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Research article

Assessment of seabird vulnerability to offshore wind farms in China

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ABSTRACT

Offshore wind farm (OWF) development is expanding worldwide, yet its ecological implications for seabirds remain insufficiently understood in many regions. China now hosts the fastest-growing OWF industry globally, while systematic assessments of seabird vulnerability are lacking due to limited ecological data. In this study, we adapt and localize established international methodologies to evaluate the vulnerability of 75 seabird species to OWFs. Species Vulnerability Indices (SVIs) were derived from three dimensions: collision risk, displacement vulnerability, and population sensitivity. Pelicans, albatrosses, boobies, and grebes emerged as the most vulnerable groups. To demonstrate its practical application, we applied the framework in the outer Yangtze River Estuary using three seasons of boat-based survey data. Results showed predominantly low-to medium-risk species, with relatively minor risks in deeper eastern waters. This framework provides a practical, quantitative tool to integrate seabird conservation into China's OWF planning, supporting biodiversity-sensitive marine spatial management.

1. Introduction

In response to global climate change and the imperative of energy transition, the rapid expansion of low-carbon and renewable energy has become critical for achieving the Sustainable Development Goals (SDGs) (Fuso Nerini et al., 2018; Jaiswal et al., 2022). As a key low-carbon technology, offshore wind power is increasingly important due to its high wind resource efficiency, stable energy output and minimal land requirements (Díaz and Guedes Soares, 2020). Despite these advantages, the construction and operation of offshore wind farms (hereafter, OWFs) can adversely affect coastal and marine ecosystems by altering habitats, generating underwater noise, and creating collision risks (Fox et al., 2006; Watson et al., 2024). These impacts extend to various marine species, including seabirds, marine mammals, and fish populations (Bailey et al., 2014; Bergström et al., 2014).

Seabirds are top predators and key indicator groups within marine ecosystems, relying extensively on dynamic coastal and offshore environments for breeding, foraging, and migration (Croxall et al., 2012). Studies have shown that OWFs can directly cause mortalities through collisions (Everaert and Stienen, 2006; Rothery et al., 2009), and indirectly affect seabirds by disrupting foraging behavior and creating migratory barriers, which reduces foraging efficiency and breeding success (Fox et al., 2006; Masden et al., 2009; Peschko et al., 2020). Given these potential impacts, long-term monitoring networks have been established in the North Sea using before-after-control-impact (BACI) designs to track changes in the behavior and population dynamics of specific seabird groups before and after wind farm construction (Larsen and Guillemette, 2007; Furness et al., 2013; Mendel et al., 2019; Peschko et al., 2021). By combining multi-species ecological parameters, researchers have developed systematic risk assessment frameworks integrating multi-dimensional indicators such as avoidance risk and conservation importance (Furness et al., 2013; Kelsey et al., 2018; Fauchald et al., 2024). These frameworks provide crucial support for OWF siting decisions and guide mitigation strategies (Garthe and Hüppop, 2004; Lamb et al., 2024).

China's offshore wind industry has experienced the fastest growth in installed capacity globally, reaching over 26 GW by 2021 and accounting for about 50 % of the global total (Zhang and Wang, 2022;

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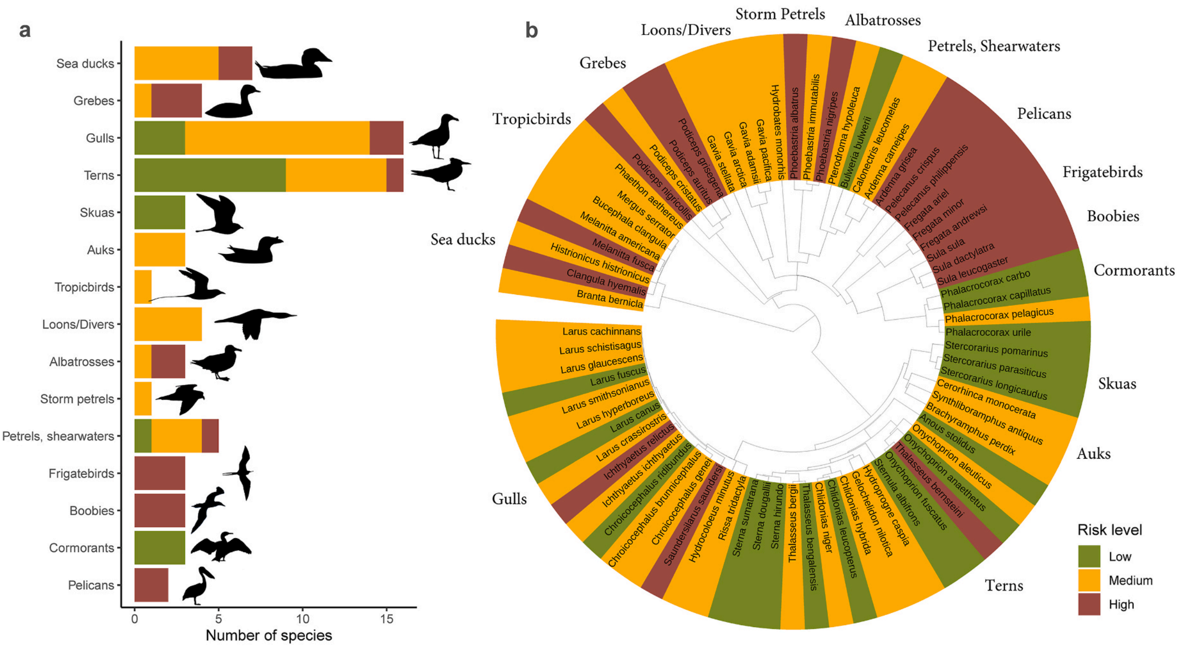

Fig. 1. Estimated risk levels of different seabird groups to offshore wind farms. (a) Bar chart showing the number of species at high, medium, and low risk levels across bird groups. (b) Phylogenetic distribution of risk levels among the 75 seabird species in this study. Leaf colors at tree tips denote risk-level categories. All of the phylogenies are based on trees from (Jetz et al., 2012) and available at birdtree.org.

GWEC, 2025). Large-scale projects continue to be planned and constructed, especially in deep-sea areas (Hughes et al., 2024). However, systematic and quantitative risk assessments for seabird impacts remain underdeveloped due to limited ecological data and the challenges of offshore surveys (Chen et al., 2018; Su et al., 2020). Although a few studies have examined the effects of onshore wind farms on waterbirds (Zhao et al., 2020; Cheng et al., 2021; Lai et al., 2024), comparable assessments for offshore seabird communities are still lacking. Furthermore, the distinct species composition, ecological behaviors, and conservation priorities of seabirds in Chinese waters limit the direct applicability of assessment frameworks developed for European marine environments.

To address this gap, we develop a regional seabird vulnerability assessment framework adapted from well-established international methodologies (Garthe and Hüppop, 2004; Furness et al., 2013; Reid et al., 2023). We evaluated the vulnerability of 75 seabird species inhabiting Chinese coastal waters to OWFs from three dimensions: collision risk, displacement vulnerability, and population sensitivity. In addition, we apply this framework for the first time in the Yangtze River Estuary, a major OWF development zone in eastern China, using field survey data to preliminarily identify high-risk areas for seabirds.

2. Methods

2.1. Species vulnerability assessment

2.1.1. Species selection

We included all seabird species that regularly occurred in Chinese coastal waters according to Zheng (2023) and (Ma and Chen, 2018). This includes species from the orders of Procellariiformes and Suliformes, Pelecanidae in Pelecaniformes, and Laridae in Charadriiformes. Sea ducks, grebes that frequently utilize oceanic habitats were also included. Species were excluded if they: (1) live exclusively in freshwater habitats in China, such as Black-bellied Tern (*Sterna acuticauda*) and White Pelican (*Pelecanus onocrotalus*); or (2) are classified vagrants (e.g., Japanese Murrelet *Synthliboramphus wumizusume*). Shorebirds, raptors, and passerines that occur offshore were not considered in the study. Finally, our database includes 75 species across eight orders and 14 families (Table S1). In the following analysis, the term "group" refers to species grouped by genus or broader taxonomic affinities for comparative purposes; we defined a total of 15 groups.

2.1.2. Risk scores

To ensure the vulnerability assessment reflects the status of seabird diversity in China while considering the availability of relevant data, we adapted parameters from previous studies (Garthe and Hüppop, 2004; Desholm, 2009; Furness et al., 2013; Reid et al., 2023). We assessed the vulnerability of Chinese seabirds to OWFs based on three dimensions and six metrics: (1) collision risk: flight agility, percentage time flying at rotor height (ca. 20–350 m); (2) displacement vulnerability: avoidance risk assessed based on existing empirical studies, habitat specialization; (3) population sensitivity: threatened status, generation time.

(1) Collision risk

a. Flight maneuverability. Wing loading (body mass [g]/wing area [cm^2]) was used as a proxy for flight maneuverability. Compared with other wing morphology metrics such as aspect ratio, wing loading directly relates to collision risk by indicating turning capacity in flight, which determines a bird's ability to avoid turbine blades (Fernández-Juricic et al., 2018). Species with low wing loading (lighter body mass relative to wing area) have higher agility and thus lower collision risk. Values from published sources were scored on a 1–5 scale using quintiles (lowest = 1, highest = 5), with lower scores indicating better maneuverability. The bird body mass and wing area data were mainly collected from (Spear and Ainley, 1997; Alerstam et al., 2007; Dunning, 2007; Pennycuick, 2008; Hedenström and Akesson, 2016; Shiomi et al., 2024), detailed information is provided in Supplementary data.

b. Percentage time flying at rotor height. The proportion of time spent within the rotor-swept zone (~30–350 m) is a critical determinant of collision likelihood (Cook et al., 2012). Species that fly predominantly out of rotor height face minimal collision risk, while species frequently within this zone are more vulnerable. Data were compiled from published studies on seabird flight heights (Garthe and Hüppop, 2004; Cook et al., 2012; Furness et al., 2013; Reid et al., 2023), and new data on

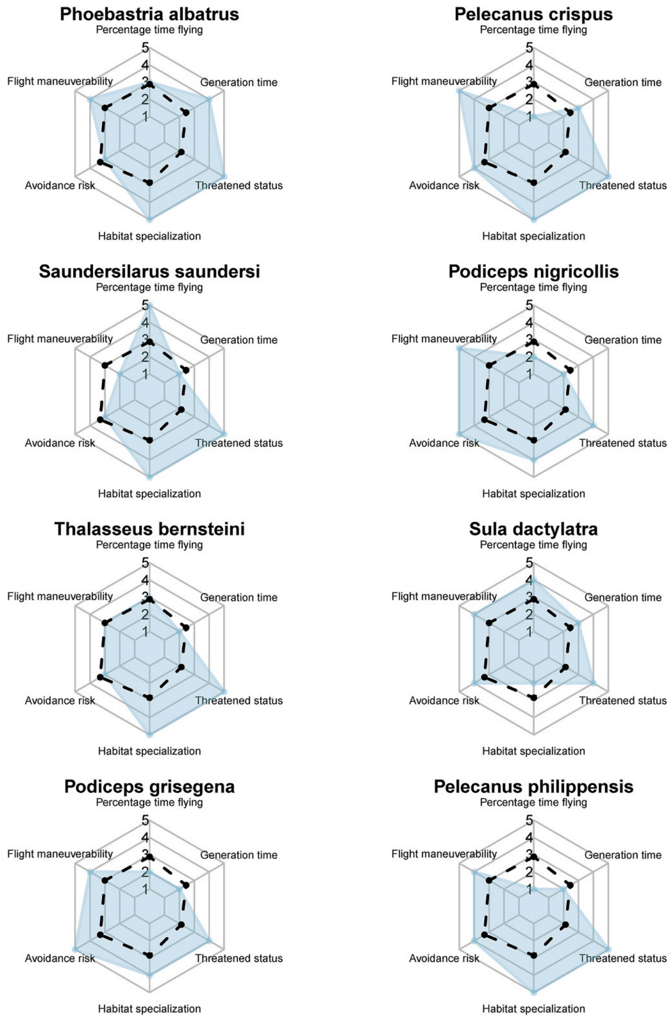

Fig. 2. Six category scores contributing to the overall species vulnerability index (SVI) for offshore wind farms, shown for the eight species with the highest SVI values. Blue points and shaded areas represent individual species scores, while the black dotted line indicates the average score across all 75 species assessed.

flight heights when relevant (e.g., Cheng et al., 2024).

(2) Displacement vulnerability

c. Avoidance risk. Given limited empirical data for Chinese OWFs, avoidance or attraction responses were categorized using the five-tier framework established by Dierschke et al. (2016): 1–Strong attraction; 2–Weak attraction; 3–Neutral/balanced response; 4–Weak avoidance; 5–Strong avoidance. Given technological advances (e.g., GPS tracking) in assessing avian responses to OWFs, we updated this framework through a systematic Web of Science search using the terms: (offshore) AND (wind farm OR wind turbine OR wind energy OR wind power) AND (bird* OR avian OR aves OR seabird* OR waterbird* OR shorebird*)). As of January 2025, we identified 498 relevant studies. After screening for relevance and data availability, a total of 22 studies were retained and used to update avoidance scores for species not covered in Dierschke et al. (2016), or where new empirical data were available. Reported responses were directly mapped to the criteria defined in Dierschke et al. (2016), without conducting a formal meta-analysis or applying structured expert elicitation. Details and reference lists for each species are provided in Supplementary Data.

d. Habitat specialization. Marine bird species vary in the range of habitats they use. Some are habitat generalists, while others rely on highly specific features. The breadth of habitats a species can use reflects its capacity to relocate when its preferred habitat is affected by anthropogenic structures. We quantified habitat specialization as the number of level-2 marine habitat types in the IUCN Habitat Classification Scheme (Marine Neritic, Marine Oceanic, Marine Intertidal, Marine Coastal/Supratidal (IUCN, 2023); used by the species during breeding or nonbreeding periods (Wang et al., 2022). The values were converted to 1–5 scores using quintile divisions, with higher scores indicating a higher degree of habitat specialization in marine habitats by the species.

(3) Population sensitivity

e. Threatened status. To reflect regional conservation priorities, we mainly adopt threatened status information from *China's Species Red List* (Jiang et al., 2016), which follows the IUCN Red List criteria (IUCN, 2022) but emphasizes national conservation status, especially for species that are globally common but regionally rare. For species classified as Data Deficient (DD) in *China's Species Red List*, IUCN ratings were additionally referenced. China's List of State Key Protected Wild Animals (LSKPWA) was also used to identify Class I and II species of conservation concern (NFGA and MARA, 2021). Finally, species were classified into five categories: 1–Least Concern (LC) on both lists, or LC on one and DD on the other; 2–Near Threatened (NT) on either list; 3–Vulnerable (VU) on either list; 4–Class II in LSKPWA or Endangered (EN) on either list; 5–Class I in LSKPWA or Critically Endangered (CR) on either list.

f. Generation time. Generation time (GT) was used to characterize species' capacity to recover from increased mortality due to OWFs. GT estimates (Bird et al., 2020) were based on age at first breeding, maximum lifespan, and annual adult survival. GT was categorized as: 1–$<$5 years; 2–5~10 years; 3–10~15 years; 4–15~20 years; 5– $\geq$20 years.

Where species-specific data were unavailable, we substituted estimates from the closest relative or averaged values for the genus or family (Supplementary data). Following (Garthe and Hüppop, 2004), the Species Vulnerability Index (SVI) for OWF exposure was calculated as:

$$SVI = \frac{a+b}{2} \times \frac{c+d}{2} \times \frac{e+f}{2}$$

Species were then classified as low, medium, or high risk based on the 25th and 75th percentiles of SVI values.

2.2. Case study

2.2.1. Study area and data collection

The case study was conducted in the coastal waters adjacent to the outer Yangtze River Estuary (122.51°–123.8°E, 31.78°–30.73°N), an area representative of China's planned intensive offshore wind development zone in the East China Sea. Three seasonal boat-based surveys were conducted in spring (April), summer (July), and autumn (October) 2024, respectively. For each survey, six transects were set cover the typical range of water depths and distances from shore within the target offshore wind development zone, with an average length of 67 ± 21 km. The transects were designed to provide representative coverage of the coastal waters adjacent to the outer Yangtze River Estuary, balancing survey effort with the logistical constraints of offshore boat-based monitoring. During the surveys, observers recorded birds on the water and in-flight using binoculars (8–12 ×). Survey tracks were georeferenced using GPS, and start and end times were recorded for each transect.

2.2.2. Data analysis

To standardize for variation in transect length, species-specific observation rates were calculated as:

$$\text{Observation Rate}_i = \frac{N_i}{L}$$

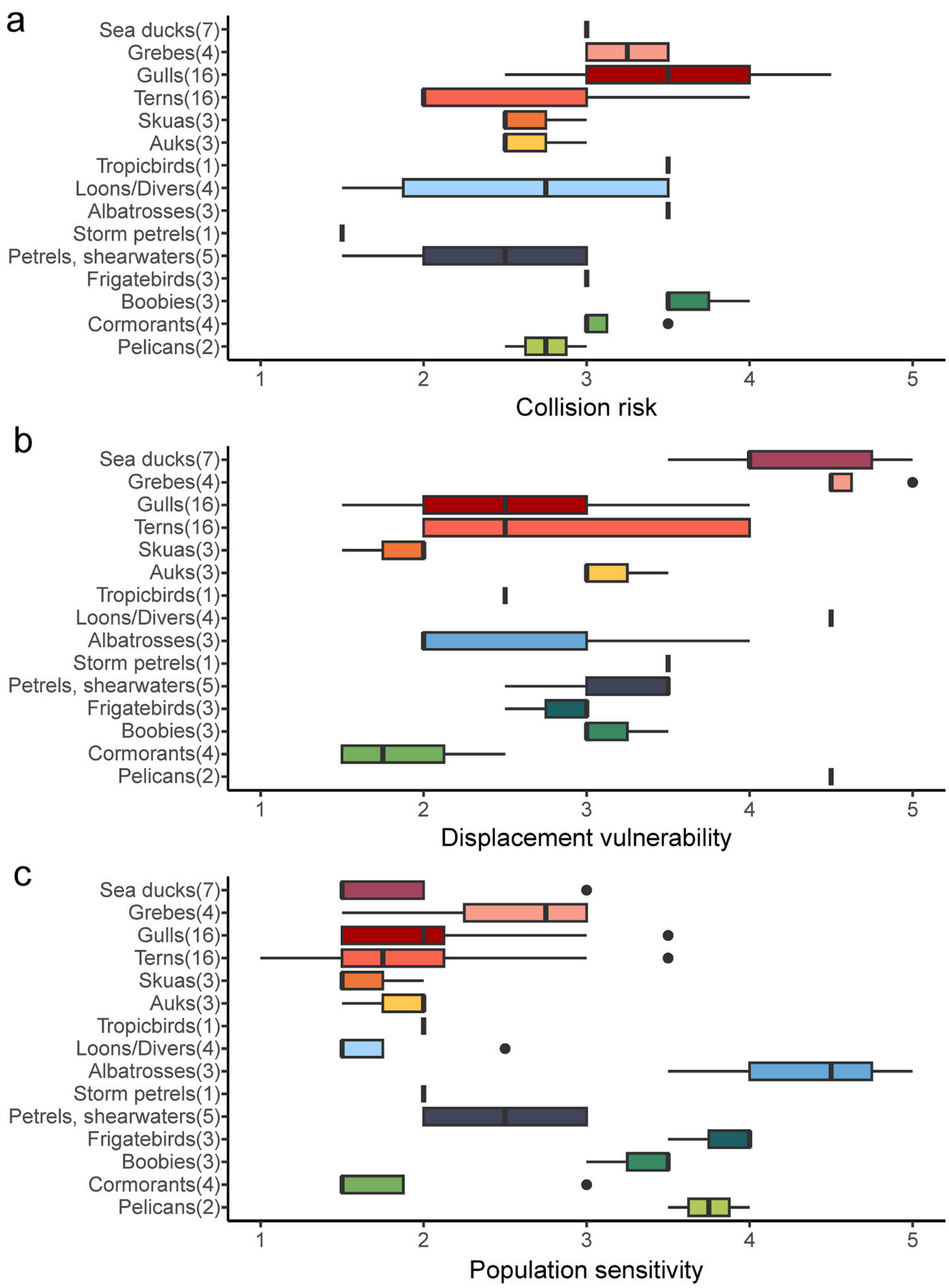

Fig. 3. Boxplots of (a) collision risk, (b) displacement vulnerability, and (c) population sensitivity scores across different bird groups. The number of species included in this study for each group is given in parentheses.

where N_i is the number of individuals of species i, and L is the transect length (km).

To address the linear trait of transect data, we discretized transects into point sets. Species-specific observation rate surfaces were then generated at 2.5 × 2.5 km resolution using inverse distance weighting (IDW) interpolation implemented in the *sf* and *gstat* packages (Pebesma, 2004, 2018; Gräler et al., 2016). Grid-level collision risk (Risk_t) was quantified by integrating species densities with their SVI scores:

$$\text{Risk\_t} = \sum_{i=1}^{n} (Density_i \times SVI_i)$$

where n is the number of species per grid cell.

To address uncertainty in SVI estimates, we applied normally distributed perturbations (±20 %) and conducted 10,000 Monte Carlo simulations, yielding mean risk estimates with 95 % confidence intervals for each grid cell.

Similarly, each cell was then classified as low, medium, or high risk based on the 25th and 75th percentiles of mean risk values.

3. Results

3.1. Species vulnerability assessment

A total of 75 seabird species in China were included in the assessment (Fig. 1). The species vulnerability index (SVI) ranged from 6 to 63, with a mean of 21.05. Species with high overall SVI rankings did not necessarily score highly across all individual metrics (Fig. 2). Species identified as high-risk (n = 19) included all frigatebirds (3 species), boobies (3 species), and pelicans (2 species), as well as two-thirds of the albatrosses (3 species) and three-quarters of the grebes (4 species) (Fig. 1).

Table 1
Bird survey results and evaluated Species Vulnerability Index (SVI) risk values from three surveys in the offshore waters of the Yangtze Estuary.

Species name	Scientific name	Number	Season[1]	Risk[2]
Streaked Shearwater	*Calonectris leucomelas*	17	2, 3	26.3
Greater Crested Tern	*Thalasseus bergii*	26	1	21
Black-tailed Gull	*Larus crassirostris*	5	1, 3	16.9
Caspian Tern	*Hydroprogne caspia*	3	1	11.3
Slaty-backed Gull	*Larus schistisagus*	3	3	18
Mew Gull	*Larus canus*	17	1, 2, 3	9.0
Siberian Gull	*Larus hyperboreus*	1	1	16.0
Lesser Black-backed Gull	*Larus fuscus*	48	3	9.0
Pomarine Skua	*Stercorarius pomarinus*	5	3	9.0
Undetermined gull/tern species	-	2	3	16.2

[1]Season:1-Srping; 2-Summer; 3-Autumn.
[2]Risk level: Green-Low risk; Yellow-Medium risk.

Collision risk was highest for groups such as albatrosses and boobies (Fig. 3a), displacement vulnerability was highest for grebes, pelicans, and divers (Fig. 3b), and population sensitivity was highest for albatrosses, frigatebirds, and pelicans (Fig. 3c). Overall, pelicans, albatrosses, boobies, and grebes appear to be the most vulnerable to the potential impacts of OWF development. In contrast, skuas and cormorants are less likely to be affected (Fig. 1).

3.2. Seabird risk map in the outer Yangtze River Estuary

During the three seasonal boat-based surveys, a total of 127 individuals (including two unidentified gull species) from 9 seabird species were recorded (Table 1). All recorded species were classified as low and medium risk in our assessment, with a mean SVI of 15.3, ranking them on average in the lower 63 % of all species assessed. The spatial analysis indicates that OWF construction in the eastern part of the study area would likely pose relatively minor ecological risks to seabirds (Fig. 4). This pattern may reflect a combination of local environmental conditions (e.g., deeper waters, lower nearshore productivity) and the typical coastal foraging behavior of seabirds, although our current data do not allow us to distinguish the relative contributions of these factors.

4. Discussion

With China's offshore wind industry expanding rapidly, understanding species-specific vulnerabilities has become increasingly important. Our study provides the first regional, multi-dimensional risk assessment for seabirds in China. This framework is designed as a decision-support tool for offshore wind planning. We illustrate its application through a case study in the outer Yangtze River Estuary, using available field data to demonstrate how the framework can be populated and used to preliminarily identify areas of higher and lower ecological risk for seabirds. This approach offers a foundation for incorporating ecological considerations into the early stages of offshore wind development in China.

Our results reveal taxonomic differences in SVI values among seabird groups (Fig. 1), which are broadly consistent with findings from other regions with intensive OWF development. Studies in Scottish waters (Furness et al., 2013) and the Pacific area (Kelsey et al., 2018) have shown that large-bodied species with low flight maneuverability, and those frequently using the rotor-sweep zone, are highly susceptible to collision, such as gannets and pelicans. Consistently, our study identifies albatrosses and boobies as having high collision risk (Fig. 3a). Likewise, divers, sea ducks, and grebes, which rely heavily on underwater vision or hearing to forage, are particularly sensitive to underwater noise and human disturbance, resulting in high risk levels (Kelsey et al., 2018; Mendel et al., 2019; Lamb et al., 2024). In contrast, many opportunistic species such as skuas and cormorants, which are smaller-bodied and/or capable of using diverse habitats, tend to be less affected by these risks (Petersen et al., 2006; Langston, 2013). Their behavioral flexibility may also allow them to exploit artificial structures within OWFs as additional roosting or foraging sites (Wilhelmsson and Malm, 2008; Lindeboom et al., 2011). Nevertheless, regional differences in species assemblages, population status, and flyway dependence can lead to divergences in final vulnerability rankings. For example, along China's coasts, gulls and terns constitute 40 % of the species assessed (32 out of 75), and their high flight maneuverability and foraging plasticity generally result in low to medium vulnerability (Fig. 1). Certain species, however, show differences in final risk rankings between regions: in European waters, the black-legged kittiwake (*Rissa tridactyla*) is of particular concern due to population declines and low reproductive output (Peschko et al., 2020), while in China, the Chinese crested tern (*Thalasseus bernsteini*) is highly vulnerable due to its extremely small global population and restricted breeding habitats (BirdLife International, 2018). Overall, our findings highlights both functional-group consistency and regional-specific uniqueness, underscoring the need for localized adaptation of vulnerability frameworks rather than directly transferring rankings from other geographies.

Our results further indicate that species with a high overall SVI do not necessarily rank high in all individual metrics. Among the top eight species with the highest SVI values, each had at least one or two metrics scoring below the average (Fig. 2). This suggests that relying on a single

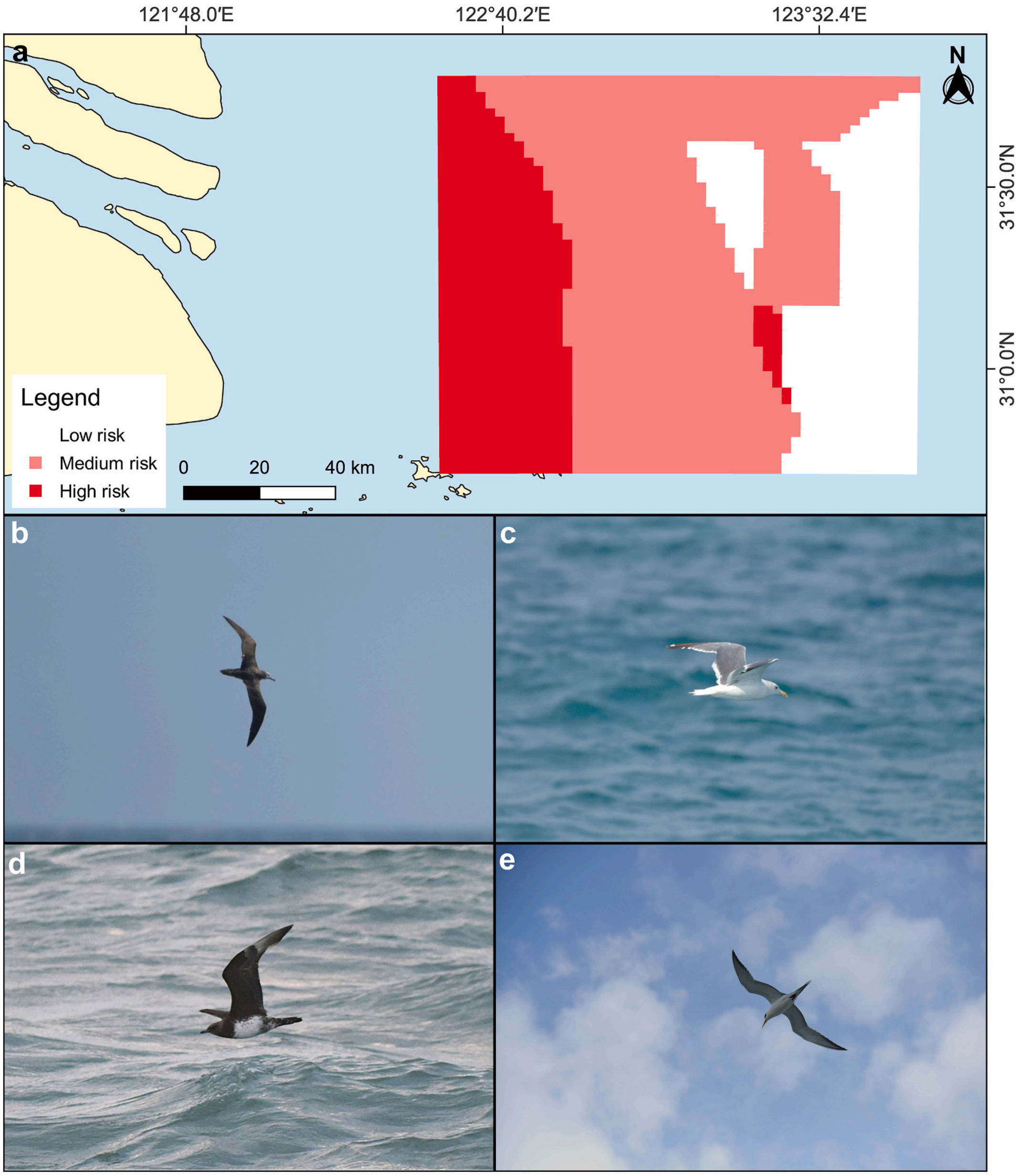

Fig. 4. (a) Mean risk map of offshore wind farm impacts on birds in the study area, based on survey results. Photos of seabirds recorded during the surveys: (b) Streaked Shearwater (*Calonectris leucomelas*), (c) Siberian Gull (*Larus smithsonianus*), (d) Pomarine Skua (*Stercorarius pomarinus*) and (e) Greater Crested Tern (*Thalasseus bergii*).

metric may under- or overestimate actual risks for certain species, given the high heterogeneity in sensitivity to collision, displacement, and population impacts. For example, in the North Sea, kittiwakes (*Rissa tridactyla*) may show limited avoidance behavior around OWFs but frequently fly at rotor height, making collision risk a major concern (Peschko et al., 2020). Therefore, the integrated framework applied in this study helps to overcome the limitations of collision-focused models and better reflects the ecological realities of seabirds (Dierschke et al., 2016).

The coastal waters adjacent to the outer Yangtze River Estuary is both a major OWF development zone and an important distribution area for seabirds, making it a representative case study (Ma and Chen, 2018). However, our spatial results alone cannot distinguish whether the relatively low risk areas in the eastern part mainly reflect local environmental features (e.g., water depth, food availability) or seabird foraging and movement patterns, given the limited environmental covariates collected during the surveys. Our field surveys only recorded species ranked as low to medium risk in our assessment framework. This result likely reflects limitations in spatial coverage, transect density, and seasonal timing rather than the area's true ecological risk level. Overall, the case study is not meant to provide a definitive risk map for the whole region, but rather to illustrate how local observations can be incorporated into the assessment workflow.

Despite providing a comprehensive framework, this study has several limitations. The SVI index assumes equal weighting of collision, displacement, and population impacts, which may oversimplify species-specific sensitivities. Also, current data limitations preclude detailed analyses by season or life stage, which are vital for understanding species' vulnerability during breeding and chick-rearing stages. For example, critically endangered species like the Chinese crested tern (Lu et al., 2020) and some boobies breeding in the Nansha Islands may be especially sensitive during these periods (Thaxter et al., 2019; Peschko et al., 2020). These limitations highlight the need for additional data and iterative refinement of the framework.

Based on our findings, several actionable recommendations can support marine spatial planning and OWF development in China: (1) Expand field surveys to include multiple seasons and key breeding/migration periods to better capture temporal variation in species distributions. (2) Increase spatial coverage and transect density of surveys, supported by technologies such as satellite tracking, radar, acoustic monitoring to identify flight corridors and foraging hotspots (Drewitt and Langston, 2006; Masden et al., 2010; Garthe et al., 2023). (3) Establish baseline monitoring in areas prior to turbine installation and retain reference sites without OWFs to support impact assessment (Marques et al., 2021). (4) Apply the framework to inform siting choices, including turbine layout optimization, avoidance of seabird concentration areas, and designation of buffer zones. (5) Periodically update vulnerability assessments as more ecological and demographic data become available to support adaptive management.

In summary, this study develops and applies a multi-dimensional seabird vulnerability assessment framework that addresses a significant research gap in China's offshore wind and seabird risk management. The application to a representative case study demonstrates the framework's practicality and adaptability to identify high, medium, and low risk areas. With continued long-term monitoring and the integration of diverse data sources, this framework can be refined to provide a robust basis for scientific site selection, risk management, and the balanced coexistence of OWF development and seabird conservation in China. Beyond China, this approach can be adapted to other rapidly developing coastal regions where offshore renewable energy expansion poses emerging challenges to marine biodiversity.

CRediT authorship contribution statement

Chuyu Cheng: Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization. **Weimin Yao:** Writing – review & editing, Funding acquisition. **Yanlong He:** Writing – review & editing, Conceptualization. **Jun Shi:** Writing – review & editing, Investigation. **Mianhao Song:** Writing – review & editing, Investigation. **Yuerui Wang:** Writing – review & editing, Investigation. **Can Jiang:** Writing – review & editing. **Bingqing Liu:** Writing – review & editing. **Lixia Zhao:** Writing – review & editing. **Junlin Ren:** Writing – review & editing, Supervision.

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Declaration of competing interest

The authors declare no conflict of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.128188.

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