterbirds prefer artificial pond habitats compared to landbirds. Therefore, judging environmental merits through waterbird habitat preferences is a very reliable approach (Bilgin et al., 2016).

The results of this study showed that most waterbirds chose to inhabit natural wetlands, restored wetlands, or nature reserves. This could be, as discussed above, due to the many conservation measures implemented by the government and the public to maintain the environmental quality at a good level for 20 years, or alternatively, it could be due to the destruction of the original traditional habitats of waterbirds or limited food resources (Yang et al., 2017; Boggie et al., 2018; Wolfe et al., 2014).

Through field observations, nature reserves or wetland parks have been in established in the five waterbird hotspot regions examined in this study, but it is also possible that the number of birdwatchers has increased since the construction of tourist facilities.

The YRDNR is an important stopover site, wintering ground and breeding ground for inland northeast Asia, the western Pacific Rim and middle part of the East Asia-Australasian Flyway (Cao and Liu, 2008; Wang et al., 2013). This study shows that bird resources are rich in this region, which include many rare and endangered birds. The extensive extraction of petroleum resources from this wetland in the late 20th century led to environmental problems such as land pollution, fragmentation of the wetland landscape and surface exposures (Bi et al., 2011). Since 2002, when the YRDNR initiated a wetland restoration project in 2002 through artificial injection of freshwater, the natural wetlands and bird habitats in the lower reaches of the Yellow River have significantly improved, although some problems still exist (Cui et al., 2009). The BW is one of the most biodiverse areas in the study area and is an important stop during the north–south migration of migratory birds

in eastern Asia. The area has been severely artificialized over the past four decades, which has led to water scarcities, plant community degradation and soil salinization. However, since 2000, under the standardized management and protection of the government, the environment has greatly improved and was included in the List of Wetlands of International Importance in September 2020. This has resulted in a gradual upgrading of the BW from a low suitability area to a high suitability area over a period of 20 years. In contrast to the Tianjin government, since 2010, Qinhuangdao has implemented a waterfront ecological restoration and wetland bird sanctuary fencing project, and annual birdwatching activities have been conducted in the wetlands, leading to an increased number of birdwatchers, especially during the breeding season. This can have a great impact on the breeding and lives of waterbirds, which have been declining rapidly in species and numbers at the BNWP since 2010. Although the high suitability area has been increasing in size, our study determined that waterbirds have not chosen this area. In fact, we can see that ecological protection in the BNWP has played the opposite role, improved habitat quality, but has also introduced more human disturbances.

A study in northeastern China showed that national-level nature reserves are more effective than local-level nature conservation efforts (Wu et al., 2022a; Wu et al., 2022b). This finding is consistent with research showing that the waterbird diversity in the LEW is increasing. For the CWP, the decline in waterbirds after 2018 could be due to the absence of birdwatchers or the inability of suitable habitats to persist, and our observations found that waterbirds were unable to roost in deep water as well as in areas with very high vegetation.

In general, after the national comprehensive management of ecological and environmental problems in the Bohai Rim region occurred in recent years, the high suitability areas in the area have gradually recovered.

4.3. Suggestions for habitat restoration and management

The results of the MaxEnt model showed that three variables,

namely, NDVI, LC and MTWM, were the main factors that determined the waterbird distributions in the Bohai Rim. The large contribution of the NDVI index to the model confirms that this factor is significantly correlated with bird diversity and population dynamics (Liang et al., 2021; Paillisson et al., 2002). The effects of climate change and environmental pollution on plants have emerged as a multifactorial stress combination (Zandalinas et al., 2021). A study of shrubland areas in Lebanon showed that the NDVI was a good predictor of mesic plant species, so various factors can affect bird communities through plants (Hammoud and Stephan, 2022). One of the main manifestations of the global warming trend over the past 100 years is the increased maximum temperature of the warmest month (IPCC, 2022). Animal behaviors and community distributions are directly influenced by warming trends (Thomas et al., 2004; Gaget et al., 2018). A study conducted in northeast China showed that global warming affects waterbird diversity, especially in spring (Li et al., 2021). More specifically, rising maximum temperatures can alter the wintering ranges and migration routes of waterbirds (Haig et al., 2019). Land cover may represent food, shelter and natural enemies. Offshore wetlands are the type of land cover on which waterbirds depend; however, the rapid development of various industries in the Bohai Rim Economic Zone, one of the most economically developed regions in northern China, has led to a rapid shift in land use types (Zong et al., 2022). Economic development and urbanization can lead to the replacement of natural shorelines by artificial shorelines, environmental pollution, and wetland fragmentation, which has caused large shifts in habitat selection by waterbirds within 20 years (Meng et al., 2017; Wu et al., 2022a; Wu et al., 2022b). Through extensive field surveys, we found that the actual situation is consistent with the results simulated in this paper. The main causes of waterbird changes in each research point, especially in the five hotspot regions, were indeed NDVI (e.g., plant community degradation, surface exposure) and LC (e.g., water shortage, anthropogenic disturbance).

Our study shows that the GDP, DS, DR, DW, PD and TAR contribute to the temporal and spatial variations in waterbirds. The high contribution of DW in 2005 could be because there were few artificial breeding ponds at that time, and waterfowl could easily obtain food from ponds. A pronounced negative relationship between human activities and waterbird diversity was observed in the central part of the Gulf of Gabès in Tunisia (Hamza, 2020). In the study area, climatic factors such as PS and PDM had a lower influence in the current waterbird habitat suitability model. This may be due to attributing the significant impacts on wildlife distributions from a combination of climate change and anthropogenic activities to the contributions of the NDVI and LC (Rezende et al., 2020). This result is consistent with previous studies wherein rainfall and temperature can affect plant growth and soil biochemical properties that subsequently influence faunal activity (Tan and Jiang, 2016).

According to the analysis in this paper, environmental quality is a major factor that affects the migration and activity of waterbirds in the study area. Therefore, we must carefully consider habitat restoration and management strategies from an ornithological perspective to ensure that no harm is done to birds and habitats. Then, in combination with the driving factors, those areas with suboptimal conservation effectiveness are optimized to promote an increase in waterbird diversity and effective protection of the environment. We found from our field observations that food and shallow habitat are necessary conditions for waterbirds, especially for waders with long legs (Fig. 7). Therefore, we should select specific habitat restoration measures and refined management measures based on the necessary conditions observed in the field.

First of all, one of the fundamental roles of China's Bohai Rim wetlands in undertaking the migratory stopover, wintering and breeding role of birds is to provide suitable and sufficient food, and the diversity of habitats provides the possibility of diverse food sources. Aquatic life and water quality in the aquatic environment are key factors. Around the provision of food, the water environment and mudflats should be restored to their original state to ensure that water quality is up to standard and can be regulated. Moderate human interventions will also be necessary to enter the reserve as a daily technical task, so that the control of the water environment and the provision of food for birds can be controlled and meet the requirements of change. Secondly, water level regulation was performed for coastal mudflats. According to the needs of most waterbird and plant growth, the water level control should be $0.1 \sim 0.4$ m, and it needs to be a mutable marshy area. As the

Fig. 7. Example photo of waterbird sample. (A) Oriental stork, (B) relict gull, (C) Eurasian curlew, (D) Kentish plover.

water surface freezes in winter, it is necessary to leave deep water in a certain area of the lot, and the water depth is controlled at 1.5 m ~ 2.0 m or more to leave enough space for fish to spend the winter. Thirdly, environmental ecological monitoring needs to be strengthened. Environmental ecological monitoring should be carried out all year round to reduce the disturbance caused by human activities to birds and provide strong scientific support for habitat management. The above measures will help to improve habitat functions and waterbird diversities.

In this study, some of our data were obtained from open-source data from different birdwatchers, and the number of birdwatchers largely determined the number of waterbirds, which reduced the regularity of the results to some extent. However, observations and statistics of animals make it difficult to achieve absolute accuracy at any given time and to maintain long-term observations. However, this is also a difficult factor when conducting large-scale biodiversity research. As an exploratory study, our work still has a long way to go in terms of biodiversity conservation. Studies that use 3S techniques to explore the dynamics of organisms over multiple years at large regional scales and using models to find their drivers are still the trend.

5. Conclusion

This study recorded the numbers and species of waterbirds along China's Bohai Rim from 2002 to 2021. The results showed that the waterbird richness along China's Bohai Rim gradually increased over the 20-year study period, and more waterbird species were detected in wetland habitats than in other habitats. There are at least five waterbird hotspot regions that require special attention, including the Yellow River Delta Nature Reserve, Beidagang Wetland, Beidaihe National Wetland Park, Liaohe Estuary wetland and Caofeidian Wetland Park. Then, we quantified the potential suitable habitats and analyzed the driving factors of waterbirds using the MaxEnt model. The driving factors that have the greatest influence on waterbird changes are the NDVI, land cover and maximum temperature of the warmest month. The above work is conducive to revealing the spatiotemporal change mechanism of the Bohai Rim waterbird community and understanding the main factors that affect waterbird distributions. In addition, we recommend decreasing the management intensity of protected areas to reduce human disturbances. An enhanced systematic waterbird investigation can be useful to provide basic information for the long-term detection of waterbirds in the Bohai Rim. This will provide a reference and theoretical support for waterbird conservation and rational habitat use.

CRediT authorship contribution statement

Zhimei Huang: Conceptualization, Formal analysis, Resources, Data curation, Visualization, Writing – original draft. **Yalan Lu:** Formal analysis, Resources, Visualization, Data curation. **Weiqing Meng:** Conceptualization, Writing – review & editing, Project administration, Funding acquisition. **Xunqiang Mo:** Methodology, Validation, Supervision, Project administration. **Wenbin Xu:** Data curation, Visualization. **Haofan Yun:** Formal analysis, Data curation. **Mengxuan He:** Methodology, Validation, Supervision, Project administration. **Yidong Wang:** Methodology, Validation, Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2023.110229.

References

Amano, T., Székely, T., Koyama, K., Amano, H., Sutherland, W.J., 2010. A framework for monitoring the status of populations: An example from wader populations in the East Asian-Australasian flyway. Biol. Conserv. 10.

Arizaga, J., Cepeda, X., Maguregi, J., Unamuno, E., Ajuriagogeaskoa, A., Borregón, L., Azkona, A., Unamuno, J.M., 2014. The Influence of the Creation of a Lagoon on Waterbird Diversity in Urdaibai, Spain. Waterbirds 37, 111–118. https://doi.org/10.1675/063.037.0115.

Bai, J., Zhao, Q., Wang, W., Wang, X., Jia, J., Cui, B., Liu, X., 2019. Arsenic and heavy metals pollution along a salinity gradient in drained coastal wetland soils: Depth distributions, sources and toxic risks. Ecol. Ind. 96, 91–98. https://doi.org/10.1016/j.ecolind.2018.08.026.

Barter, M., 2002. Shorebirds of the Yellow Sea: Importance, Threats and Conservation Status. Emu - Austral Ornithology 117, 321–322. https://doi.org/10.1071/MUv104n3_BR1.

Bi, X., Wang, B., Lu, Q., 2011. Fragmentation effects of oil wells and roads on the Yellow River Delta, North China. Ocean Coast. Manag. 54, 256–264. https://doi.org/10.1016/j.ocecoaman.2010.12.005.

Bilgin, R., Ebeoğlu, N., İnak, S., Kırpık, M.A., Horns, J.J., Şekercioğlu, Ç.H., 2016. DNA Barcoding of Birds at a Migratory Hotspot in Eastern Turkey Highlights Continental Phylogeographic Relationships. PLoS One 11, e0154454.

Boggie, M.A., Collins, D.P., Donnelly, J.P., Carleton, S.A., 2018. Land Use, anthropogenic disturbance, and riverine features drive patterns of habitat selection by a wintering waterbird in a semi-arid environment. PLoS One 13, e0206222.

Calder, R.S.D., Shi, C., Mason, S.A., Olander, L.P., Borsuk, M.E., 2019. Forecasting ecosystem services to guide coastal wetland rehabilitation decisions. Ecosyst. Serv. 39, 101007 https://doi.org/10.1016/j.ecoser.2019.101007.

Cao, M., Liu, G., 2008. Habitat suitability change of red-crowned crane in Yellow River Delta Nature Reserve. J. For. Res. 7.

Chatterjee, A., Adhikari, S., Pal, S., Mukhopadhyay, S.K., 2020. Foraging guild structure and niche characteristics of waterbirds wintering in selected sub-Himalayan wetlands of India. Ecol. Ind. 108, 105693 https://doi.org/10.1016/j.ecolind.2019.105693.

Chen, Y., Song, Q., Pan, L., Jia, M., Li, C., Hu, B., Wu, G., 2018. Trace metals, organic carbon and nutrients in the Beidagang Wetland Nature Reserve, northern China. PLoS One 13, e0204812.

Crowe, O., Wilson, J., Aznar, I., More, S., 2009. A review of Ireland's waterbirds, with emphasis on wintering migrants and reference to H5N1 avian influenza. Ir. Vet. J. 62, 800. https://doi.org/10.1186/2046-0481-62-12-800.

Cui, P., Wu, Y., Ding, H., Wu, J., Cao, M., Chen, L., Chen, B., Lu, X., Xu, H., 2014. Status of Wintering Waterbirds at Selected Locations in China. Waterbirds 37, 402–409. https://doi.org/10.1675/063.037.0407.

Cui, B., Yang, Q., Yang, Z., Zhang, K., 2009. Evaluating the ecological performance of wetland restoration in the Yellow River Delta, China. Ecol. Eng. 35, 1090–1103. https://doi.org/10.1016/j.ecoleng.2009.03.022.

Dauda, T.O., Baksh, M.H., Shahrul, A., Mohd, S., 2017. Birds' species diversity measurement of Uchali Wetland (Ramsar site) Pakistan. J. Asia-Pac. Biodivers. 10, 167–174. https://doi.org/10.1016/j.japb.2016.06.011.

De Coster, G., Banks-Leite, C., Metzger, J.P., 2015. Atlantic forest bird communities provide different but not fewer functions after habitat loss. Proc. R. Soc. B 282, 20142844. https://doi.org/10.1098/rspb.2014.2844.

Duan, H., Xia, S., Jackson, M.V., Zhao, N., Liu, Y., Teng, J., Meng, Z., Yu, X., Shi, J., 2020. Identifying new sites of significance to waterbirds conservation and their habitat modification in the Yellow and Bohai Seas in China. Global Ecol. Conserv. 22, e01031.

Duan, H., Yu, X., Xia, S., Liu, Y., 2022. Comparison of IUCN and species distribution modeling-estimated ranges of shorebirds in Coastal Mainland China. Global Ecol. Conserv. 38, e02236.

Eglington, S.M., Noble, D.G., Fuller, R.J., 2012. A meta-analysis of spatial relationships in species richness across taxa: Birds as indicators of wider biodiversity in temperate regions. J. Nat. Conserv. 20, 301–309. https://doi.org/10.1016/j.jnc.2012.07.002.

Ekumah, B., Armah, F.A., Afrifa, E.K.A., Aheto, D.W., Odoi, J.O., Afitiri, A.-R., 2020. Geospatial assessment of ecosystem health of coastal urban wetlands in Ghana. Ocean Coast. Manag. 193, 105226 https://doi.org/10.1016/j.ocecoaman.2020.105226.

Elith, J., H. Graham, C., P. Anderson, R., Dudík, M., Ferrier, S., Guisan, A., J. Hijmans, R., Huettmann, F., R. Leathwick, J., Lehmann, A., Li, J., G. Lohmann, L., A. Loiselle, B., Manion, G., Moritz, C., Nakamura, M., Nakazawa, Y., McC. M. Overton, J.,

Townsend Peterson, A., J. Phillips, S., Richardson, K., Scachetti-Pereira, R., E. Schapire, R., Soberón, J., Williams, S., S. Wisz, M., E. Zimmermann, N., 2006. Novel methods improve prediction of species' distributions from occurrence data. Ecography 29, 129–151. 10.1111/j.2006.0906-7590.04596.x.

Elith, J., Phillips, S.J., Hastie, T., Dudík, M., Chee, Y.E., Yates, C.J., 2011. A statistical explanation of MaxEnt for ecologists: Statistical explanation of MaxEnt. Divers. Distrib. 17, 43–57. https://doi.org/10.1111/j.1472-4642.2010.00725.x.

Gabel, W., Frederick, P., Zabala, J., 2021. Alligator presence influences colony site selection of long-legged wading birds through large scale facilitative nest protector relationship. Sci. Rep. 11, 1019. https://doi.org/10.1038/s41598-020-80185-5.

Gaget, E., Galewski, T., Jiguet, F., Le Viol, I., 2018. Waterbird communities adjust to climate warming according to conservation policy and species protection status. Biol. Conserv. 227, 205–212. https://doi.org/10.1016/j.biocon.2018.09.019.

Gao, X., Zhou, F., Chen, C.-T.-A., 2014. Pollution status of the Bohai Sea: An overview of the environmental quality assessment related trace metals. Environ. Int. 62, 12–30. https://doi.org/10.1016/j.envint.2013.09.019.

Gawlik, D.E., 2002. THE EFFECTS OF PREY AVAILABILITY ON THE NUMERICAL RESPONSE OF WADING BIRDS. Ecol. Monogr. 72, 329–346. https://doi.org/10.1890/0012-9615(2002)072[0329:TEOPAO]2.0.CO;2.

Grand, J., Saunders, S.P., Michel, N.L., Elliott, L., Beilke, S., Bracey, A., Gehring, T.M., Gnass Giese, E.E., Howe, R.W., Kasberg, B., Miller, N., Niemi, G.J., Norment, C.J., Tozer, D.C., Wu, J., Wilsey, C., 2020. Prioritizing coastal wetlands for marsh bird conservation in the U.S. Great Lakes. Biol. Conserv. 249, 108708 https://doi.org/10.1016/j.biocon.2020.108708.

Graves, E.E., Holyoak, M., Kelsey, T.R., Meese, R.J., 2013. Understanding the contribution of habitats and regional variation to longterm population trends in tricolored blackbirds 14.

Green, A.J., Elmberg, J., 2014. Ecosystem services provided by waterbirds: Ecosystem services provided by waterbirds. Biol. Rev. 89, 105–122. https://doi.org/10.1111/brv.12045.

Gregory, R.D., van Strien, A., 2010. Wild Bird Indicators: Using Composite Population Trends of Birds as Measures of Environmental Health. Ornithol. Sci. 9, 3–22. https://doi.org/10.2326/osj.9.3.

Haig, S.M., Murphy, S.P., Matthews, J.H., Arismendi, I., Safeeq, M., 2019. Climate-Altered Wetlands Challenge Waterbird Use and Migratory Connectivity in Arid Landscapes. Sci. Rep. 9, 4666. https://doi.org/10.1038/s41598-019-41135-y.

Hammoud, Y., Stephan, J., 2022. Novelty predictors for shrub (and climbers) ecological niche modeling, based on their successional stage. Eco. Inform. 71, 101771 https://doi.org/10.1016/j.ecoinf.2022.101771.

Hamza, F., 2020. Impacts of human activities on diversity of wintering waterbirds: Assessment in Mediterranean coastal area. Ocean Coast. Manag. 198, 105317 https://doi.org/10.1016/j.ocecoaman.2020.105317.

Hansen, B.D., Szabo, J.K., Fuller, R.A., Clemens, R.S., Rogers, D.I., Milton, D.A., 2021. Insights from long-term shorebird monitoring for tracking change in ecological character of Australasian Ramsar sites. Biol. Conserv. 260, 109189 https://doi.org/10.1016/j.biocon.2021.109189.

Harte, J., Newman, E.A., 2014. Maximum information entropy: a foundation for ecological theory. Trends Ecol. Evol. 29, 384–389. https://doi.org/10.1016/j.tree.2014.04.009.

Heo, Lee, Kim, Kwon, Park, Kang, Kim, Kim, Kim, 2019. Fungal Diversity in Intertidal Mudflats and Abandoned Solar Salterns as a Source for Biological Resources. Marine Drugs 17, 601. 10.3390/md17110601.

Hernandez, P.A., Graham, C.H., Master, L.L., Albert, D.L., 2006. The effect of sample size and species characteristics on performance of different species distribution modeling methods. Ecography 29, 773–785. https://doi.org/10.1111/j.0906-7590.2006.04700.x.

Hsu, C.-H., Chou, J.-Y., Fang, W.-T., 2019. Habitat Selection of Wintering Birds in Farm Ponds in Taoyuan, Taiwan. Animals 9, 113. https://doi.org/10.3390/ani9030113.

Hu, R., Wen, C., Gu, Y., Wang, H., Gu, L., Shi, X., Zhong, J., Wei, M., He, F., Lu, Z., 2017. A bird's view of new conservation hotspots in China. Biol. Conserv. 211, 47–55. https://doi.org/10.1016/j.biocon.2017.03.033.

IPCC, 2022. Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA.

Ismail, A., Rahman, F., 2013. Does Weather Play an Important Role in the Early Nesting Activity of Colonial Waterbirds A Case Study in Putrajaya Wetlands, Malaysia.pdf.

IUCN (2017). The IUCN Red List of Threatened Species. Version 2. Retrieved from www.iucnredlist.org.

IUCN (2018). The IUCN Red List of Threatened Species. Version 2018–1. Retrieved from www.iucnredlist.org.

Jackson, M.V., Carrasco, L.R., Choi, C., Li, J., Ma, Z., Melville, D.S., Mu, T., Peng, H., Woodworth, B.K., Yang, Z., Zhang, L., Fuller, R.A., 2019. Multiple habitat use by declining migratory birds necessitates joined-up conservation. Ecol. Evol. 9, 2505–2515. https://doi.org/10.1002/ece3.4895.

Jackson, M.V., Choi, C.-Y., Amano, T., Estrella, S.M., Lei, W., Moores, N., Mundkur, T., Rogers, D.I., Fuller, R.A., 2020. Navigating coasts of concrete: Pervasive use of artificial habitats by shorebirds in the Asia-Pacific. Biol. Conserv. 247, 108591 https://doi.org/10.1016/j.biocon.2020.108591.

Kufa, C.A., Bekele, A., Atickem, A., 2022. Impacts of climate change on predicted habitat suitability and distribution of Djaffa Mountains Guereza (Colobus guereza gallarum, Neumann 1902) using MaxEnt algorithm in Eastern Ethiopian Highland. Global Ecol. Conserv. 35, e02094.

Li, X., Anderson, C.J., Wang, Y., Lei, G., 2021. Waterbird diversity and abundance in response to variations in climate in the Liaohe Estuary, China. Ecol. Indicat. 132, 108286 https://doi.org/10.1016/j.ecolind.2021.108286.

Liang, J., Meng, Q., Li, X., Yuan, Y., Peng, Y., Li, X., Li, S., Zhu, Z., Yan, M., 2021. The influence of hydrological variables, climatic variables and food availability on Anatidae in interconnected river-lake systems, the middle and lower reaches of the Yangtze River floodplain. Sci. Total Environ. 768, 144534 https://doi.org/10.1016/j.scitotenv.2020.144534.

Liao, J., Liao, T., He, X., Zhang, T., Li, D., 2020. The effects of agricultural landscape composition and heterogeneity on bird diversity and community structure in the Chengdu Plain, China. Global Ecology and Conservation 15.

Lin, Y., Cui, Q., Li, H., He, C., 2022. Assessment of importance of 64 Ramsar sites in China for waterfowl. Global Ecol. Conserv. 33, e01950.

Liu, H., Zhang, S., Li, Z., Lu, X., Yang, Q., 2004. Impacts on Wetlands of Large-scale Land-use Changes by Agricultural Development: The Small Sanjiang Plain, China. AMBIO: J. Human Environ. 33, 306–310. https://doi.org/10.1579/0044-7447-33.6.306.

Meng, W., Hu, B., He, M., Liu, B., Mo, X., Li, H., Wang, Z., Zhang, Y., 2017. Temporal-spatial variations and driving factors analysis of coastal reclamation in China. Estuar. Coast. Shelf Sci. 191, 39–49. https://doi.org/10.1016/j.ecss.2017.04.008.

Ogden, J.C., 2014. Waterbirds as indicators of ecosystem health in the coastal marine habitats of southern Florida: 1. Selection and justification for a suite of indicator species 16.

Paillisson, J.-M., Reeber, S., Marion, L., 2002. Bird assemblages as bio-indicators of water regime management and hunting disturbance in natural wet grasslands. Biol. Conserv. 106, 115–127. https://doi.org/10.1016/S0006-3207(01)00239-7.

Phillips, S.J., Anderson, R.P., Schapire, R.E., 2006. Maximum entropy modeling of species geographic distributions. Ecol. Model. 190, 231–259. https://doi.org/10.1016/j.ecolmodel.2005.03.026.

Phillips, S.J., Dudík, M., 2008. Modeling of species distributions with Maxent: new extensions and a comprehensive evaluation. Ecography 31, 161–175. https://doi.org/10.1111/j.0906-7590.2008.5203.x.

Pocewicz, A., Estes-Zumpf, W.A., Andersen, M.D., Copeland, H.E., Keinath, D.A., Griscom, H.R., 2013. Modeling the Distribution of Migratory Bird Stopovers to Inform Landscape-Scale Siting of Wind Development. PLoS One 8, e75363.

Pöysä, H., Linkola, P., 2021. Extending temporal baseline increases understanding of biodiversity change in European boreal waterbird communities. Biol. Conserv. 257, 109139 https://doi.org/10.1016/j.biocon.2021.109139.

Rezende, G., Sobral-Souza, T., Culot, L., 2020. Integrating climate and landscape models to prioritize areas and conservation strategies for an endangered arboreal primate. Am. J. Primatol. 82 https://doi.org/10.1002/ajp.23202.

Ronconi, R.A., Allard, K.A., Taylor, P.D., 2015. Bird interactions with offshore oil and gas platforms: Review of impacts and monitoring techniques. J. Environ. Manage. 147, 34–45. https://doi.org/10.1016/j.jenvman.2014.07.031.

Song, K., Choi, Y.-E., Han, H.-J., Chon, J., 2021. Adaptation and transformation planning for resilient social-ecological system in coastal wetland using spatial-temporal simulation. Sci. Total Environ. 789, 148007 https://doi.org/10.1016/j.scitotenv.2021.148007.

Steen, V., Skagen, S.K., Noon, B.R., 2014. Vulnerability of Breeding Waterbirds to Climate Change in the Prairie Pothole Region, U.S.A. PLoS One 9, e96747.

Sun, X., Liu, W., Li, S., Chen, P., Cao, M., Randhir, T.O., Zhang, Y., 2021. Species richness patterns of waterbirds overwintering on the Jiangsu coast for coastal reclamation. Ocean Coast. Manag. 205, 105488 https://doi.org/10.1016/j.ocecoaman.2020.105488.

Tan, Z., Jiang, J., 2016. Spatial–Temporal Dynamics of Wetland Vegetation Related to Water Level Fluctuations in Poyang Lake, China 15.

Thomas, C.D., Cameron, A., Green, R.E., Bakkenes, M., Beaumont, L.J., Collingham, Y.C., Erasmus, B.F.N., de Siqueira, M.F., Grainger, A., Hannah, L., Hughes, L., Huntley, B., van Jaarsveld, A.S., Midgley, G.F., Miles, L., Ortega-Huerta, M.A., Peterson, A.T., Phillips, O.L., Williams, S.E., 2004. Extinction risk from climate change 427, 4.

Tu, H.-M., Fan, M.-W., Ko, J.-C.-J., 2020. Different Habitat Types Affect Bird Richness and Evenness. Sci. Rep. 10, 1221. https://doi.org/10.1038/s41598-020-58202-4.

Wang, H., Gao, J., Ren, L.-L., Kong, Y., Li, H., Li, L., 2013. Assessment of the red-crowned crane habitat in the Yellow River Delta Nature Reserve, East China. Reg. Environ. Chang. 13, 115–123. https://doi.org/10.1007/s10113-012-0325-2.

Wang, X., Kuang, F., Tan, K., Ma, Z., 2018. Population trends, threats, and conservation recommendations for waterbirds in China. Avian Res. 9, 14. https://doi.org/10.1186/s40657-018-0106-9.

Wang, Z., Li, N., Gao, S., An, S., 2020. Response of wintering waterbird diversity to reclamation history and post-reclamation habitat along Yellow Sea coast. Integr. Zool. 15, 595–602. https://doi.org/10.1111/1749-4877.12464.

Wang, C., Wang, G., Dai, L., Liu, H., Li, Y., Qiu, C., Zhou, Y., Chen, H., Dong, B., Zhao, Y., Zhang, Y., 2021. Study on the effect of habitat function change on waterbird diversity and guilds in Yancheng coastal wetlands based on structure–function coupling. Ecol. Ind. 122, 107223 https://doi.org/10.1016/j.ecolind.2020.107223.

Wang, R., Yang, X., 2021. Nestedness theory suggests wetland fragments with large areas and macrophyte diversity benefit waterbirds. Ecol. Evol. 11, 12651–12664. https://doi.org/10.1002/ece3.8009.

Wei, F., Han, G., Han, M., Zhang, J., Li, Y., Zhao, J., 2019. Temporal-spatial Dynamic Evolution and Mechanism of Shoreline and the Sea Reclamation in the Bohai Rim During 1980–2017. Sci. Geogr. Sin. 39 (6), 997–1007 (in Chinese). 10.13249/j.cnki.sgs.2019.06.015.

Wen, C., Gu, Y., Huang, Y., 2020. The Global Comparative Analysis on the Outstanding Universal Values of the Serial Nominated Properties of Migratory Bird Sanctuaries along the Coast of Yellow Sea and Bohai Sea in China. Study on Natural and Cultural. Heritage 04, 001–012 (in Chinese). 10.19490/j.cnki.issn2096-698X.2020.04.001-012.

Wen, L., Saintilan, N., Reid, J.R.W., Colloff, M.J., 2016. Changes in distribution of waterbirds following prolonged drought reflect habitat availability in coastal and inland regions. Ecol. Evol. 6, 6672–6689. https://doi.org/10.1002/ece3.2091.

Whelan, C.J., Wenny, D.G., Marquis, R.J., 2008. Ecosystem Services Provided by Birds. Ann. N. Y. Acad. Sci. 1134, 25–60. https://doi.org/10.1196/annals.1439.003.

Wolfe, J.D., Johnson, M.D., Ralph, C.J., 2014. Do Birds Select Habitat or Food Resources? Nearctic-Neotropic Migrants in Northeastern Costa Rica. PLoS One 9, e86221.

Wu, H., Fang, S., Yang, Y., Cheng, J., 2022a. Changes in habitat quality of nature reserves in depopulating areas due to anthropogenic pressure: Evidence from Northeast China, 2000–2018. Ecol. Ind. 12.

Wu, W., Zhi, C., Gao, Y., Chen, C., Su, H., Lu, W., Tian, B., 2022b. Increasing fragmentation and squeezing of coastal wetlands: Status, drivers, and sustainable protection from the perspective of remote sensing. Sci. Total Environ. 811, 152339 https://doi.org/10.1016/j.scitotenv.2021.152339.

Xia, S., Yu, X., Millington, S., Liu, Y., Jia, Y., Wang, L., Hou, X., Jiang, L., 2016. Identifying priority sites and gaps for the conservation of migratory waterbirds in China's coastal wetlands 11.

Xu, Q., Zhou, L., Xia, S., Zhou, J., 2022. Impact of Urbanisation Intensity on Bird Diversity in River Wetlands around Chaohu Lake, China. Animals 12, 473. https://doi.org/10.3390/ani12040473.

Yang, H.-Y., Chen, B., Barter, M., Piersma, T., Zhou, C.-F., Li, F.-S., Zhang, Z.-W., 2011. Impacts of tidal land reclamation in Bohai Bay, China: ongoing losses of critical Yellow Sea waterbird staging and wintering sites. Bird Conservat. Int. 21, 241–259. https://doi.org/10.1017/S0959270911000086.

Yang, H., Ma, M., Thompson, J.R., Flower, R.J., 2017. Protect coastal wetlands in China to save endangered migratory birds. PNAS 114. https://doi.org/10.1073/pnas.1706111114.

Zandalinas, S.I., Fritschi, F.B., Mittler, R., 2021. Global Warming, Climate Change, and Environmental Pollution: Recipe for a Multifactorial Stress Combination Disaster. Trends Plant Sci. 26, 588–599. https://doi.org/10.1016/j.tplants.2021.02.011.

Zhou, J., Zhou, L., Xu, W., 2020. Diversity of wintering waterbirds enhanced by restoring aquatic vegetation at Shengjin Lake, China. Sci. Total Environ. 737, 140190 https://doi.org/10.1016/j.scitotenv.2020.140190.

Zong, S., Hu, Y., Bai, Y., Guo, Z., Wang, J., 2022. Analysis of the distribution characteristics and driving factors of land use conflict potentials in the Bohai Rim coastal zone. Ocean Coast. Manag. 226, 106260 https://doi.org/10.1016/j.ocecoaman.2022.106260.