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RESEARCH ARTICLE

An ecological risk assessment for the impacts of offshore wind farms on birds in Australia

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Abstract

An ecological risk assessment, based on life-history and behavioural attributes of 273 bird taxa, was used to identify which of those taxa are at high risk from negative interactions with offshore wind farms in Australia. The marine area of Australia was divided by state/territory boundaries perpendicular to the coast into eight regions, with Western Australia further divided into north and south, and a Bass Strait region bounded by the Victoria coast and the north coast of Tasmania. These regions were subdivided into coastal, inshore and offshore sub-regions and a risk summary for all bird taxa occurring in each of these sub-regions produced. In coastal and inshore sub-regions of Bass Strait, South Australia and Tasmania, the species with the highest risk scores were Orange-bellied Parrot *Neophema chrysogaster*, Furneaux White-fronted Tern *Sterna striata incerta*, Swift Parrot *Lathamus discolor*, Shy Albatross *Thalassarche cauta*, Far Eastern Curlew *Numenius madagascariensis* and Anadyr Bar-tailed Godwit *Limosa lapponica anadyrensis*. In offshore sub-regions in southern Australia, the highest risk species were all albatrosses, comprising Northern Royal *Diomedea sanfordi*, Eastern Antipodean *D. antipodensis antipodensis*, Gibson's *D. antipodensis gibsoni*, Wandering *D. exulans*, Amsterdam *D. amsterdamensis* and Grey-headed Albatross *T. chrysostoma*. Compared to onshore installations, there are logistical challenges to quantifying the potential and realized impacts of offshore wind farms that require different approaches to data collection and analyses. The extensive development of offshore wind farms in the Northern Hemisphere provides examples of best and emerging approaches to quantify and mitigate negative impacts of offshore wind farms that can be applied in an Australian context. Despite differences in the species involved, the same approaches to identifying high-risk species and to the monitoring and mitigation of negative impacts should be applied in a coordinated, regional-scale approach to the development of offshore wind farms in Australia.

KEYWORDS
birds, ecological risk assessment, mitigation, monitoring, offshore wind farms

INTRODUCTION

Generating electricity from offshore wind has significant benefits in emissions reductions, however, it also brings potential risks to birds. These include deaths as a result of direct collisions, displacement away from preferred habitats caused by disturbance from operating turbines and associated ship and helicopter traffic, barrier effects that impact preferred movement/migration routes, and attraction by artificial resting sites and increased food availability, associated with the creation of new substrate at turbine bases and fishing bans near sites (Bailey et al., 2014; Best & Halpin, 2019). Although the effects of these different impacts are often not easily separable, it is important to include them in any risk analysis to avoid an under-estimation of impacts where only the direct collision-related risks are included.

A widely adopted approach to identify taxa at greatest risk from anthropogenic activities is through an ecological risk assessment. Methods for conducting ecological risk assessments for birds are well developed and have been applied to assess the potential impacts of offshore wind farms on seabirds in the Northern Hemisphere (Furness et al., 2013; Garthe & Hüppop, 2004) as well as other commercial activities, such as fishing, that negatively impact seabirds (Hobday et al., 2011; Richard et al., 2017).

The specific data requirements and methods of implementation of ecological risk assessments may differ among different scenarios; however, the overarching principles are generally consistent with the tiered approach developed by Hobday et al. (2011). When developing an ecological risk assessment, it is essential that interpretation of the outputs is guided by data availability and the assumptions made where data are scarce and/or missing. The tiered approach provides a mechanism to progress an ecological risk assessment that takes account of, but is not curtailed by, these concerns, as they do not impact the process of assembling the comprehensive information needed to categorize the scale and intensity elements of a Level 1 assessment and providing a semi-quantitative assessment (Level 2) to highlight high-risk species of concern.

Offshore wind farms have been in operation in Europe for over 20 years and there is a wealth of experience in the assessment and mitigation practices that provide a benchmark for the conduct of impact assessment elsewhere (Green et al., 2016). Offshore wind farms are a much more recent area of interest in Australia although their development is projected to be relatively rapid (Briggs et al., 2021) with consultation processes underway for offshore renewable energy projects including in Bass Strait (https://consult.dcceew.gov.au/oei-gippsland). Although there are differences in the species assemblages involved between the Northern Hemisphere and Australia, the macro-ecological nature of the risk assessment processes for birds and offshore wind farms means that there is general applicability of the best-practice approaches to location selection, mitigation strategies and monitoring of impacts in the Australian context. Reviewing the data requirements of the methods and approaches outlined also provides an opportunity to highlight any knowledge/information gaps that should be addressed to support the further development of offshore wind farms.

The impacts of offshore wind farm developments on birds are typically assessed in a two-step process that involves quantifying the magnitude of bird mortality and then assessing the change in the population that this additional mortality would produce in the light of any conservation objectives of the species/site in question (Furness et al., 2013; Garthe & Hüppop, 2004). However, as it is not practicable nor possible to conduct surveys for carcasses of birds that have been killed by offshore wind farms (compared to onshore settings), the methodological and analytical approaches used to estimate the numbers of bird fatalities for onshore wind farms are unlikely to be appropriate in offshore locations. Further, collisions with ships and other marine infrastructure are known to be more frequent during periods of poor weather and/or poor visibility, such as fog and misty conditions, and during storms with high wind speeds (Black, 2005; Hüppop et al., 2016; Montevecchi, 2006; Newton, 2007; Rodríguez et al. 2014). This means that the conditions that create an elevated collision risk also make it impossible to make visual observation of collisions.

In order to provide the information required to adequately assess the potential risks associated with an offshore wind farm proposal, the suite of taxa included was based on their potential presence in the area of an offshore wind farm, rather than restricting the analysis to seabirds. Our approach includes shorebirds, seabirds and other taxa that either breed in or are regularly recorded in Australian Commonwealth waters adjacent to the Australian mainland including threatened taxa and migratory taxa protected under international agreements. Migratory terrestrial taxa that are known or suspected of migrating or moving across Commonwealth waters are also included.

By extending established methods developed and adopted elsewhere for providing sensitivity indices for birds that are potentially impacted by offshore wind farms to the Australian context, we have provided a definitive reference source of life-history and behavioural attributes that can be used to identify taxa that might interact with offshore wind farms. These attributes can then be 'scored' so that the relative risk of particular taxa can be quantified based on a combination of their likelihood of impact(s) from collision or displacement and the potential consequences of such interactions.

METHODS

Species

The methodology in this assessment follows the approach taken by Garthe and Hüppop (2004) and Furness et al. (2013) to categorize the risk of negative interactions of birds and offshore wind farms. Garthe and Hüppop (2004) provided risk scores for 26 marine bird species in the German Exclusive Economic Zone (EEZ), while Furness et al. (2013) assessed the risk for 38 marine bird species in Scottish waters.

Expanding their approach to include the suite of birds that might interact with offshore wind farms in Australia inevitably involves a much greater number of taxa simply as a result of geographic scale. Species that feed in inter-tidal areas, as well as wholly marine species, following the feeding habitat classifications in Garnett et al. (2015), were included as were taxa that transit through coastal and inshore regions during annual migration or dispersive movements, based on expert knowledge and Menkhorst et al. (2017). The number of taxa included reflects the large biogeographic scales involved, and the inclusion of all bird taxa, not just seabirds, that have the potential to interact with offshore wind farms. The taxonomy and nomenclature adopted by Garnett and Baker (2021) was used in compiling the species list.

Spatial distribution

The Australian EEZ was divided into eight regions where state/territory boundaries met the coast, the EEZ off Western Australia was divided at approximately 27°S to reflect the differences in bird species assemblages between the Northern and Southern areas of the state and, in particular, the internationally important shorebird areas in the northern region (Figure 1).

To reflect the regional interest in offshore wind farm proposals, and the migration and dispersive movement of birds through the region, we also created a Bass Strait region bounded by the northern coast of Tasmania between Woolnorth Point and Cape Portland and extending to the coast of Victoria. A separate Tasmania region, for all areas south of approximately 40.5°S was also created.

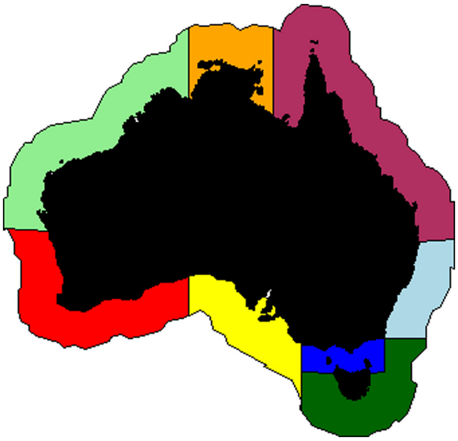

FIGURE 1 Spatial regions used in the risk assessment. Regions are Southern Western Australia (red), Northern Western Australia (pale green), Northern Territory (orange), Queensland (maroon), New South Wales (pale blue), Bass Strait (dark blue), Tasmania (dark green), and South Australia (yellow). Each region was subsequently divided into three sub-regions (see text).

Each region was further divided into three sub-regions: (1) 'coastal' (intertidal shoreline to 2 km from the coast), (2) 'inshore' (2–20 km from the coast), and (3) 'offshore' (21–200 km from the coast). A set of 12 feeding habitat types (Garnett et al., 2015) relevant to offshore wind farms was used to identify the coastal/onshore/offshore sub-regions in which each taxon was likely to occur.

Risk scores

Garthe and Hüppop (2004) and Furness et al. (2013) expressed overall risk as a combination of a Vulnerability and a Conservation score. In adapting this nomenclature to that of a semi-quantitative (level 2) ecological risk assessment of Hobday et al. (2011), we have considered vulnerability to be equivalent to susceptibility, and the conservation score to be equivalent to productivity (see below).

Research on bird interactions with offshore wind farms is a relatively new field in Australia compared to Europe and North America, and this is reflected in the very limited availability of empirical, species-specific data for the key attributes that have been included in the risk assessment approaches used elsewhere. Given these limitations, we have attempted to take a simplified, consistent, quantitative basis for attribute scoring based on peer-reviewed, publicly available data. This approach was taken in order to allow for reproducibility of results and to allow a structured updating process if and when new information becomes available. The principle sources of data for the key attributes used in this assessment process are shown in Table 1.

Productivity

A productivity risk score was calculated based on the following attributes that were each scored on 5-point scales:

Conservation status

For Conservation Status, we used Garnett and Baker (2021), which provided a contemporary national overview of the conservation status of all

TABLE 1 Data sources used for key attributes

Attributes	Sources
Conservation status	Garnett and Baker (2021)
Generation time	Bird et al. (2020)
Australian distribution, feeding habitats	Garnett et al. (2015), Menkhorst et al. (2017)
Morphology (wing dimensions and body mass)	Tobias et al. (2022)

birds occurring in Australia and its territories, using population sizes and trends, identified threats and recommending research and management actions to minimize those threats. This is a similar approach to that of Furness et al. (2013), who derived a conservation score that included the proportion of biogeographic population in Scotland, adult survival and UK threat status.

While we have used the Garnett and Baker (2021) assessment of the conservation status of Australian birds, we recognize the importance of the conservation status listing in a statutory context. The Federal Environment Protection and Biodiversity Conservation Act 1999 (EPBC) includes an appendix for threatened species. Therefore, while the EPBC listing was not included in the actual risk scoring, we have included the EPBC status and whether the taxon is listed as Migratory and/or Marine in the output files (see Tables S1 and S2). Conservation Status was scored as in Table 2. For taxa that Garnett and Baker (2021) did not assess, the conservation status was assumed to be equivalent to Least Concern and given a score of 1.

Generation time

The Generation Times (G) for each species were taken from Bird et al. (2020) and are based on age of first reproduction, maximum longevity and annual adult survival. This attribute is used to provide an index of the ability of a population to respond to the impacts of increased mortality caused by offshore wind farms. Generation Time was scored as in Table 3.

Productivity score

As the Conservation Status for each taxon includes an assessment of population size, population trend and threats, it was given a higher weighting relative to the Generation Time, such that the overall Productivity score for each taxon was:

$$\textit{Productivity}\ (P) = \left(\left(\text{Conservation Status}^{*}\ 1.5 + \text{Generation Time}\right)/2\right.$$

TABLE 2 Allocation of conservation status scores

APAB 2020 status	Conservation status score
Least Concern	1
Near-threatened	2
Vulnerable	3
Endangered	4
Critically endangered	5

TABLE 3 Allocation of generation time scores

Generation time	Generation time score
<5 years	1
≥5 and <10 years	2
≥10 and ≤15 years	3
>15 and ≤20 years	4
>20 years	5

Susceptibility

A susceptibility risk score was calculated based on the following attributes that were each scored on 5-point scales:

Flight height

The percentage of time that birds would be expected to fly below ((a) 0–30 m), inside ((b) 30–350 m) and above ((c) >350 m) the rotor swept area of a turbine was estimated for all taxa. Acknowledging that flight height data are generally lacking for many Australian birds, these height categories were chosen to reflect the current and projected swept area of turbine blades in offshore installations (Briggs et al., 2021). The proportion of time that a taxon was estimated to fly in one of three height categories was initially given a precautionary default of 25%, 50% and 25% for the three height categories.

Where possible, the allocation to height categories was revised based on available data from species/families that also occur in Europe (Galtbalt et al., 2021; Piersma et al., 1997) and data on the altitude used by migrating passerines (see for example Bruderer et al., 2018) and extensive observational experience of relevant birds taxa (see Table S1). To account for the relative risk in each height category, the height categories were weighted (1, 3, 0.5) as birds flying below rotor height are still likely to be impacted by the wind farm, by displacement and/or barrier effects, but at a lower level than direct collision; birds flying at heights above the installations are likely to be impacted less than those flying below.

Hence the overall Flight Height (FH) risk was:

$$\mathrm{FH} = \mathrm{a} + \left(\mathrm{b}^{*}\, 3\right) + \left(\mathrm{c}^{*}\, 0.5\right)$$

Since FH can take values between 50 and 300, the final flight height attribute was scored on a scale of 1–5 as in Table 4.

Flight manoeuvrability

Furness et al. (2013) suggested that the scores for the attribute of flight mobility were 'considered to be a consequence of morphology rather than behaviour'. Therefore, we have used wing loading, which is the mass of a bird divided by the wing area, as a consistent metric of morphology that provides a proxy for flight manoeuvrability. The approach follows Warham (1990) and Gauld et al. (2022), such that taxa with a low wing loading are light and manoeuvrable (i.e., low risk), in contrast to taxa with a high wing loading that have relatively short-winged rapid flight, and have lower manoeuvrability (i.e., high risk).

Data from Tobias et al. (2022) on the wing length, wing width and body mass of all bird taxa were used to determine a wing loading index (FM) where

TABLE 4 Allocation of flight height scores

Flight Height (FH) value	Flight height score
≤50	1
>50 and ≤100	2
>100 and ≤150	3
>150 and ≤200	4
>200	5

FM = body mass/(wing length * wing width). The Flight Manoeuvrability attribute was scored on a scale of 1–5 as in Table 5.

Habitat specialization

Garnett et al. (2015) provided a species-specific characterization of the non-trivial utilization of 12 relevant feeding habitat types defined by Commonwealth of Australia (2006). For this assessment, each taxon was given a habitat specialization score to reflect its ability to switch to alternative feeding habitat(s) as a result of disturbance or displacement according to the number of the habitat types in which it occurred, as in Table 6.

Susceptibility score

Given the importance of flight height and flight manoeuvrability in assessing the susceptibility of impacts on birds from wind farms, the habitat specialization was given a lower weighting relative in the overall susceptibility score such that the overall score for each taxon was:

$$\textit{Susceptibility}\,(S) = \left(\text{Flight Height} + \text{Flight Manoeuvrability} + \left(\text{Habitat Specialization}^{*}0.5\right)\right)/3$$

For those taxa considered to be external migrants (i.e., an obligate annual seasonal migrant that is only present for part of the year in Australia), the

TABLE 5 Allocation of flight manoeuvrability scores

Flight Manoeuvrability (FM) value	Flight manoeuvrability score
<0.01	1
≥0.01 and <0.02	2
≥0.02 and <0.03	3
≥0.03 and ≤0.04	4
>0.04	5

TABLE 6 Allocation of habitat specialization scores

Habitat specialization value	Habitat specialization score
≥9	1
6, 7 or 8	2
4 or 5	3
2 or 3	4
1	5

susceptibility risk score was discounted by a factor of 0.5. External migrants that do not normally feed in coastal and inshore sub-regions (non-foraging taxa) were assumed to occur in these sub-regions as they transit through them on migration; with the exception of external migrant seabirds that forage in the offshore sub-regions. In offshore sub-regions, non-foraging external migrants were assumed to be flying at high altitude and would not interact with any offshore installation (Galtbalt et al., 2021; Liechti et al., 2018; Piersma et al., 1997), and were excluded in the taxa list for that sub-region.

In addition to taxa that are known to make annual migrations across Bass Strait, taxa that occur in inshore and offshore sub-regions in both Victoria and Tasmania were assumed to move across Bass Strait either as annual migrants or as part of dispersive movements. Within these taxa, those that do not normally occur in coastal and inshore sub-regions were included in those sub-regions as they transit through them during cross-Bass Strait movements. Recognizing that these movements are restricted to a part of the year, the susceptibility risk scores were discounted by a factor of 0.5 for those taxa in these ‘transit’ sub-regions.

A similar approach was taken for taxa in Queensland and the Northern Territory that make annual dispersive movements across Torres Strait or other parts of Australia's northern coastline. As with external migrants, when they are in transit through offshore sub-regions, Bass Strait and Torres Strait migrants were assumed to be flying at high altitude such that they would not interact with any offshore installations, and were excluded from the taxa list for that sub-region. The susceptibility adjustment process was first applied to external migrants and then to any other taxa that occurred in the Bass Strait region, such that the susceptibility risk was only adjusted once. The taxa for which the susceptibility risk scores were discounted are shown in the Table S2.

Overall risk

The overall measures of relative risk (R) for each taxon were then estimated following the method of Williams et al. (2011) as the Euclidean distance from the taxon to the origin for a two-dimensional plot of P on S such that $R = ((P - X_0)^2 + (S - Y_0)^2)^{1/2}$ where X_0 and Y_0 are the x, y origin coordinates.

All analyses were conducted in R (R Core Team 2021).

RESULTS

A total of 273 taxa were included in the risk assessment. There was a bimodal distribution of susceptibility scores (Figure 2a), in part as a result of the discounting applied to those species that are only exposed to risk for part of the year. Some taxa had different susceptibility scores in different sub-regions resulting in 341 unique taxon/overall risk combinations. There were 32 instances where the difference in the overall risk score between sub-regions resulted in a difference in the overall risk category. The distribution of productivity scores (Figure 2b), for which each species had a single score, was skewed towards low scores as 80% of species had a conservation status of Least Concern that created a corresponding low score.

The division between low - medium and medium - high risk were based on the 25th and 75th percentiles for the unique set of overall risk scores for all taxa/sub-region combinations; this resulted in 85 taxa classed as low risk, 139 as medium risk and 81 as high risk (Figure 3).

The coastal and inshore sub-regions of Queensland had the highest number of taxa as they include external and dispersive migrants that move

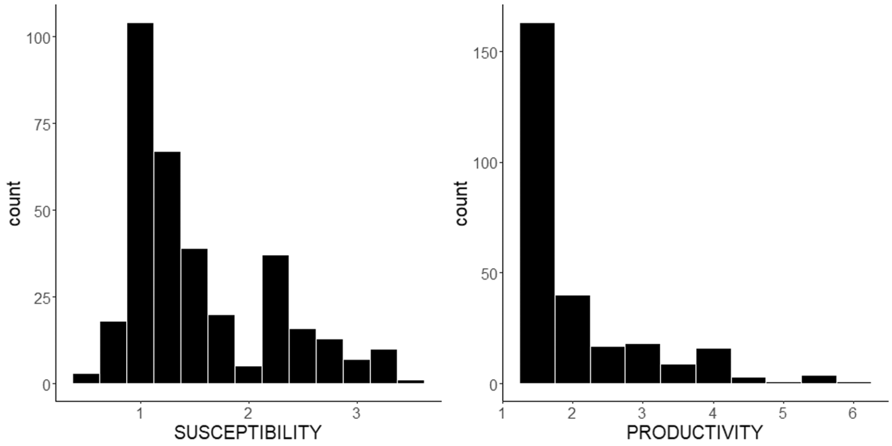

FIGURE 2 Distribution of (a) susceptibility, and (b) productivity scores for all taxa derived from the attribute scoring in the ecological risk assessment.

across Torres Strait (Table 7). The offshore sub-regions have the fewest taxa but the highest mean overall risk and highest proportion of high-risk taxa. The productivity - susceptibility plots for each sub-region emphasized the highest risk taxa occurring in the inshore and offshore sub-regions (Figure 4). There was a distinct bimodality in susceptibility in the offshore regions (Figure 4) that reflected a combination of discounting for seasonal occurrence and the influence of higher flight manoeuvrability risk scores for large albatrosses compared to smaller petrels and shearwaters. Details of the overall risk, productivity and susceptibility scores and the attribute scores are provided for each sub-region in the Table S2.

Of the 81 high-risk taxa, 11 mostly external migrant shorebirds occurred in the greatest number ($n = 16$) of sub-regions. There were 29 taxa, primarily widely distributed seabirds, that occurred in five or six sub-regions, and there were 17 taxa with restricted distributions that occurred in one or two sub-regions (Table 8). For coastal sub-regions, the taxa with the highest risk scores were Orange-bellied Parrot *Neophema chrysogaster*, Furneaux White-fronted

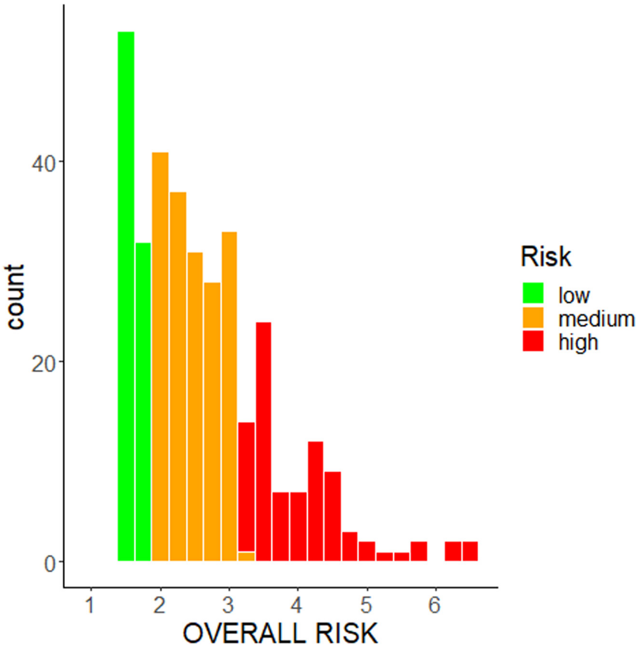

FIGURE 3 The distribution of overall risk scores for all taxa.

TABLE 7 Number of taxa, mean risk score and number of high-risk taxa in the coastal (coast), inshore (in) and offshore(off) sub-regions of Bass Strait (BST), New South Wales (NSW), Northern Territory (NT), Queensland (QLD), South Australia (SA), Tasmania (TAS), West Australia North (WAN) and West Australia South (WAS) regions

Region and sub-region	Taxa	Mean risk score	High-risk taxa
BST_coast	126	2.69	37
BST_in	131	2.40	25
BST_off	54	3.63	32
NSW_coast	89	2.83	27
NSW_in	53	2.74	17
NSW_off	50	3.61	29
NT_coast	121	2.53	26
NT_in	123	2.27	16
NT_off	16	2.83	4
QLD_coast	163	2.40	28
QLD_in	167	2.19	18
QLD_off	44	3.36	19
SA_coast	94	2.88	31
SA_in	53	2.85	20
SA_off	43	3.75	26
TAS_coast	69	3.00	26
TAS_in	41	3.03	18
TAS_off	52	3.68	32
WAN_coast	101	2.70	29
WAN_in	69	2.59	19
WAN_off	23	2.97	7
WAS_coast	91	2.84	31
WAS_in	56	2.75	20
WAS_off	46	3.73	28

Tern *Sterna striata incerta*, Western Hooded Plover *Thinornis cucullatus tregellasi*, Swift Parrot *Lathamus discolor*, Shy Albatross *Thalassarche cauta*, Far Eastern Curlew *Numenius madagascariensis* and Anadyr Bar-tailed Godwit *Limosa lapponica anadyrensis*, with these taxa occurring mostly in Bass Strait, South Australia and Tasmania (Table 8). The same taxa, except for Western Hooded Plover, were also the highest risk taxa in inshore regions.

In offshore regions in southern Australia, the highest risk taxa were nine albatross taxa, comprising Northern Royal Albatross *Diomedea sanfordi*, Eastern Antipodean Albatross *D. antipodensis antipodensis*, Grey-headed Albatross *T. chrysostoma*, Gibson's Albatross *D. antipodensis gibsoni*, Wandering Albatross *D. exulans*, Campbell Albatross *T. impavida*, Amsterdam Albatross *D. amsterdamensis*, Indian Yellow-nosed Albatross *T. carteri* and Shy Albatross.

DISCUSSION

Ecological risk assessment

The approach taken in this study was to include all bird taxa considered likely to occur in Australia's coastal and marine areas that could potentially be impacted by offshore wind farms. Including such a high number of species necessitated a consistent approach to using the available data,

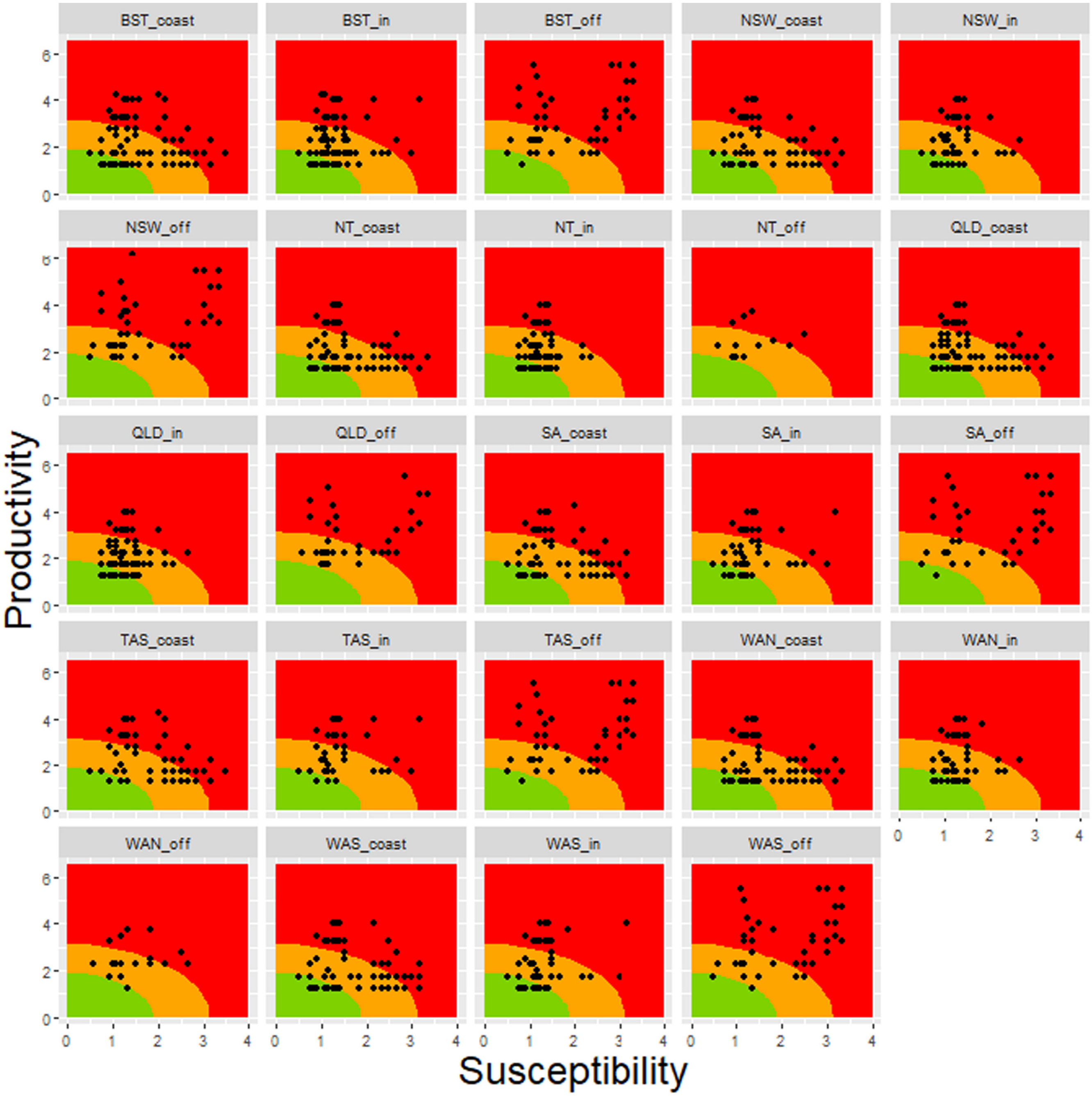

FIGURE 4 Risk plots for birds and offshore wind farms (sub-region labels as per Table 7). Green indicates low risk; orange indicates medium risk and red indicates high risk. Each dot may represent one or more taxon as multiple taxa may have the same risk score.

which inevitably requires a number of assumptions and generalizations. However, by extending the species included beyond what might typically be considered 'marine birds', this has highlighted the importance of terrestrial species such as Orange-bellied and Swift Parrots in the Bass Strait region.

The ecological risk assessment approach provides a rigorous method to identify taxa that are potentially at high risk of impact from an offshore wind farm. The identification of high-risk taxa in an ecological risk assessment enables appropriate survey designs, suitable for detecting those taxa, to be specified when detailed assessment of development proposals are undertaken before approval by regulators. Further, this information on high-risk

TABLE 8 Occurrence of high-risk taxa in the coastal (coast), inshore (in) and offshore(off) sub-regions of Bass Strait (BST), New South Wales (NSW), Northern Territory (NT), Queensland (QLD), South Australia (SA), Tasmania (TAS), West Australia North (WAN) and West Australia South (WAS) regions

Common name	BST_ coast	BST_in	BST_ off	NSW_ coast	NSW_in	NSW_ off	NT_ coast	NT_in	NT_off	QLD_ coast	QLD_ in	QLD_ off	SA_ coast	SA_ in	SA_ off	TAS_ coast	TAS_ in	TAS_ off	WAN_ coast	WAN_ in	WAN_ off	WAS_ coast	WAS_in	WAS_off
Northern Royal Albatross			🟥			🟥									🟥			🟥						🟥
Eastern Antipodean Albatross						🟥																		
Grey-headed Albatross			🟥			🟥									🟥			🟥						🟥
Gibson's Albatross			🟥			🟥						🟥			🟥			🟥						🟥
Wandering Albatross			🟥			🟥						🟥			🟥			🟥						🟥
Campbell Albatross			🟥			🟥						🟥			🟥			🟥						🟥
Amsterdam Albatross			🟥												🟥			🟥						🟥
Indian Yellow-nosed Albatross			🟥			🟥						🟥			🟥			🟥						🟥
Shy Albatross	🟥	🟥	🟥											🟥	🟥		🟥	🟥					🟥	🟥
Light-mantled Sooty Albatross			🟥			🟥						🟥			🟥			🟥						🟥
White-capped Albatross			🟥			🟥						🟥			🟥			🟥						🟥
Orange-bellied Parrot	🟥	🟥											🟥			🟥								
Southern Royal Albatross			🟥			🟥									🟥			🟥						🟥
Australian Gould's Petrel			🟥			🟥						🟥			🟥			🟥						
Furneaux White-fronted Tern	🟥	🟥														🟥	🟥							
Western Hooded Plover																						🟥		
Southern Buller's Albatross			🟥			🟥												🟥						
Sooty Shearwater			🟥			🟥						🟥			🟥			🟥						🟥
Black-browed Albatross			🟥			🟥						🟥			🟥			🟥						🟥
Grey Petrel			🟥															🟥						🟥
Tasmanian Wedge-tailed Eagle	🟥	🟥																						

TABLE 8 (Continued)

Common name	BST_ coast	BST_in	BST_ off	NSW_ coast	NSW_in	NSW_ off	NT_ coast	NT_in	NT_off	QLD_ coast	QLD_ in	QLD_ off	SA_ coast	SA_ in	SA_ off	TAS_ coast	TAS_ in	TAS_ off	WAN_ coast	WAN_ in	WAN_ off	WAS_ coast	WAS_in	WAS_off
Swift Parrot	🟥	🟥																						
Sooty Albatross			🟥			🟥									🟥			🟥						🟥
Far Eastern Curlew	🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥	
Anadyr Bar-tailed Godwit	🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥	
Southern Giant-Petrel			🟥			🟥						🟥			🟥			🟥						🟥
Alaskan Bar-tailed Godwit	🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥							
Yakutian Bar-tailed Godwit	🟥	🟥					🟥	🟥					🟥	🟥					🟥	🟥				
Eastern Black-tailed Godwit	🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥					🟥	🟥		🟥	🟥	
Palaearctic Ruddy Turnstone	🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥	
Curlew Sandpiper	🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥	
Indian Ocean Red-tailed Tropicbird																				🟥	🟥		🟥	🟥
Recherche Cape Barren Goose																						🟥		
Northern Giant-Petrel			🟥												🟥			🟥						🟥
Hutton's Shearwater			🟥			🟥			🟥			🟥			🟥			🟥			🟥			🟥
Black Petrel						🟥																		
Eastern Musk Duck	🟥															🟥								
Eastern Hooded Plover	🟥	🟥		🟥									🟥			🟥								
Black Swan	🟥			🟥						🟥			🟥			🟥			🟥			🟥		
Australian Pelican	🟥			🟥			🟥			🟥			🟥			🟥			🟥			🟥		
New Caledonian Gould's Petrel			🟥			🟥						🟥			🟥			🟥						
Tasman Little Tern	🟥	🟥			🟥					🟥	🟥			🟥			🟥							
Beach Stone-curlew				🟥			🟥			🟥									🟥					
Great-winged Petrel			🟥												🟥			🟥			🟥			🟥
Indo-Pacific Great Frigatebird									🟥			🟥									🟥			

(Continues)

TABLE 8 (Continued)

Common name	BST_ coast	BST_in	BST_ off	NSW_ coast	NSW_in	NSW_ off	NT_ coast	NT_in	NT_off	QLD_ coast	QLD_ in	QLD_ off	SA_ coast	SA_ in	SA_ off	TAS_ coast	TAS_ in	TAS_ off	WAN_ coast	WAN_ in	WAN_ off	WAS_ coast	WAS_in	WAS_off
Streaked Shearwater						🟥			🟥			🟥									🟥			🟥
Mongolian Lesser Sand Plover	🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥	
Kamchatkan Lesser Sand Plover							🟥	🟥		🟥	🟥								🟥	🟥		🟥	🟥	
Western Musk Duck																						🟥		
Australian Fairy Tern	🟥	🟥		🟥	🟥								🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥	
Houtman Abrolhos Lesser Noddy																				🟥			🟥	
Asian Dowitcher							🟥	🟥		🟥	🟥								🟥	🟥		🟥	🟥	
Common Greenshank	🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥	
Short-tailed Shearwater		🟥	🟥		🟥	🟥					🟥	🟥		🟥	🟥		🟥	🟥					🟥	🟥
Australasian Gannet		🟥	🟥		🟥	🟥					🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥			
White-headed Petrel			🟥			🟥									🟥			🟥						🟥
New Siberian Islands Red Knot	🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥	
North-eastern Siberian Red Knot	🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥	
Sharp-tailed Sandpiper	🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥	
Black-faced Cormorant	🟥	🟥											🟥	🟥		🟥	🟥					🟥	🟥	
Banded Stilt	🟥												🟥			🟥			🟥			🟥		
Red-necked Avocet	🟥			🟥			🟥			🟥			🟥						🟥			🟥		
Wrangel Island Grey Plover	🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥	
Southern Fulmar			🟥															🟥						🟥
Eastern Grey Plover	🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥		🟥	🟥					🟥	🟥		🟥	🟥	
Hoary-headed Grebe	🟥			🟥			🟥			🟥			🟥			🟥			🟥			🟥		
Blue-winged Parrot	🟥												🟥			🟥								

TABLE 8 (Continued)

Common name	BST_ coast	BST_in	BST_ off	NSW_ coast	NSW_in	NSW_ off	NT_ coast	NT_in	NT_off	QLD_ coast	QLD_ in	QLD_ off	SA_ coast	SA_ in	SA_ off	TAS_ coast	TAS_ in	TAS_ off	WAN_ coast	WAN_ in	WAN_ off	WAS_ coast	WAS_in	WAS_off
Matsudaira's Storm-Petrel									🟥												🟥			
Australian White Ibis	🟥			🟥			🟥			🟥			🟥						🟥			🟥		
Australian Pied Oystercatcher	🟥			🟥			🟥			🟥			🟥			🟥			🟥			🟥		
Grey-faced Petrel			🟥			🟥						🟥						🟥						🟥
Australian Great Crested Grebe	🟥			🟥						🟥			🟥			🟥			🟥			🟥		
Yellow-billed Spoonbill	🟥			🟥			🟥			🟥			🟥						🟥			🟥		
White-bellied Sea-Eagle	🟥			🟥			🟥			🟥			🟥			🟥			🟥			🟥		
Slender-billed Prion			🟥			🟥									🟥			🟥						🟥
Fairy Prion			🟥			🟥						🟥			🟥			🟥						🟥
Mottled Petrel			🟥			🟥						🟥						🟥						
Soft-plumaged Petrel			🟥			🟥									🟥			🟥						🟥
Royal Spoonbill	🟥			🟥			🟥			🟥			🟥			🟥			🟥			🟥		
Glossy Ibis	🟥			🟥			🟥			🟥			🟥						🟥			🟥		
Salvin's Albatross			🟥			🟥												🟥						

Note: Red cells indicate the occurrence of a high-risk taxon in a sub-region (see Tables S1 and S2 for all risk scores).

taxa can be included with species composition data collected during pre-construction surveys where there is the potential for high-risk taxa, particularly rare species and nocturnal migrants, to be under-reported or absent during surveys. In this way, the ecological risk assessment provides an essential precursor to the development of baseline data and mitigation approaches as part of the management of risks associated with offshore wind farms.

The height at which birds fly, relative to the rotor swept area of turbine blades, is recognized as one of the most important attributes of birds that influences the risk of collision with wind farms (Band, 2011; Cook et al., 2012). Empirical flight height data are lacking for almost all Australian birds, and while it is possible to use data from elsewhere for some migrants and globally distributed taxa (e.g., gulls, terns and gannets) the assumptions required make it clear that more research is urgently needed to better quantify flight heights in relation to assessments of proposed offshore wind farm developments. Thaxter et al. (2015) considered that radar was the most commonly used method for measuring flight height in many offshore surveys; however, as species identification is often not possible with this method, other methods of collecting flight height data are often used simultaneously to allow cross-validation of species' identifications. Recent advances in light detection and ranging (LiDAR: light radar) and digital aerial imaging make it possible to collect more accurate estimates of the flight heights of birds (Largey et al., 2021). LiDAR is a remote sensing technique that records the three-dimensional location of surfaces by emitting frequent, short-duration laser pulses. Cook et al. (2018) conducted a trial using LiDAR and digital aerial photography to measure the flight heights of seabirds. A validation of the flight height estimated from LiDAR showed that flight height could be measured to an accuracy of within 1 m. Animal borne devices, including global positioning systems (GPS) and altimeters, also have the potential to provide flight altitude information for some bird species, although there are both logistic and analytical challenges with this approach (see Péron et al., 2020).

The default attribute score for flight height was chosen to be precautionary, and it would be expected that, as more data become available, these scores would be modified. This precaution is also reflected in the use of an additive rather than a multiplicative calculation of risk, for example, using a multiplicative approach would mean that penguins (with 0 m flight height) would appear to be at no risk; however, they are potentially susceptible to other impacts from wind farms and it is important that this is reflected in the overall risk assessment.

In order to provide a consistent, quantitative basis for attribute scoring we used proxies for risk attributes based on peer-reviewed, publicly available data. For example, we used a relatively simple morphology-based index of flight manoeuvrability that was consistent across all taxa investigated. This approach could be refined with the inclusion of more taxon-specific flight characteristics, such as the amount of time spent soaring or gliding, average flight speed and whether the taxon moves in flocks or as individuals, to better describe the susceptibility of high-risk taxa (Gauld et al. 2022). Similarly, the attribute scoring for habitat specialization could be improved with species-specific data, especially at regional scales. We also recognize that the choice of weightings applied to the risk attributes in the estimation of the susceptibility and productivity could be further refined, including an analysis of the sensitivity of the overall risk to the choice of these weightings. In particular, the effects of discounting the susceptibility scores for seasonal migrants should be considered a first step in determining the estimates of risk for individual taxa in a particular region.

It is implicit in taking a semi-quantitative ecological risk assessment approach that it should be seen as a step in a process that can be refined with improvements in data availability. A key element of this development should include the application of the process at regional scales, especially where there are more, local-scale data available. As the available input data improve, especially when undertaking regional scale assessments, an exploration of the sensitivity of the outcomes to input data, weighting and attribute scoring should be undertaken to allow further methodological refinement. Conducting the sensitivity analyses at regional scales, rather than at an Australia-wide scale, would also alleviate the confounding effects of regional differences.

Monitoring of impacts

There is a range of behavioural responses shown by birds to the presence of turbines and associated infrastructure, including construction and support vessels. Within the spectrum of behavioural responses, the reviewed literature places most of the emphasis on avoidance behaviour that occurs in both the horizontal (flying around a wind farm) and vertical (flying over or under a wind farm) planes (Masden et al., 2010). However, birds can also be attracted to wind farm infrastructure and support vessels as potential roosting sites, or in response to a localized increase in food availability (Dierschke et al., 2016; Krijgsveld, 2014; Leopold et al., 2012; Peschko et al., 2020; Vanermen et al., 2015). Identifying the potential impacts on birds of a proposed offshore wind farm, and identifying mitigation opportunities, begins with the taxa that are likely to be present in the area of the proposed installation. This is because the biological characteristics and the regulatory status of the taxa involved will determine the mitigation approaches to be considered and implemented.

Achieving the most accurate overall assessment of how birds use an area of interest will likely involve using a range of available methods, recognizing the strengths and limitations of each. For example, boat-based visual surveys provide the best taxon-specific identification, but are limited in spatial and temporal coverage, whereas aerial surveys have greater spatial coverage with lower taxon identification resolution, and radar provides extensive temporal coverage, including at night, but without identification of taxa. Relying on a single type of survey methodology is unlikely to generate an overview of the use by birds of offshore areas at the scales required for the assessment of wind farm projects. Using data from all available sources will pose analytical challenges, however, accessible statistical methods for combining data from different sources to gain the maximum insights into seabird distributions have been developed (Matthiopoulos et al., 2022).

Depending on existing infrastructure near to a proposed offshore wind farm, it is possible to locate radar installations to examine the use of a specific area by birds, and how this may change over time and the scale of construction. Observations of avoidance behaviour, using a combination of radar and camera observations, with consistent survey methods, can provide data to examine taxon-specific changes at a site before and after construction, and allow comparisons with control sites (Skov et al., 2012). Weather radars have been used to track the departure of migratory shorebirds and the migration routes of land birds (Lane & Jessop, 1985; Sivakumar et al., 2021; Tulp et al., 1994; Walsh et al., 2017; Weisshaupt et al., 2018). The existing network of these weather radar stations around Australia provides a potential resource for tracking birds around Australia's coastline, including across Bass and Torres Straits.

Mitigation of impacts

By far the most significant mitigation measure to avoid negative impacts on birds and wildlife is the appropriate siting of wind farms and associated infrastructure. It seems obvious that the greater the separation of the wind farm and areas of high numbers or importance for birds will minimize impacts, and for that reason, the availability of large-scale bird distribution data in areas of potential wind farm development is critical to underpin all assessments. Wildlife sensitivity maps use a sensitivity or risk score for each taxon, with the distribution of each taxon represented by whether it occurs in a grid cell, with the risk scores summed across all taxa that occur in each grid cell (Gauld et al., 2022). As such, sensitivity maps represent a natural progression from the very large-scale, regional ecological risk assessment approach used here to allow much finer scale environmental processes and risks to be mapped.

Once a location has been identified that avoids the overlap of areas of high risk to birds and the offshore wind farm, then the additional technical measures to mitigate impacts can be considered. The timing of turbine operation, including the temporary shutdown of turbines (referred to as curtailment) at defined critical times can be effective in avoiding or reducing the risk of bird collision at offshore wind farms (Brabant et al., 2021). In Australia, high numbers of migratory shorebirds are known to fly from Northern Hemisphere breeding grounds in the Spring and depart Australia in the Autumn, providing temporal windows of elevated potential collision risk (Howell et al., 2020). There are also regular Spring and Autumn movements between the Australian mainland and Tasmania that involve species of high conservation status such as Orange-bellied and Swift Parrots (Menkhorst et al., 2021; Webb et al., 2021). Detailed knowledge of when and where such periods of elevated risk may occur can be used to trigger seasonal changes in the wind farm operations. Automated curtailment systems have been developed for use at terrestrial wind farms (McClure et al., 2021) and it may be possible that such an approach could be modified for use in some offshore settings.

In the offshore sub-regions, albatrosses were the predominant high-risk group. The flight of albatrosses, typically using a flight technique known as dynamic soaring that uses the wind shear stress near the sea surface, combined with the result from Johnston et al. (2014), suggest that, for the offshore sub-regions, building taller turbines (with a greater distance between the sea-surface and the bottom of the rotor swept area) could provide a potentially effective mitigation approach that would also be effective for shearwaters and petrels that have similar flight height profiles to albatrosses.

A strategic approach to offshore wind farms in Australia

It is the cumulative impact of additional mortalities, over the lifetime of all wind farms, that will create an impact on the population of a bird taxon. Further, the displacement effects introduced by one wind farm will likely have consequences for the way birds interact with other wind farms in an area. Therefore, the cumulative impacts of the development of offshore wind farms in a region requires a holistic synthesis, rather than assessing and managing each project in isolation. For an area of particular interest to offshore wind farm development, such as Bass Strait, it will be important to create a coordinated, regional-scale approach, including detailed sensitivity maps at a regional scale. This approach would mean that, rather than relying on a composite suite of data from individual wind farm projects/proposals, the data from each wind farm project can fit within a single unified data layer to which individual projects contribute within a structured plan.

The use of consistent survey methods will facilitate potential synergies from using comparable data on the potential impact on birds, and other taxa.

Quantifying the increase in mortality rate, and the impact that this is likely to have at the population level, is restricted by uncertainties in the combined set of demographic parameters influencing bird populations. In recognition of this challenge, it may be possible to take measures to reduce other pressures on populations. Such compensatory measures, referred to as offsetting, have been applied in response to impacts of birds on onshore wind farms, include enhancing habitats away from wind farms and creating sanctuaries/nature reserves in areas of importance to a species to improve survival (see European Commission, 2020). However, an important challenge with the use of compensatory mitigation is the ability to parameterize the ecological and economic cost–benefit analyses required to ensure that the measures taken are effective offsetting to avoid unexpected or unintended outcomes that undermine the overall objectives (Finkelstein et al., 2008; Gordon et al., 2015).

The offshore wind energy industry in Australia has a unique opportunity to learn from the experience of processes and technologies that have been used to mitigate the impacts of wind farms on seabirds in Europe. Despite differences in the taxa involved, the same approaches to identifying high-risk taxa, and to the monitoring and mitigation of negative impacts, should be applied in a coordinated, regional-scale approach to the development of offshore wind farms in Australia's EEZ.

AUTHOR CONTRIBUTIONS

Keith Reid: Conceptualization (equal); formal analysis (lead); methodology (lead); writing – original draft (lead). **G. Barry Baker:** Funding acquisition (lead); investigation (equal); project administration (lead); validation (equal); writing – review and editing (equal). **Eric J. Woehler:** Writing – review and editing (equal).

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DATA AVAILABILITY STATEMENT

All data used in this paper are publicly available.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.