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Research article

Behavioral and functional responses of different bird clades to offshore windfarms in yellow sea, China

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ABSTRACT

Offshore windfarms (OWFs) constitute a rapidly expanding source of renewable energy that inevitably affects marine biodiversity, especially those built within critical areas for biodiversity conservation. To understand the potential effect of OWFs on bird communities, we systematically tracked bird communities and their behavior within OWFs near the Migratory Bird Sanctuaries along the Coast of the Yellow Sea in China from 2020 to 2022 using voyage investigations. The results indicated that bird diversity was greater within OWFs than in seawaters away from the OWFs. The composition of the bird community varied at different distance scales and the closer to the windfarm, the higher the number of birds from the Laridae and Anatidae. In addition, the flight heights of Laridae, Accipitridae, and Anatidae overlapped with the rotor-swept zones, and there were significant altitudinal variations in the OWFs and nearby waters. Based on 16 functional traits and the devised risk assessment function, we found that OWFs could have distinct impacts on different birds. Birds of the family Accipitridae, which have a larger body size, are likely to experience more stress from OWFs than other families. And, fish-eating birds, such as Laridae and Anatidae, have higher risk scores due to their closer proximity to the windfarm, medium body size and greater number of individuals. However, Passeriformes with smaller body size and fewer individuals have lower risk values. Our study revealed in detail the different strategies used by birds to cope with OWFs and provides a theoretical basis for rationalizing the conservation of bird diversity at these locations.

1. Introduction

The biodiversity of marine and coastal habitats is experiencing unprecedented deleterious changes owing to the rapid development of marine activities worldwide (Eddy et al., 2021; Herbert-Read et al., 2022; Xu et al., 2021; Perino et al., 2022). The conservation of marine ecosystems and biodiversity is of great concern to different international organizations and countries (Gjerde et al., 2022; Zhou et al., 2021). The fifteenth Conference of the Parties to the United Nations Convention on Biological Diversity released a global biodiversity framework that aims to slow and then reverse the loss of marine biodiversity, ensuring that, by 2030, at least 30% of coastal and marine areas, especially those of particular importance for biodiversity and ecosystem functions and services, are effectively conserved and managed (CBD, 2022). Although offshore windfarms (OWFs) play a vital role in mitigating the impacts of climate change and constitute a source of renewable energy, their construction inevitably impacts biodiversity conservation (Dinh et al., 2022; Virtanen et al., 2022). Therefore, it is important to understand not

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only how OWF construction directly affects biodiversity, but also how biodiversity responds to OWFs, which has synergistic value for biodiversity conservation and sustainable development.

Sustainable development is a global priority, and its aims include reducing greenhouse gas emissions while enhancing energy production (Virtanen et al., 2022). To meet this goal, countries around the world are vigorously developing their wind power industry and have formulated long-term plans for future development (Díaz and Soares, 2020; Dinh et al., 2022). For instance, the Spanish government has stipulated the generation of 89 GW of wind and solar photovoltaic energy in the draft of the national integrated Energy and Climate Plan for 2021–2030 (Ministerio Para la Transición Ecológica y el Reto Demográfico, 2020). In October 2023, the U.S. government approved the construction of the nation's largest OWF project, which is to be located approximately 23.5 nautical miles offshore from Virginia Beach (Powers et al., 2022). In addition, driven by its carbon neutrality goals, renewable energy growth in China is accelerating rapidly, and China has become the world's largest developer of offshore wind power (Fan et al., 2022; Xia et al., 2023). For example, the world's biggest OWF in terms of single-unit capacity has been built in Pingtan City, Fujian Province, China, with a planned offshore area of 7.63 km^2. This OWF can reduce sulfur dioxide emissions by about 63.34 tons and carbon dioxide emissions by approximately 283,800 tons. Based on the current green development goals of the United Nations Framework Convention on Climate Change, global OWF construction is in a long-term rapid development stage (de Vasconcelos et al., 2022). Notably, however, there is a high overlap between areas of windfarm construction and biodiversity hotspots, such as nature reserves, key migratory flyways, and natural heritage sites, which may lead to a decline in habitats, thereby posing a potential risk for biodiversity conservation (Virtanen et al., 2022).

The boom in the construction of wind power projects directly or indirectly increases the environmental pressures on flora and fauna, posing a major challenge to biodiversity conservation (Virtanen et al., 2022). Numerous studies have reported that wind power construction can affect the survival of animals such as birds, bats, and dolphins, leading to high mortality, behavioral avoidance, and reproductive failure, among other effects (Gaultier et al., 2020; Hung, 2020; Cabrera-Cruz et al., 2020; Serrano et al., 2020). Bird mortality rates have been estimated to range between 0.02 and 7.36 birds per turbine per year (Wang et al., 2015). A study in dozens of windfarms in the UK found that the densities of Willow Ptarmigan (*Lagopus scoticus*), Common Snipe (*Gallinago*), and Eurasian Curlew (*Numenius arquata*) declined during the windfarm construction phase, and the densities of two species failed to recover after the construction phase, suggesting that windfarms may have an irreversible inhibitory effect on some birds (Pearce-Higgins et al., 2012). Windfarms also elicit changes in habitat topography, altering its original microclimate and affecting habitat choice for birds (Lindeboom et al., 2015). The most obvious and well-studied negative impacts above the sea surface around OWFs have been detected among species of conservation value. Several seabird species, such as the Common Murre (*Uria aalge*) and the Northern Gannet (*Morus bassanus*), show a distinct avoidance of operational OWFs (Vanermen et al., 2015). Through GPS tracking and radar monitoring, some birds were found to change flight direction or flight altitude inside and outside of windfarms, which may be an indication of windfarm avoidance (Chen et al., 2021; Schwemmer et al., 2023). Tracking of the Black-faced Spoonbill (*Platalea minor*), an endangered bird listed in the IUCN red list, has shown that the migration routes of this bird highly coincide with the presence of windfarms (Chen et al., 2021).

Studies to date have primarily focused on the threat of OWFs to biodiversity, and there is a knowledge gap concerning how different bird phylogenetic guilds respond to the operation and construction of windfarms, especially regarding behavioral and functional traits, which are important for clarifying bird-specific protection. There may also be variation in the adaptability of different bird species to windfarms owing to differences in functional traits such as diet, flight altitude, and body size. Studies on terrestrial windfarms have shown that populations of larger-bodied, fast-flying, migratory species are more sensitive to windfarms (Gasparatos et al., 2017). A survey of a terrestrial windfarm in Germany showed that it had a greater negative effect on waders and raptors than on smaller birds such as finches (Gasparatos et al., 2017). There may be differences in the responses of distinct functional groups of birds to OWFs. Thus, to determine the precise effects of windfarms on bird communities, the functional traits of different birds need to be considered (Thaxter et al., 2017).

Recognizing this conflict between the development of OWFs and biodiversity conservation (Boussarie et al., 2023), we sought to address key questions relating to how birds respond to OWFs. Unlike terrestrial windfarms, where several habitats may coexist, OWFs are characterized by a single marine habitat and are thus more appropriate for investigating the adaption of different bird guilds to habitat change. To understand the effect of OWFs on bird diversity, and how birds respond to the presence of OWFs, standard monitoring of a marine bird community was conducted in OWFs adjacent to marine and coastal biodiversity hotpots where the development of OWFs is most intensive. Furthermore, this study was conceived to ascertain whether there are differences in the degree of stress caused by wind power construction on different birds, by integrating functional traits such as morphology and behavior.

2. Material and methods

2.1. Study areas

To fully understand the impacts of OWFs on bird communities, fieldwork was undertaken in the offshore waters adjacent to the Yellow Sea-Bohai World Natural Heritage Site, China (Fig. 1). The study area included Jiangsu Yancheng Wetland National Nature Reserve and Dafeng Elk National Nature Reserve, extensive natural habitats that support an abundance of birds and many rare and endangered species. The offshore waters adjacent to the World Natural Heritage Site also have foraging and roosting areas, which are important habitats for marine birds (Wei et al., 2023). However, owing to the ease of piling and the abundance of wind resources, offshore waters are a hotspot for the construction of OWFs with a high density of wind turbines. The number of installed OWFs in Jiangsu has been estimated to account for 37% of the OWFs in the country and can produce more than 11 million kilowatts of energy, the most in China. The Renewable Energy Development Special Plan of Jiangsu stipulated that, by 2025, the province's total wind power installed capacity should reach 28 million kilowatts or more, with offshore wind power accounting for at least 15 million kilowatts. Accordingly, given their roles as hotspots of development and conservation, the heritage site and the offshore waters are suitable for studying how to balance the construction of OWFs with bird diversity conservation.

2.2. Field survey of bird diversity

To collect comprehensive bird diversity and behavioral data in the study area, the research team used voyage surveys to conduct bird surveys within the OWFs and surrounding sea areas during full tides in the four seasons from 2020 to 2022. It is not feasible to conduct marine bird surveys during a non-full tide phase. At low tide, while large flocks of birds may be observed foraging on the mudflats, it will be challenging to collect data on some functional traits such as flight height. Additionally, habitat characteristics exert a stronger influence on birds, and habitats such as mudflats enhance the information on habitat variables in this study. This makes it difficult to integrate the observed traits on the response of birds to windfarms at sea and on mudflats. During high tide, the mudflats outside the seawalls in the study area are completely covered by seawater, creating a single seawater habitat. Birds that use the mudflats would fly to the high-tide habitat inside the seawalls. To eliminate the potential impact of habitat-related factors, we focused on

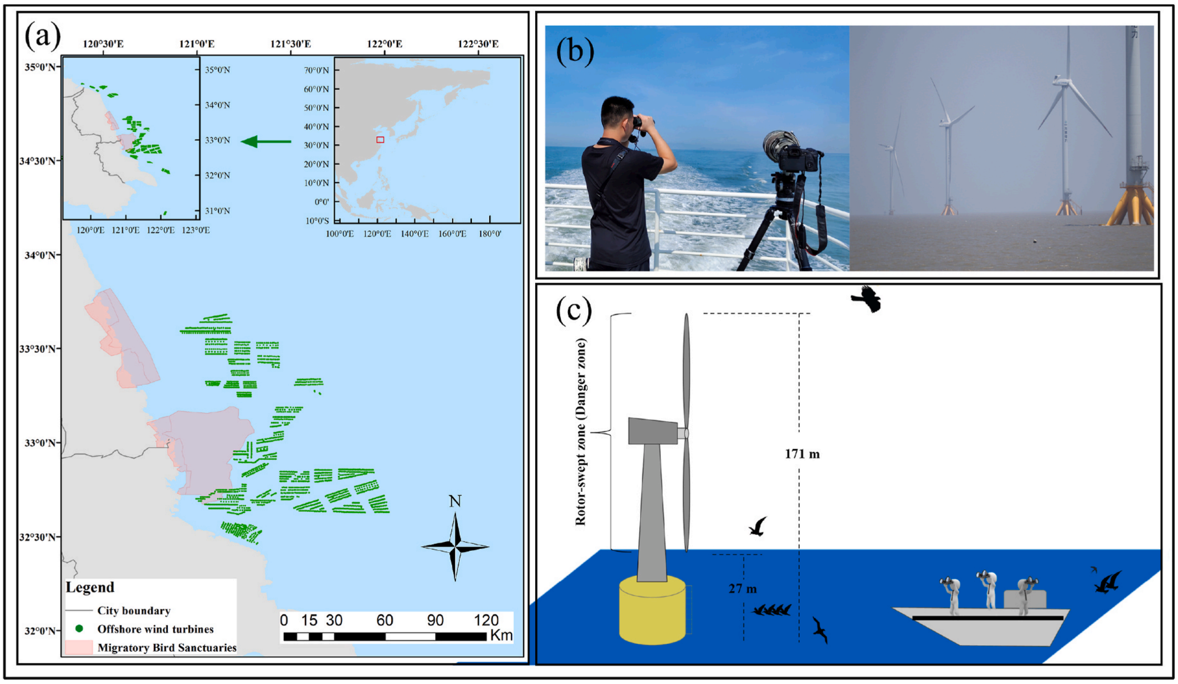

Fig. 1. The situation of offshore wind turbines and field survey in the offshore waters of the Southern Yellow Sea (created using ArcGIS 10.2 software). (a) All the offshore wind turbines in the study area. (b) The strategy used for the bird field survey and the characteristics of the offshore windfarms. (c) A schematic diagram describing the rotor-swept zone and systematic observations.

investigating the bird communities in marine habitats within or outside offshore windfarms and did not gather data on any birds in other types of habitats, such as intertidal mudflats or fishing ponds. Furthermore, birds in these areas near the land but without OWFs was not observed in the study period. The survey of the marine bird community would commence when the vessel has sailed a distance of at least 1 km from the shoreline and 1 h after the full tide. This timing allows for the observation of the remaining bird communities in the study area, which are predominantly marine-based. In this way, environmental variables such as habitat topography and land use could be mitigated, thereby guaranteeing the reliability of comparisons across study areas. Moreover, in consideration of the environmental assessment report for the construction of offshore wind farms, our focus is on bird diversity surveys within a 10-km radius of the OWF. In the event that the survey site is situated at a distance of greater than 10 km from OWFs, it is our contention that wind power exerts a negligible or non-existent influence on birds. Consequently, we elect to exclude the bird survey data pertaining to that particular site.

For each survey, the team consisted of at least three people who could professionally identify bird species. Investigators equipped with binoculars and a monocular stood on either side of the vessel as well as fore and aft to guarantee the reliability and completeness of the survey data. Bird species (richness), bird numbers (abundance), coordinates, flight altitude, and other data were simultaneously recorded. Each bird within visual distance was observed and related information was recorded as far as possible. For birds whose flight was at a higher altitude than the maximum altitude of the rotors, we used a camera and telephoto lens to help identify the species. The number of birds was decided by each observer at each site and latitude and longitude were recorded using a GPS (Garmin GPSMAP 67). The average value (meters) of the estimated flight height from all observers was considered the final height. Based on the flight height and the height of the wind turbines, the operating altitude range of the rotor (height: 27–171 m) was defined as the danger zone for flying birds because of the risk of bird strike (depicted in Fig. 1). Furthermore, heights above (>171 m) and below (<27 m) those defining the danger zone were considered safe zones for flying birds.

2.2. *The identification of OWF turbines*

Offshore windfarm turbines were identified based on satellite imagery datasets. Multi-source remote sensing images with a 30 m × 30 m resolution ratio, acquired by Landsat-7 Thematic Mapper (TM) and Landsat-8 Operational Land Imager (OLI), were collected and integrated to determine the status of OWFs in the study area. Remote sensing images acquired from December 2020 to October 2022 were obtained from the Geospatial Data Cloud (https://www.gscloud.cn/home). After 2022, offshore windfarm development in the study area slows down and less new wind power is built.

An OWF consists of several to hundreds of metal-structured wind turbines hundreds of meters apart. The reflectance of a wind turbine is higher than that of the surrounding seawater owing to its metal structure (Xu et al., 2020). Generally, the reflectance of OWF turbines is higher in the near-infrared band than in the other bands. Moreover, OWTs typically appear as spot-like bright targets in near-infrared images due to their small size. The turbines in the study area are shown as a series of green dots in Fig. 1. As expected, there was a high density of offshore wind turbines in the study area.

2.3. *The dataset of avian functional traits*

Trait-based analyses of biodiversity response to anthropogenic disturbance are prolific and recent global analyses have pointed towards widespread loss of functional diversity across thousands of species and multiple taxonomic groups (Etard et al., 2022). Functional traits are commonly used to quantify functional diversity as an emergent response to environmental gradients across space and time, and provide a predictive method for establishing the mechanistic processes underlying community disassembly (Socolar and Wilcove, 2019). Thus, such “functional response traits” was used to describe species-specific response to anthropogenic disturbance (Ausprey et al., 2022). To figure out the functional response of birds to offshore windfarm, we selected functional traits that were closely related to behavioral ability and body size considering the probability of a bird strike. Data relating to three functional trait groups—morphology, behavior, and diet—were obtained from existing datasets (Tobias et al., 2022; Wang et al., 2021; Wilman et al., 2014). Morphology comprised six types of functional traits, including mass, body length, tarsus length, wing length, tail length, and Kipp's distance. Mass, body length, tarsus length, and wing length can serve as direct indicators of bird size. Kipp's distance, measured directly or calculated as wing length minus first-secondary length, can reflect the ability of flight or migration (Baldwin et al., 2010). Behavior comprised flight height and the minimum distance to offshore turbines, which was measured using ArcGIS 10.2 software based on the observed sites and the nearest offshore turbine. If the minimum distance to offshore turbines = 0, this meant that birds were located inside the OWFs. The maximum distance was 10,000 m. The information on proportion obtained by integrating the list of survey bird species with the summary of dietary variables for birds was used to characterize eight diet types based on Wilman et al. (2014). These included diet-Inv, diet-Vend, diet-Vect, diet-Vfish, diet-Scav, diet-Fruit, diet-Seed, and diet-PlantO. The description of the eight dietary variables is summarized in Table S1. The mentioned functional traits are supplied in Table S2.

After Z-score normalization of the 16 above-mentioned functional traits, a principal component analysis (PCA) of the different bird species was employed to analyze the combined relationships among these traits using three R packages, namely, "FactoMineR" (Lê et al., 2008), "factoextra" (Kassambara and Mundt, 2017) and "corrplot" (Wei et al., 2017).

2.4. Bird risk assessment for offshore windfarms

To objectively reflect the degree of threat to birds posed by windfarm turbines, five factors were taken into account—the number of individuals, body length, Kipp's distance, flight height, and distance to offshore turbines, which was attributed in units of 1000 (i.e., 0, 1 000, 2 000, and so on). According to the correlation matrix among the 16 above-mentioned functional traits of birds (Table S3), body length was closely correlated with other morphological traits, and could reflect a change in morphology. Meanwhile, given that dietary traits were not related to the strike risk of birds, they were excluded from risk evaluation. Thus, these five variables can represent morphology, behavioral ability, and population size, which are closely related to the risk of collision. These factors are divided into 2 types. Type 1 factors have a risk-free lower bound and a critical upper bound (Wang et al., 2007), which can be defined as

$$\mathrm{R}(Y)=\begin{cases}0, Y\le Y_1\\ \dfrac{Y-Y_1}{Y_2-Y_1}, Y_1<Y<Y_2\\ 1, Y\ge Y_2\end{cases} \tag{1}$$

where R(Y) is the risk function, Y_1 is the risk-free lower bound, and Y_2 is the critical upper bound. The number of individuals, body length, Kipp's distance, and distance to windfarm turbines are treated as a Type 1 factor. Considering the attributes of birds, we set $Y_1 = 0$ and $Y_2 =$ maximum value of Y. Notably, as, theoretically, the shorter the distance to windfarm turbines is, the higher the level of threat becomes, the risk function for distance is defined as 1-R (Y). Two sets of analyses were performed. In one, the distances for each species were averaged to explore the average response of birds, while in the other, the distances for different individuals of each species were retained to explore the effect of distance on the level of threat.

Type 2 factors have an intermediate value, and the closer to this value, the greater the risk. There is no risk when the factor is below or above a certain value, thus a critical lower bound and a critical upper bound need to be defined (Wang et al., 2007). Type 2 factors can be defined as

$$\mathrm{R}(Z)=\begin{cases}0, Z\le Z_1; Z\ge Z_3\\ \dfrac{Z-Z_1}{Z_2-Z_1}, Z_1<Z\le Z_2\\ \dfrac{Z-Z_3}{Z_2-Z_3}, Z_2<Z<Z_3\end{cases} \tag{2}$$

where R(Z) is the risk function, Z_1 is the lower bound, Z_2 is the intermediate value, and Z_3 is the upper bound. Flight height is treated as a Type 1 factor. Considering that the size of the rotor-swept zone ranges from 27 to 171 m, Z_1 was set to 27, Z_2 to 99 (the mean of the rotor-swept zone), and Z_3 to 171.

Subsequently, exploratory factor analysis was used to determine the weight of each factor. Bartlett's test was used to indicate suitability for exploratory factor analysis ($p < 0.05$). The maximum variance rotation method was employed to calculate linear combination coefficients and composite score coefficients, which were used to calculate the weight of each factor.

2.5. Statistical analysis

Because of the effects of sea waves and fog, a few birds could not be identified in situ. These ambiguous and uncertain data were excluded from the statistical analysis. To unravel the relationships between flight height for the different bird guilds and their distance to OWF, a linear model and Pearson's correlation were applied to integrate the flight height of different orders or families with the distance to offshore turbines. The linear model was developed with the "lme4" package (https://github.com/lme4/lme4).

To determine the composition of the bird community and its phylogenetic structure, a global phylogenetic tree of 50 birds was pruned by subsampling 5000 "Hackett All Species: a set of 10,000 trees with 9993 OTUs each" from BirdTree (http://birdt ree.org; Jetz et al., 2007). Then, the 5000 trees were used to construct a new maximum clade credibility tree with a 0.7 posterior probability limit using TreeAnnotator software v.1.10.4 (available from http://tree.bio.ed.ac.uk/software/figtree/) in the Beast package. Figtree software and the "phytools" package (https://github.com/liamrevell/phytools) were used to adjust and display the phylogenetic tree.

3. Results

3.1. The bird composition in the offshore windfarms

In this study, a total of 49 species were identified and their numbers were counted. Bird diversity in the OWFs and surrounding areas was rich and abundant and comprised seven major groups, including the orders Charadriiformes, Accipitriformes, Passeriformes, and Anseriformes (Fig. 2). Laridae and Anatidae were the dominant guilds, accounting for 83% of the total number of birds; *Mareca falcata* and *Sterna hirundo* were particularly dominant, accounting for 44% of the total number of individuals. On a distance scale, it was found that the bird community within the OWFs and closer-scale distances (distance to offshore turbines <3 km) consisted of a greater number of orders and families (Fig. 2). In contrast, at intermediate and larger-scale distances, the structure of the bird community was simpler and Charadriiformes was dominant. Besides, birds from Accipitriformes were mostly observed at longer distances. This indicated that bird diversity was higher in areas with OWFs and neighboring waters than in sea areas without OWFs.

In this study, the operating altitude range of the rotor (height: 27–171 m) was considered the danger zone. We found that over half of the bird individuals flew through altitudes within the rotor-swept zone near the OWFs and surrounding waters (Fig. S1). In contrast, with increasing distance, bird individuals were in the safe zone in most cases,

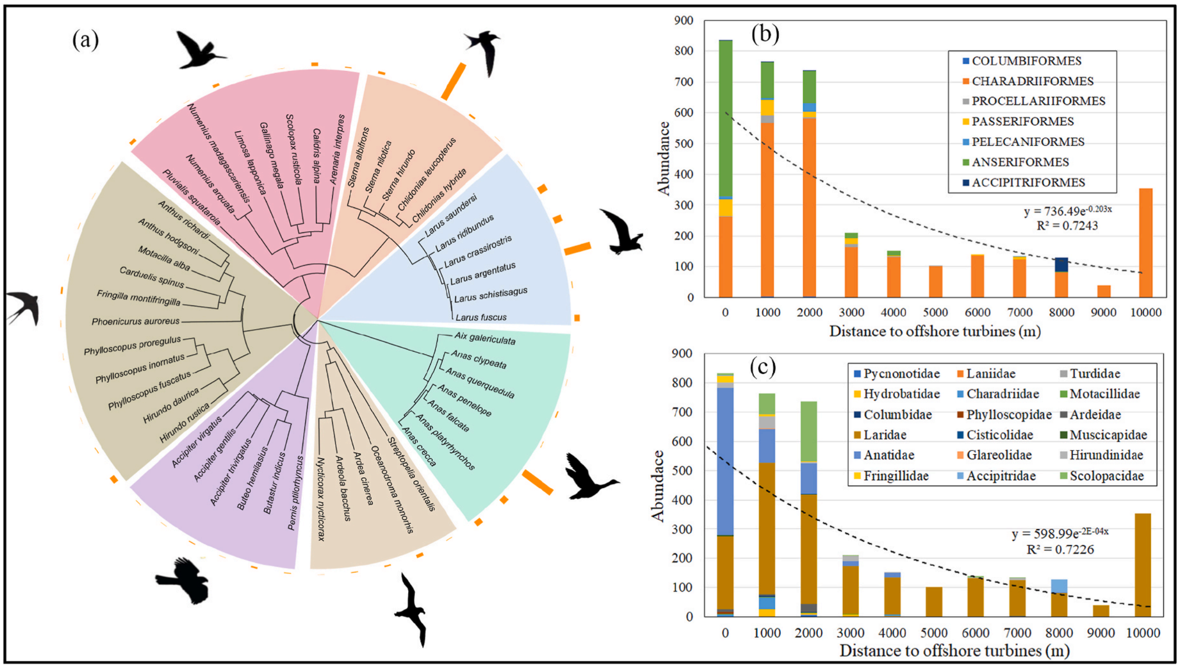

Fig. 2. Population structure sampling for all birds in the offshore windfarms. (a) Phylogenetic relationship and clade clustering for all the bird species. (b, c) Changes in bird orders and families with increasing distance to offshore turbines. The dotted line indicates the fitted change in abundance with changing distance based on the exponential function. The fitted equation and R-squared value are also labeled in the histogram.

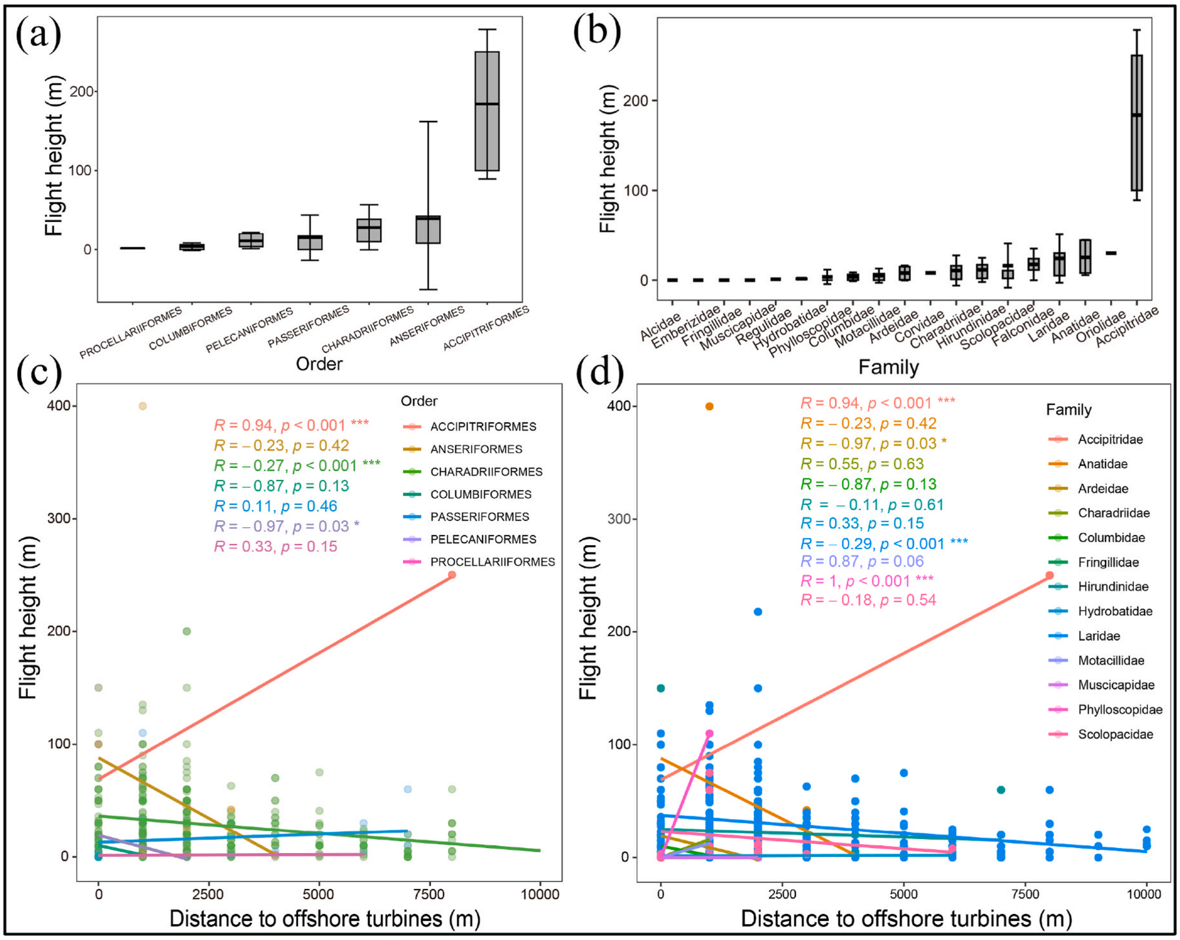

Fig. 3. The flight heights and related changes of birds in the different orders and families with increasing distance to windfarms. A distance of 0 m indicates that the sites are located within the windfarms.

but were less abundant.

3.2. *Behavioral features of birds*

The flight height of birds facing the OWFs varied significantly among the different guilds. The mean flight heights of Accipitriformes were significantly higher than those of other orders, while birds from Procellariiformes had the lowest flight heights, with most flying close to the sea surface, such as Swinhoe's Storm Petrel (*Oceanodroma monorhis*; mean flight height = 1.6 m). Similarly, birds from Accipitridae had greater flight heights than birds from other families, while birds from the family Alcidae had the lowest flight heights. Notably, the flight heights of Accipitridae, Oriolidae, Anatidae, Laridae, and Falconidae displayed a high degree of overlap with the rotor-swept zone.

At different distances to the OWFs, birds of different guilds tended to adopt different flight heights (Fig. 3). Birds from Accipitriformes flew at higher altitudes at greater distances from the OWFs, but their flight heights decreased significantly with decreasing distances to the OWFs (Pearson's $R = 0.94$, $p < 0.001$). In contrast, the flight heights of birds from Charadriiformes (Pearson's $R = -0.27$, $p < 0.001$) and Pelecaniformes (Pearson's $R = -0.97$, $p = 0.03 < 0.05$) were significantly greater near the OWFs than at more distant sea areas. Similarly, birds from Accipitridae had significantly lower flight heights near the OWFs than in more distant sea areas, the opposite of that seen for Laridae and Ardeidae. The flight heights of birds of other guilds did not vary significantly in the study area.

The cumulative values for abundance, height, and distance to offshore turbines were mostly concentrated in the lower right region of the ternary phase diagram, indicating that fewer individuals flew in the OWF and nearby waters, and most of those that did, flew at lower heights (Fig. 4). Additionally, overall, the flight heights of birds increased with increasing distance from the OWFs.

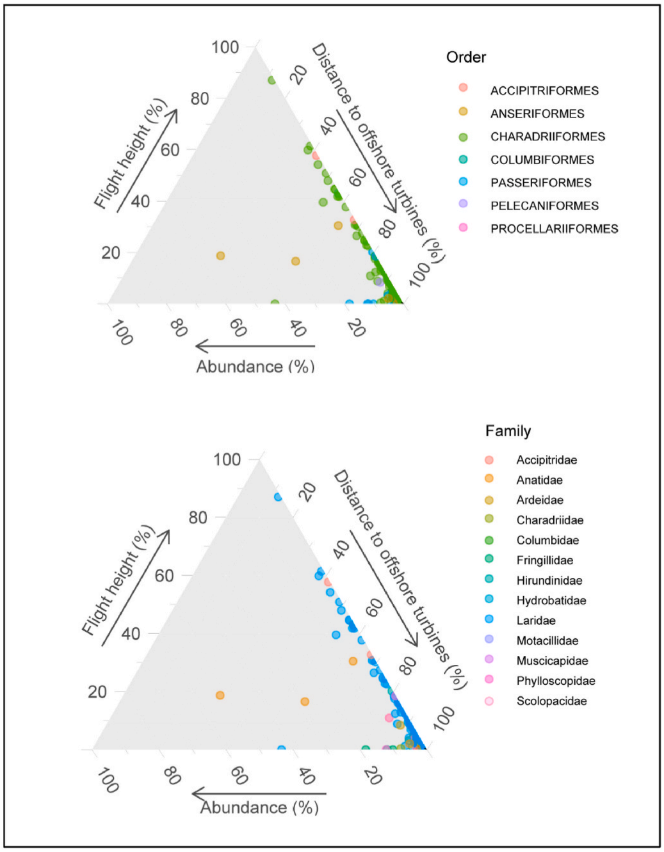

Fig. 4. Ternary diagrams based on the distance to offshore turbines, flight height, and bird abundance.

3.3. *Principal component analysis of functional traits of birds*

To understand the differences in adaptation to OWFs among the different bird guilds, we analyzed their dietary and morphological traits. Body length, mass, and tarsus length did not change significantly with increasing distance to offshore turbines (Fig. S2). In contrast, tail length, wing length, and Kipp's distance increased significantly in birds the further from offshore turbines they were found. Comparing the composition of birds within the dietary types at different distance scales, birds within OWFs and surrounding waters were mainly composed of aquatic predators and herbivores aquatic, and there were also some granivores and invertivores (Fig. S3). In more distant waters, aquatic predators were dominant, but several vertivores were also observed.

Based on morphological, behavioral, and dietary traits, PCA was used to identify the principal components of different functional traits of birds in the OWFs and surrounding waters (Fig. 5). The results showed that the explanation rate of the two principal components was 56.81% at both the order and family levels (Table S4), which was highly reliable for explaining the functional groups. Meanwhile, diet (42.45% of the total weight) and morphology (41.46% of the total weight) had higher weights for grouping and describing the birds in the OWFs and surrounding waters (Table S5). The weights of flight height and distance to offshore turbines were 5.25% and 4.13%, respectively. At the order level, birds could be categorized into five functional groups, and birds from Accipitriformes, with their larger size, were clustered in the first coordinate as a functional group. Fish-eating and medium-sized birds from Charadriiformes formed the second functional group. The smaller-sized Passeriformes and the herbivorous Anseriformes each formed a functional group, while the other orders of birds together formed a functional group. Different from the analysis at the order level, at the family level, six functional groups were formed. Birds from Laridae formed one functional guild, while birds from Scolopacidae and Anatidae together formed another. Birds from Fringillidae also formed a functional guild.

3.4. *Risk assessment for the different bird species*

Based on the risk function, we evaluated the risk values for 49 observed bird species to infer the threat level of the OWFs to different bird species (Table 1). For the top 10 bird species, it was found that raptors and waterfowl were associated with the highest risk level, and accounted for 62.89% of the total number of birds (Fig. S4, Table 1). The risk values for these species were all greater than 0.45. Some endangered species, such as *Mareca falcata*, and *Numenius madagascariensis*, had an even higher risk value. Factor analysis was used to determine the weights of the different variables, and the risk value was calculated as $R(Z) = 0.1876 \times$ number of individuals $+ 0.2582 \times$ flight height $+ 0.0748 \times$ distance to offshore turbines $+ 0.2319 \times$ body length $+ 0.2474 \times$ Kipp's distance. Flight height, body size, and Kipp's distance had greater weights on the level of risk, while distance to offshore turbines had a lower weight.

4. Discussion

4.1. *The significance of bird diversity for the evaluation of OWFs*

Global biodiversity is in rapid decline, with marine and migratory birds being particularly threatened (Şekercioğlu et al., 2004; Sauer et al., 2019; Kersey and Antonelli, 2023; Spatz et al., 2023). The construction of offshore projects will inevitably affect biodiversity and ecosystem stability (Strain et al., 2021). Further reducing the impacts of OWFs on bird diversity is necessary for the rational construction and operation of windfarms in the future (Vaissière et al., 2014; Virtanen et al., 2022). The long-term surveys undertaken in this study confirmed that OWFs are

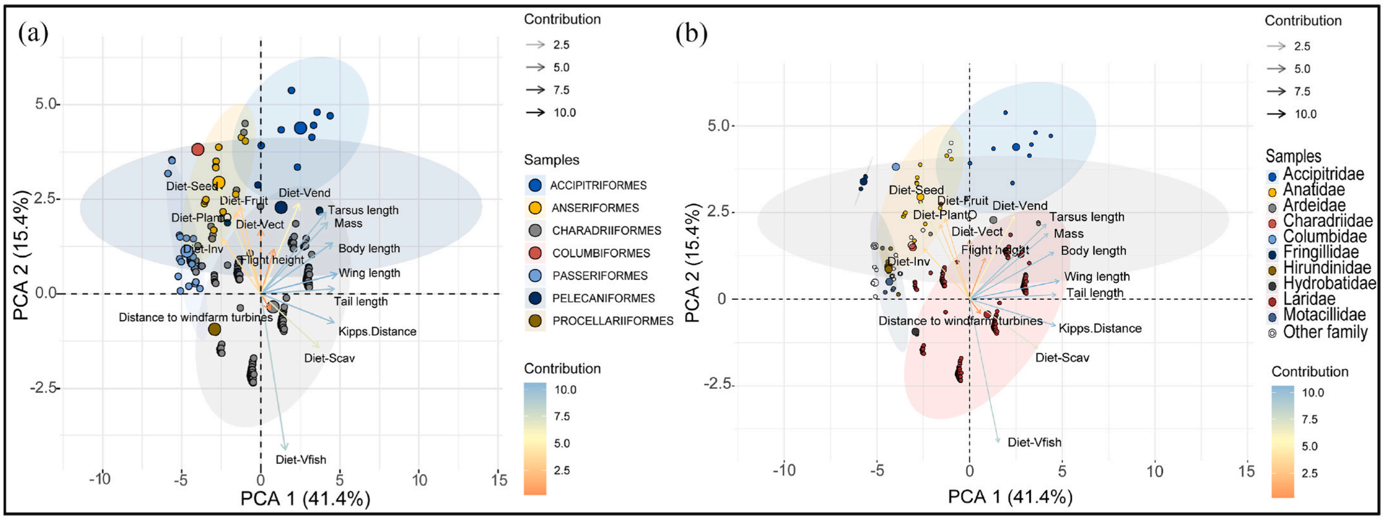

Fig. 5. Principal component analysis of different bird guilds based on 16 functional traits. The further the arrow is away from the center, the greater the weight of the explanatory variable. The less transparent and bluer the line, the higher the explanatory contribution of the variable.

not ecological wastelands for bird communities. Instead, bird diversity is higher in OWFs than in sea areas where they have not been constructed (Ter Hofstede et al., 2022). Accordingly, our study makes a significant contribution to the systematic understanding of the different strategies adopted by different guilds of birds in response to OWFs. Furthermore, it is important to formulate scientific conservation and development policies for the key bird migration corridors (East Asian-Australasian Flyway) paying attention to the entire bird community rather than focusing on specific or endangered bird species alone.

To comprehensively assess the impacts of OWFs on different guilds of birds, it is essential to measure the level of risk using reliable evaluation methods. Unlike bird mortality surveys in terrestrial windfarms, where the bodies of dead birds are found near wind turbines (De Lucas et al., 2012; Marques et al., 2014), it is difficult to obtain evidence of bird collision in OWFs. Therefore, there is an urgent need to scientifically evaluate the level of stress that OWFs elicit in different bird species. Previous evaluation indices have considered some bird traits, such as flight height, maneuverability, and habitat specialization while neglecting traits such as feeding habits and distance to wind farms (Brignon et al., 2022; Furness et al., 2013; Thaxter et al., 2017). This may have led to there being a weak relationship between risk assessment and recorded mortality in wind farms (Ferrer et al., 2012). In the present study, we devised a new risk function that integrates flight height, morphology, dietary characteristics, and distance to offshore wind turbines, and found that flight height and body size appear to be key factors influencing collision mortality risk (Furness et al., 2013). Furthermore, dietary traits are also a major factor influencing the level of risk of different birds. Marine habitats and their food resources are distinct from those on land, and birds in OWFs and surrounding areas tend to favor roosting at the sea surface and eating fish. This explains why many bird species from the Laridae family were at a high risk of collision, second only to Accipitridae.

4.2. *The effect of OWFs on bird diversity*

OWFs may have multiple and cascading impacts on different birds (Thaker et al., 2018). Bird community monitoring at terrestrial wind farms has shown that large birds, such as raptors, are more vulnerable to wind energy, which has been verified at several wind farms in the US and Europe (Thaker et al., 2018). Similarly, this study found that there is a higher risk coefficient for Accipitridae in the offshore wind farm area, while body length and flight height have a higher impact weight. Larger birds, such as those from Accipitridae, have a higher risk of collision both on land and within OWFs (Carrete et al., 2012; De Lucas et al., 2008). This provides further evidence that, whether on land or at sea, the Accipitridae represents a key and non-negligible guild for evaluating the impact of wind farms on biodiversity. Such impacts may impede the migratory, reproductive and other activities of these species. In contrast, wind farms have a minimal impact on the stress levels of small birds, such as finches, that migrate during the day. The risk coefficients of this study indicate that the risk index for finch birds in the vicinity of offshore wind farms is low. This may be attributed to their smaller body size and population size. Moreover, OWFs can be beneficial for small-sized migratory birds. Birds from diurnal-migratory Passeriformes and Columbiformes are smaller, slower, have lower flight heights, and aggregate in small flocks, which results in a lower risk level. This clearly indicates that OWF turbines may, to a certain extent, be helpful for smaller bird species, allowing them to replenish their energy as they fly across the sea. In our field survey, we observed relatively few migratory Passeriformes and Columbiformes birds perching on wind turbines at OWFs (Fig. S5).

It is noteworthy that the OWFs and surrounding waters exhibited a high abundance of Laridae and Anatidae birds in this study, a finding that contrasts with previous reports. Prior research on coastal onshore wind farms has demonstrated that Anatidae birds tend to avoid these structures, instead occupying habitats situated outside the wind farms (Zhao et al., 2024). This phenomenon can be explained by two distinct hypotheses. Firstly, the considerable number of vessels situated in the vicinity of offshore wind farms, both during the construction phase and for the purposes of stewardship, and the navigation of these vessels has the effect of disturbing the seabed, whereby the propellers scrape against the surface of the water. This phenomenon has been observed to prompt some of the smaller fish to either leap out of the sea or to become momentarily incapacitated, thus creating a greater opportunity for fish-eating birds, such as gulls, to feed. This phenomenon has been documented in various locations, including the northwestern Mediterranean Sea (Bodey et al., 2014; Gimeno et al., 2023). In the marine environment, vessels alone can significantly affect the distribution or behavior of many species through disturbance and attraction. At a fundamental level, the response of individual birds to the presence of humans as top predator can have important effects on population processes (Gimeno et al., 2023). Secondly, we postulated OWFs could serve as “ecological traps”, whereby animals mistakenly prefer habitats that lower their fitness following rapid environmental change (Degraer et al., 2020; Hale and Swearer, 2016), by providing abundant aquatic organisms as “bait” for fish-eating bird species. OWFs area known to affect

Table 1
The risk value and information for 49 bird species in the study area.

No.	Latin name	Risk value	IUCN Red list	Number of individuals	Trophic niche
1	*Buteo hemilasius*	0.68	LC	1	Vertivore
2	*Mareca falcata*	0.59	NT	513	Herbivore aquatic
3	*Larus vegae*	0.59	LC	685	Aquatic predator
4	*Sterna hirundo*	0.51	LC	1035	Aquatic predator
5	*Buteo japonicus*	0.5	LC	1	Vertivore
6	*Larus fuscus*	0.5	LC	88	Aquatic predator
7	*Larus schistisagus*	0.49	LC	10	Omnivore
8	*Limosa lapponica*	0.47	NT	40	Aquatic predator
9	*Ardea cinerea*	0.46	LC	35	Aquatic predator
10	*Larus crassirostris*	0.45	LC	234	Aquatic predator
11	*Anas platyrhynchos*	0.43	LC	91	Herbivore aquatic
12	*Numenius arquata*	0.4	NT	160	Aquatic predator
13	*Numenius madagascariensis*	0.38	EN	16	Aquatic predator
14	*Chroicocephalus ridibundus*	0.37	LC	335	Aquatic predator
15	*Spatula clypeata*	0.36	LC	2	Aquatic predator
16	*Chroicocephalus saundersi*	0.35	VU	253	Aquatic predator
17	*Mareca penelope*	0.34	LC	5	Omnivore
18	*Gelochelidon nilotica*	0.33	LC	1	Omnivore
19	*Nycticorax*	0.31	LC	5	Aquatic predator
20	*Aix galericulata*	0.29	LC	3	Herbivore aquatic
21	*Anas crecca*	0.28	LC	82	Herbivore aquatic
22	*Pernis ptilorhynchus*	0.28	LC	8	Invertivore
23	*Butastur indicus*	0.28	LC	21	Vertivore
24	*Pluvialis squatarola*	0.27	LC	47	Aquatic predator
25	*Accipiter gentilis*	0.27	LC	2	Vertivore
26	*Ardeola bacchus*	0.26	LC	15	Aquatic predator
27	*Sternula albifrons*	0.26	LC	139	Aquatic predator
28	*Spatula querquedula*	0.25	LC	15	Herbivore aquatic
29	*Scolopax rusticola*	0.25	LC	1	Omnivore
30	*Chlidonias leucopterus*	0.24	LC	72	Aquatic predator
31	*Chlidonias hybrida*	0.24	LC	9	Aquatic predator
32	*Arenaria interpres*	0.21	LC	12	Aquatic predator
33	*Streptopelia orientalis*	0.21	LC	4	Omnivore
34	*Phylloscopus inornatus*	0.21	LC	2	Invertivore
35	*Hydrobates monorhis*	0.21	NT	47	Aquatic predator
36	*Gallinago megala*	0.2	LC	1	Aquatic predator
37	*Cecropis daurica*	0.19	LC	32	Invertivore
38	*Calidris alpina*	0.19	LC	6	Aquatic predator
39	*Hirundo rustica*	0.18	LC	109	Invertivore
40	*Accipiter trivirgatus*	0.17	LC	10	Vertivore
41	*Fringilla montifringilla*	0.15	LC	26	Omnivore
42	*Motacilla alba*	0.15	LC	6	Invertivore
43	*Anthus richardi*	0.14	LC	2	Invertivore
44	*Accipiter virgatus*	0.14	LC	5	Vertivore
45	*Anthus hodgsoni*	0.14	LC	1	Invertivore
46	*Spinus*	0.13	LC	4	Granivore
47	*Phoenicurus auroreus*	0.12	LC	4	Invertivore
48	*Phylloscopus fuscatus*	0.12	LC	1	Invertivore
49	*Phylloscopus proregulus*	0.11	LC	5	Invertivore

seafloor habitat, the benthos and bentho-pelagic fish, which commonly referred to as the "artificial reef effect" (Degraer et al., 2020; Methratta and Dardick, 2019). Artificial reefs are man-made structures (i.e., offshore turbines) deliberately placed in the sea to mimic characteristics of natural reefs, and provide new habitats, setting the stage for colonization by epifaunal communities, and that have habitat-forming properties (Degraer et al., 2020). In the southern North Sea, OWFs structures provide a novel mussel offshore habitat, with high abundances exhibited on turbine foundations (Krone et al., 2013). Larger species such as crabs and lobsters appear to profit from the presence of the structures and the biofouling community, appearing in increasing abundance on and around the structures (De Mesel et al., 2015). Higher-trophic-level species with mobility appear to be attracted to the OWFs structures for shelter and food availability, such as some finfish species (Degraer et al., 2020). For example, some larger gulls seem attracted to the OWFs and run the risk of colliding with the turbine blades in the Thornton Bank offshore wind farm (Vanermen et al., 2020). Similarly, Laridae birds, such as Black-tailed Gulls and Common Terns, tend to fly in close proximity to the offshore turbines and adjacent seas in this study. They often adjust their flight altitude in this study, which highly overlaps with the range of operation of the rotors. Based on the risk index, Laridae birds have a high level of collision risk. Thus, the original attraction hypothesis is complemented, the ecological trap, which refers to Laridae birds being attracted to suboptimal habitat, possibly leading to deterioration of the bird stock's condition.

4.3. Policy implications and suggestions

How to rationally couple marine bird conservation and the construction of OWFs is instructive for synergizing biodiversity conservation with climate improvement. Climate, biodiversity, and societal challenges are intertwined but are often treated as singular issues (Pörtner et al., 2023). Solutions exist with co-benefits across sectors. Three critical objectives for future spatial planning include a habitable climate, self-sustaining biodiversity, and continued development. The Kunming-Montreal Global Biodiversity Framework indicated that effective measures should be taken to conserve areas of particular importance for both biodiversity and humanity. We believe that wind power and biodiversity conservation are not opposites and that synergies are the way forward.

Coordinated efforts among scientists and policymakers can help identify and navigate development pathways that lead to climate resilience for both human society and biodiversity. Understanding the adaptive characteristics of different bird taxa to OWFs can provide solutions for the development of targeted conservation measures. Here, three measures are proposed to promote the high-quality development of offshore wind power. First, we suggest that the construction of windfarms should avoid critical areas for biodiversity protection as much as possible, even though these areas may possess abundant wind resources, they are crucial for bird survival. For example, our study found higher numbers of migratory birds along the Yellow Sea coast, highlighting the ecological value of these regions. However, we recognize that the lack of pre-construction data limits the ability to fully assess the impacts of windfarms on biodiversity. Future studies should aim to collect baseline data prior to the development of OWFs to ensure more comprehensive evaluations. Secondly, standardized monitoring of bird diversity should be enhanced with cost-effective methods. We suggest an automated monitoring system tailored to bird responses to windfarms, as our research showed that Laridae birds often fly within rotor-swept zones. Such a system, installed during turbine construction like monitoring radar, can provide real-time data to guide turbine operation and reduce collision risks. In addition, environmental factors such as wind consistency and bathymetric characteristics should also be considered in evaluating bird behavior near OWFs, as these variables may influence flight patterns and distribution. The real-time monitoring of bird diversity can help guide decisions as to when to operate the rotors. Thirdly, for raptors, implementing warning lights or distinct paint patterns on turbines can increase visibility and reduce collision risks. These measures can be integrated into windfarm construction to improve compatibility with biodiversity conservation. The implementation of more effective solutions in OWFs is urgently required to facilitate the conservation of biodiversity and thereby achieve the targets stipulated in the Kunming-Montreal Global Biodiversity Framework.

5. Conclusion

The Chinese government has invested heavily in the construction of offshore wind power due to its low-carbon and environmentally friendly characteristics. The rapid development of offshore wind power in China has made it the most developed offshore wind power construction in the world. The present study site is not only located near the Yellow Sea-Bohai World Natural Heritage Site, but also has the most developed offshore wind power construction in China, which is a typical area to study the impact of wind power on bird diversity. Through three consecutive years of tracking and monitoring bird communities in the study area, it was found that the level of bird diversity around offshore wind farms was high, and the proportion of geese and plovers was relatively high. It is worth noting that, unlike previous studies, bird communities in the offshore Yellow Sea did not respond to offshore wind farms, and bird abundance was higher near the wind farms than in the area further away from the wind farms. However, almost 50% of the individual birds active near offshore wind farms were within the operating range of the turbine's fan blades. Combining bird population, behavioral and morphological characteristics, the study found that birds of the duck family, the gull family and the larger eagle family active near offshore wind farms had a higher risk index. Therefore, instead of simply comparing the level of bird diversity inside and outside the wind farm, we should consider the composition and functional traits of the birds and analyze their threatened status. In the future, we suggest that offshore wind farms should be assessed before construction and that wind farms should not be built on important bird migration corridors. For wind farms already built, we suggest that long-term bird monitoring should be strengthened, especially in combination with automated monitoring equipment such as radar, which can provide real-time information.

CRediT authorship contribution statement

Wei Liu: Writing – original draft, Software, Methodology, Conceptualization. **Sijia Yuan:** Writing – original draft, Software, Methodology, Formal analysis. **Gang Shen:** Supervision. **Yanzhe Ding:** Investigation, Data curation. **Xiaoshou Liu:** Writing – review & editing. **Chaochao Hu:** Writing – review & editing. **Chentao Wei:** Supervision, Formal analysis. **Xiaoqiang Lu:** Supervision, Funding acquisition. **Yan Liu:** Funding acquisition.

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Declaration of competing interest

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

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Appendix A. Supplementary data

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Data availability

Data will be made available on request.

References

Ausprey, I.J., Newell, F.L., Robinson, S.K., 2022. Functional response traits and altered ecological niches drive the disassembly of cloud forest bird communities in tropical montane countrysides. J. Anim. Ecol. 91 (11), 2314–2328. https://doi.org/10.1111/1365-2656.13816.

Baldwin, M.W., Winkler, H., Organ, C.L., Helm, B., 2010. Wing pointedness associated with migratory distance in common-garden and comparative studies of stonechats (*Saxicola torquata*). J. Evolution. Biol. 23, 1050–1063. https://doi.org/10.1111/j.1420-9101.2010.01975.x.

Bodey, T.W., Jessopp, M.J., Votier, S.C., Gerritsen, H.D., Cleasby, I.R., Hamer, K.C., Patrick, S.C., Wakefield, E.D., Bearhop, S., 2014. Seabird movement reveals the ecological footprint of fishing vessels. Curr. Biol. 24 (11), 514–R515. https://doi.org/10.1016/j.cub.2014.04.041.

Boussarie, G., Kopp, D., Lavialle, G., Mouchet, M., Morfin, M., 2023. Marine spatial planning to solve increasing conflicts at sea: a framework for prioritizing offshore windfarms and marine protected areas. J. Environ. Manag. 339, 117857. https://doi.org/10.1016/j.jenvman.2023.117857.

Brignon, J.M., Lejart, M., Nexer, M., Michel, S., Quentric, A., Thiebaud, L., 2022. A risk-based method to prioritize cumulative impacts assessment on marine biodiversity and research policy for offshore wind farms in France. Environ. Sci. Pol. 128, 264–276. https://doi.org/10.1016/j.envsci.2021.12.003.

Cabrera-Cruz, S.A., Cervantes-Pasqualli, J., Franquesa-Soler, M., Muñoz-Jiménez, O., Rodríguez-Aguilar, G., Villegas-Patraca, R., 2020. Estimates of aerial vertebrate mortality at wind farms in a bird migration corridor and bat diversity hotspot. Glob. Ecol. Conserv. 22, e00966. https://doi.org/10.1016/j.gecco.2020.e00966.

Carrete, M., Sánchez-Zapata, J.A., Benítez, J.R., Lobón, M., Montoya, F., Donázar, J.A., 2012. Mortality at wind-farms is positively related to large-scale distribution and aggregation in griffon vultures. Biol. Conserv. 14, 102–108. https://doi.org/10.1016/j.biocon.2011.10.017.

CBD (Convention on Biological Diversity), 2022. Kunming-montreal global biodiversity framework. https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-04-en.pdf.

Chen, Y., Yu, Y.T., Meng, F., Deng, X., Cao, L., Fox, A.D., 2021. Migration routes, population status and important sites used by the globally threatened Black-faced Spoonbill (*Platalea minor*): a synthesis of surveys and tracking studies. Avian Res 12, 1–17. https://doi.org/10.1186/s40657-021-00307-z.

De Lucas, M., Ferrer, M., Bechard, M.J., Muñoz, A.R., 2012. Griffon vulture mortality at wind farms in southern Spain: distribution of fatalities and active mitigation measures. Biol. Conserv. 147, 184–189. https://doi.org/10.1016/j.biocon.2011.1029.

De Lucas, M., Janss, G.F., Whitfield, D.P., Ferrer, M., 2008. Collision fatality of raptors in wind farms does not depend on raptor abundance. J. Appl. Ecol. 45, 1695–1703. https://doi.org/10.1111/j.1365-2664.2008.01549.x.

De Mesel, I., Kerckhof, F., Norro, A., Rumes, B., Degraer, S., 2015. Succession and seasonal dynamics of the epifauna community on offshore wind farm foundations and their role as stepping stones for non-indigenous species. Hydrobiologia 756, 37–50. https://doi.org/10.1007/s10750-014-2157-1.

de Vasconcelos, R.M., Silva, L.L.C., González, M.O.A., Santiso, A.M., de Melo, D.C., 2022. Environmental licensing for offshore wind farms: guidelines and policy implications for new markets. Energy Pol. 171, 113248. https://doi.org/10.1016/j.enpol.2022.113248.

Degraer, S., Carey, D.A., Coolen, J.W., Hutchison, Z.L., Kerckhof, F., Rumes, B., Vanaverbeke, J., 2020. Offshore wind farm artificial reefs affect ecosystem structure and functioning. Oceanography 33, 48–57. https://www.jstor.org/stable/26965749.

Díaz, H., Soares, C.G., 2020. Review of the current status, technology and future trends of offshore wind farms. Ocean Eng. 209, 107381. https://doi.org/10.1016/j.oceaneng.2020.107381.

Dinh, Q.V., Doan, Q.V., Ngo-Duc, T., Duc, N.D., 2022. Offshore wind resource in the context of global climate change over a tropical area. Appl. Energy 308, 118369. https://doi.org/10.1016/j.apenergy.2021.118369.

Eddy, T.D., Lam, V.W., Reygondeau, G., Cisneros-Montemayor, A.M., Greer, K., Palomares, M.L.D., Bruno, J.L., Ota, Y., Cheung, W.W., 2021. Global decline in capacity of coral reefs to provide ecosystem services. One Earth 4 (9), 1278–1285. https://doi.org/10.1016/j.oneear.2021.08.016.

Etard, A., Pigot, A.L., Newbold, T., 2022. Intensive human land uses negatively affect vertebrate functional diversity. Ecol. Lett. 25 (2), 330–343. https://doi.org/10.1111/ele.13926.

Fan, Q., Wang, X., Yuan, J., Liu, X., Hu, H., Lin, P., 2022. A review of the development of key technologies for offshore wind power in China. J. Mar. Sci. Eng. 10 (7), 929. https://doi.org/10.3390/jmse10070929.

Ferrer, M., de Lucas, M., Janss, G.F., Casado, E., Munoz, A.R., Bechard, M.J., Calabuig, C.P., 2012. Weak relationship between risk assessment studies and recorded mortality in wind farms. J. Appl. Ecol. 49 (1), 38–46. https://doi.org/10.1111/j.1365-2664.2011.02054.x.

Furness, R.W., Wade, H.M., Masden, E.A., 2013. Assessing vulnerability of marine bird populations to offshore wind farms. J. Environ. Manag. 119, 56–66. https://doi.org/10.1016/j.jenvman.2013.01.025.

Gasparatos, A., Doll, C., Esteban, M., Ahmed, A., Olang, T., 2017. Renewable energy and biodiversity: implications for transitioning to a green economy. Renew. Sustain. Energy Rev. 70, 161–184. https://doi.org/10.1016/j.rser.2016.08.030.

Gaultier, S.P., Blomberg, A.S., Ijas, A., Vasko, V., Vesterinen, E.J., Brommer, J.E., Lilley, T.M., 2020. Bats and wind farms: the role and importance of the Baltic Sea countries in the European context of power transition and biodiversity conservation. Environ. Sci. Technol. 54 (17), 10385–10398. https://doi.org/10.1021/acs.est.0c00070.

Gimeno, M., García, J.A., Afán, I., Aymí, R., Montalvo, T., Navarro, J., 2023. Age-related differences in foraging behaviour at sea and interactions with fishing vessels in an opportunistic urban gull. ICES J. Mar. Sci. 80 (9), 2405–2413. https://doi.org/10.1093/icesjms/fsac120.

Gjerde, K.M., Clark, N.A., Chazot, C., Cremers, K., Harden-Davies, H., Kachelriess, D., Payne, C.R., Rodriguez-Chaves, M., Spadone, A., Thiele, T., Vierros, M., Goettsche-Wanli, G., Wright, G., 2022. Getting beyond yes: fast-tracking implementation of the United Nations agreement for marine biodiversity beyond national jurisdiction. NPJ Ocean Sustain 1, 6. https://doi.org/10.1038/s44183-022-00006-2.

Hale, R., Swearer, S.E., 2016. Ecological traps: current evidence and future directions. P. Roy. Soc. B-Biol. Sci. 283, 20152647. https://doi.org/10.1098/rspb.2015.2647.

Herbert-Read, J.E., Thornton, A., Amon, D.J., Birchenough, S.N., Côté, I.M., Dias, M.P., Godley, B.J., Keith, S.A., McKinley, E., Peck, L.S., Calado, R., Defeo, O., Degraer, S., Johnston, E.L., Kaartokallio, K., Macreadie, P.I., Metaxas, A., Muthumbi, A.W.N., Obura, D.O., Paterson, D.M., Piola, A.R., Richardson, A.J., Schloss, I.R., Snelgrove, P.V.R., Stewart, B.D., Thompson, P.M., Watson, G.J., Worthington, T.A., Yasuhara, M., Sutherland, W.J., 2022. A global horizon scan of issues impacting marine and coastal biodiversity conservation. Nat. Ecol. Evol. 6, 1262–1270. https://doi.org/10.1038/s41559-022-01812-0.

Hung, P.Y., 2020. Placing green energy in the sea: offshore wind farms, dolphins, oysters, and the territorial politics of the intertidal zone in Taiwan. Ann. Assoc. Am. Geogr. 110, 56–77. https://doi.org/10.1080/24694452.2019.1625749.

Jetz, W., Wilcove, D.S., Dobson, A.P., 2007. Projected impacts of climate and land-use change on the global diversity of birds. PLoS Biol. 5 (6), e157. https://doi.org/10.1371/journal.pbio.0050157.

Kassambara, A., Mundt, F., 2017. Package ‘factoextra’. Extract and Visualize the Results of Multivariate Data Analyses, vol. 76, p. 2. https://piyanit.nl/wp-content/uploads/2020/10/factoextra.pdf.

Kersey, P.J., Antonelli, A., 2023. Physical infrastructure and global capacity are both needed to fight biodiversity loss. Nat. Plants 9, 1940. https://doi.org/10.1038/s41477-023-01594-8.

Krone, R., Gutow, L., Joschko, T.J., Schröder, A., 2013. Epifauna dynamics at an offshore foundation–implications of future wind power farming in the North Sea. Mar. Environ. Res. 85, 1–12. https://doi.org/10.1016/j.marenvres.2012.12.004.

Lê, S., Josse, J., Husson, F., 2008. FactoMineR: an R package for multivariate analysis. J. Stat. Software 25 (1), 1–18. https://doi.org/10.18637/jss.v025.i01.

Lindeboom, H., Degraer, S., Dannheim, J., Gill, A., Wilhelmsson, D., 2015. Offshore wind park monitoring programmes, lessons learned and recommendations for the future. Hydrobiologia 756, 169–180. https://doi.org/10.1007/s10750-015-2267-4.

Marques, A.T., Batalha, H., Rodrigues, S., Costa, H., Pereira, M.J.R., Fonseca, C., Mascarenhas, M., Bernardino, J., 2014. Understanding bird collisions at wind farms: an updated review on the causes and possible mitigation strategies. Biol. Conserv. 179, 40–52. https://doi.org/10.1016/j.biocon.2014.08.017.

Methratta, E.T., Dardick, W.R., 2019. Meta-analysis of finfish abundance at offshore wind farms. Rev. Fish. Sci. Aquac. 27 (2), 242–260. https://doi.org/10.1080/23308249.2019.1584601.

Ministerio Para la Transición Ecológica y el Reto Demográfico, 2020. Plan Nacional Integrado de Energía y Clima (PNIEC) 2021–2030. https://www.miteco.gob.es/.

Pearce-Higgins, J.W., Stephen, L., Douse, A., Langston, R.H., 2012. Greater impacts of wind farms on bird populations during construction than subsequent operation: results of a multi-site and multi-species analysis. J. Appl. Ecol. 49 (2), 386–394. https://doi.org/10.1111/j.1365-2664.2012.02110.x.

Perino, A., Pereira, H.M., Felipe-Lucia, M., Kim, H., Kühl, H.S., Marselle, M.R., Meya, J.N., Meyer, C., Navarro, L.M., Klink, R., Albert, G., Barratt, C.D., Bruelheide, H., Cao, Y., Chamoin, A., Darbi, M., Dornelas, M., Eisenhauer, N., Essl, F., Farwig, N., Förster, J., Freyhof, J., Geschke, J., Gottschall, F., Guerra, C., Haase, P., Hickler, T., Jacob, U., Kastner, T., Korell, L., Kühn, I., Lehmann, G.U.C., Lenzner, B., Marques, A., Švara, E.M., Quintero, L.C., Pacheco, A., Popp, A., Rouet-Leduc, J., Schnabel, F., Siebert, J., Staude, I.R., Trogisch, S., Švara, V., Svenning, J., Pe'er, G., Raab, K., Rakosy, D., Vandewalle, M., Werner, A.S., Wirth, C., Xu, H., Yu, D., Zinngrebe, Y., Bonn, A., 2022. Biodiversity post-2020: closing the gap between global targets and national-level implementation. Conserv. Lett. 15 (2), e12848. https://doi.org/10.1111/conl.12848.

Pörtner, H.O., Scholes, R.J., Arneth, A., Barnes, D.K.A., Burrows, M.T., Diamond, S.E., Duarte, C.M., Kiessling, W., Leadley, P., Managi, S., Mcelwee, P., Midgley, G., Ngo, H.T., Obura, D., Pascual, U., Sankaran, M., Shin, Y.J., Val, A.L., 2023. Overcoming the coupled climate and biodiversity crises and their societal impacts. Science 380 (6642), eabl4881. https://doi.org/10.1126/science.abl4881.

Powers, T., Sajadi, A., Hodge, B.M., 2022. The current opportunities and challenges for offshore wind in the United States. T. Electric. J. 35 (7), 107061. https://doi.org/10.1016/j.tej.2021.107061.

Sauer, J.R., Rosenberg, K.V., Dokter, A.M., Blancher, P.J., Smith, A.C., Smith, P.A., Stanton, J.C., Panjabi, A., Helft, L., Parr, M., Marra, P.P., 2019. Decline of the North American avifauna. Science 366 (6461), 120–124. https://doi.org/10.1126/science.aaw1313.

Schwemmer, P., Mercker, M., Haecker, K., Kruckenberg, H., Kämpfer, S., Bocher, P., Fort, J., Jiguet, F., Franks, S., Elts, J., Marja, R., Piha, M., Rousseau, P., Pederson, R., Düttmann, H., Fartmann, T., Garthe, S., 2023. Behavioral responses to offshore windfarms during migration of a declining shorebird species revealed by GPS-telemetry. J. Environ. Manag. 342, 118131. https://doi.org/10.1016/j.jenvman.2023.118131.

Şekercioğlu, Ç.H., Daily, G.C., Ehrlich, P.R., 2004. Ecosystem consequences of bird declines. P. Natl. Acad. Sci. 101 (52), 18042–18047. https://doi.org/10.1073/pnas.0408049101.

Serrano, D., Margalida, A., Pérez-García, J.M., Juste, J., Traba, J., Valera, F., Carrete, M., Aihartza, J., Real, J., Mañosa, S., Flaquer, C., Garin, I., Morales, M.B., Alcalde, J.T., Arroyo, B., Sánchez-Zapata, J.A., Blanco, G., Nergo, J.J., Tella, J.L., Ibañez, C., Tellería, J.L., Hiraldo, F., Donázar, J.A., 2020. Renewables in Spain threaten biodiversity. Science 370 (6522), 1282–1283. https://doi.org/10.1126/science.abf6509.

Socolar, J.B., Wilcove, D.S., 2019. Forest-type specialization strongly predicts avian responses to tropical agriculture. P. Roy. Soc. B-Biol. Sci. 286 (1913), 20191724. https://doi.org/10.1098/rspb.2019.1724.

Spatz, D.R., Young, L.C., Holmes, N.D., Jones, H.P., VanderWerf, E.A., Lyons, D.E., Kress, S., Miskelly, C.M., Taylor, G.A., 2023. Tracking the global application of conservation translocation and social attraction to reverse seabird declines. P. Natl. Acad. Sci. 120 (16), e2214574120. https://doi.org/10.1073/pnas.2214574120.

Strain, E.M., Steinberg, P.D., Vozzo, M., Johnston, E.L., Abbiati, M., Aguilera, M.A., Airoldi, L., Aguirre, J.D., Ashton, G., Bernardi, M., Brooks, P., Chan, B.K.K., Cheah, C.B., Chee, S.Y., Coutinho, R., Crowe, T., Davey, A., Firth, L.B., Fraser, C., Hanley, M.E., Hawkins, S.J., Knick, K.E., Lau, E.T.C., Leung, K.M.Y., Mckenzie, C., Macleod, C., Mafanya, S., Mancuso, F.P., Messano, L.V.R., Naval-Xavier, L.P.D., Ng, T.P.T., O'Shaughnessy, K.A., Pattrick, P., Perkins, M.J., Perkol-Finkel, S., Porri, F., Ross, D.J., Ruiz, G., Sella, I., Seitz, R., Shirazi, R., Thiel, M., Thompson, R.C., Yee, J.C., Zabin, C., Bishop, M.J., 2021. A global analysis of complexity–biodiversity relationships on marine artificial structures. Global Ecol. Biogeogr. 30 (1), 140–153. https://doi.org/10.1111/geb.13202.

Ter Hofstede, R., Driessen, F.M.F., Elzinga, P.J., Van Koningsveld, M., Schutter, M., 2022. Offshore wind farms contribute to epibenthic biodiversity in the North Sea. J. Sea Res. 185, 102229. https://doi.org/10.1016/j.seares.2022.102229.

Thaker, M., Zambre, A., Bhosale, H., 2018. Wind farms have cascading impacts on ecosystems across trophic levels. Nat. Ecol. Evol. 2, 1854–1858. https://doi.org/10.1038/s41559-018-0707-z.

Thaxter, C.B., Buchanan, G.M., Carr, J., Butchart, S.H., Newbold, T., Green, R.E., Tobias, J.A., Foden, W.B., O'Brien, S., Pearce-Higgins, J.W., 2017. Bird and bat species' global vulnerability to collision mortality at wind farms revealed through a trait-based assessment. P. Roy. Soc. B-Biol. Sci. 284 (1862), 20170829. https://doi.org/10.1098/rspb.2017.0829.

Tobias, J.A., Sheard, C., Pigot, A.L., Devenish, A.J., Yang, J., Sayol, F., Neate-Clegg, M.H.C., Alioravainen, N., Weeks, T.L., Barber, R.A., Walkden, P.A., MacGregor, H.E.A., Jones, S.E.I., Vincent, C., Phillips, A.G., Marples, N.M., Montaño-Centellas, F.A., Leandro-Silva, V., Claramunt, S., Darski, B., Freeman, B.G., Bregman, T.P., Cooney, C.R., Hughes, E.C., Capp, E.J.R., Varley, Z.K., Friedman, N.R., Korntheuer, H., Corrales-Vargas, A., Trisos, C.H., Weeks, B.C., Hanz, D.M., Töpfer, T., Bravo, G.A., Remeš, V., Nowak, L., Carneiro, L.S., Moncada, A.J., Matysioková, B., Baldassarre, D.T., Martínez-Salinas, A., Wolfe, J.D., Chapman, P.M., Daly, B.G., Sorensen, M.C., Neu, A., Ford, M.A., Mayhew, R.J., Silveira, L.F., Kelly, D.J., Annorbah, N.N.D., Pollock, H.S., Grabowska-Zhang, A.M., McEntee, J.P., Gonzalez, J.C.T., Meneses, C.G., Muñoz, M.C., Powell, L.L., Jamie, G.A., Matthews, T.J., Johnson, O., Brito, G.R.R., Zyskowski, K., Crates, R., Harvey, M.G., Zevallos, M.J., Hosner, P.A., Bradfer-Lawrence, T., Maley, J.M., Stiles, F.G., Lima, H.S., Provost, K.L., Chibesa, M., Mashao, M., Howard, J.T., Mlamba, E., Chua, M.A.H., Li, B., Gómez, M.I., García, N.C., Päckert, M., Fuchs, J., Ali, J.R., Derryberry, E.P., Carlson, M.L., Urriza, R.C., Brzeski, K.E., Prawiradilaga, D.M., Rayner, M.J., Miller, E.T., Bowie, R.C.K., Lafontaine, R., Scofield, R.P., Lou, Y., Somarathna, L., Lepage, D., Illif, M., Neuschulz, E.L., Templin, M., Dehling, D.M., Cooper, J.C., Pauwels, O.S.G., Analuddin, K., Fjeldså, J., Seddon, N., Sweet, P.R., DeClerck, F.A.J., Naka, L.N., Brawn, J.D., Aleixo, A., Böhning-Gaese, K., Rahbek, C., Fritz, S.A., Thomas, G.H., Schleuning, M., 2022. AVONET: morphological, ecological and geographical data for all birds. Ecol. Lett. 25 (3), 581–597. https://doi.org/10.1111/ele.13898.

Vaissière, A.C., Levrel, H., Pioch, S., Carlier, A., 2014. Biodiversity offsets for offshore wind farm projects: the current situation in Europe. Mar. Pol. 48, 172–183. https://doi.org/10.1016/j.marpol.2014.03.023.

Vanermen, N., Courtens, W., Daelemans, R., Lens, L., Müller, W., Van de Walle, M., Verstraete, H., Stienen, E.W., 2020. Attracted to the outside: a meso-scale response pattern of lesser black-backed gulls at an offshore wind farm revealed by GPS telemetry. ICES J. Mar. Sci. 77 (2), 701–710. https://doi.org/10.1093/icesjms/fsz199.

Vanermen, N., Onkelinx, T., Courtens, W., Van De Walle, M., Verstraete, H., Stienen, E. W., 2015. Seabird avoidance and attraction at an offshore wind farm in the Belgian part of the North Sea. Hydrobiologia 756, 51–61. https://doi.org/10.1007/s10750-014-2088-x.

Virtanen, E.A., Lappalainen, J., Nurmi, M., Viitasalo, M., Tikanmäki, M., Heinonen, J., Atlaskin, E., Kallasvue, M., Tikkanen, H., Moilanen, A., 2022. Balancing profitability of energy production, societal impacts and biodiversity in offshore wind farm design. Renew. Sustain. Energy Rev. 158, 112087.

Wang, S., Wang, S., Smith, P., 2015. Ecological impacts of wind farms on birds: questions, hypotheses, and research needs. Renew. Sustain. Energy Rev. 44, 599–607. https://doi.org/10.1016/j.rser.2022.112087.

Wang, Y., Song, Y., Zhong, Y., Chen, C., Zhao, Y., Zeng, D., Wu, Y., Ding, P., 2021. A dataset on the life-history and ecological traits of Chinese birds. Biodivers. Sci. 29 (9), 1149. https://doi.org/10.17520/biods.2021201.

Wang, Z., Zhou, F., Li, X., Sun, R., Jiang, A., Zhang, Y., Han, X., Liang, Q., Qiu, Z., 2007. Bird risk assessment for bird strike prevention and control at airports. Ecol. Sci. 26 (1), 69–74, 008-8873(2007)01-069-06.

Wei, L., Xingshuo, Z., Haigen, X., Bo, Y., Mingchang, Cao, Tianshi, X., Yongxiang, H., Ping, Y., Jianfeng, Y., Daqing, Z., 2023. Bird diversity in Jiangsu offshore waters: its analysis and relationship with wind farms and mariculture. Mar. Sci. 47 (4), 89–107. https://doi.org/10.11759/hykx20210804001.

Wei, T., Simko, V., Levy, M., Xie, Y., Jin, Y., Zemla, J., 2017. Package 'corrplot'. Statistician 56, e24. https://peerj.com/articles/9945/Supplemental_Data_S10.pdf.

Wilman, H., Belmaker, J., Simpson, J., de la Rosa, C., Rivadeneira, M.M., Jetz, W., 2014. EltonTraits 1.0: species-level foraging attributes of the world's birds and mammals. Ecology 95 (7). https://doi.org/10.1890/13-1917.1, 2027–2027.

Xia, S., Yang, Y., Liu, Y., 2023. Potential of China's offshore wind energy. Science 379 (6635), 888. https://doi.org/10.1126/science.adh051.

Xu, H., Cao, Y., Yu, D., Cao, M., He, Y., Gill, M., Pereira, H.M., 2021. Ensuring effective implementation of the post-2020 global biodiversity targets. Nat. Ecol. Evol. 5, 411–418. https://doi.org/10.1038/s41559-020-01375-y.

Xu, W., Liu, Y., Wu, W., Dong, Y., Lu, W., Liu, Y., Zhao, B., Li, H., Yang, R., 2020. Proliferation of offshore wind farms in the North Sea and surrounding waters revealed by satellite image time series. Renew. Sustain. Energy Rev. 133, 110167. https://doi.org/10.1016/j.rser.2020.110167.

Zhao, S., Xu, H., Wang, T., Li, H., Li, X., Liu, N., Song, X., Guan, F., Chen, X., Xu, A., Li, B., 2024. Prioritizing landscapes for mitigating the impacts of onshore wind farms on multidimensional waterbird diversity in the Yellow Sea. Curr. Zool. 8, 1–13. https://doi.org/10.1093/cz/zoae008.

Zhou, W., Wang, M., Huang, M., Wei, F., 2021. A marine biodiversity plan for China and beyond. Science 371 (6530), 685–686. https://doi.org/10.1126/science.abg7976.