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An ecological risk assessment for the impacts of offshore wind farms on sharks and rays in Australia

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Abstract

Sharks and rays play pivotal ecological roles in marine ecosystems, and globally, 32.6% of shark, ray and chimera species are considered to be threatened with extinction. Yet impacts of offshore infrastructure on sharks and other elasmobranchs are often poorly understood or overlooked. Large-scale development of the offshore wind farm (OWF) industry is planned for Australian waters, which are home to an estimated 314 species of sharks and rays. Here we apply a precautionary environmental risk assessment framework based on the hierarchical productivity-susceptibility approach, aiming to estimate the magnitude of OWF impacts on sharks and rays, and to identify knowledge gaps. Of 314 species considered, 39 species were considered to be of potential concern. These species were progressed to a semi-quantitative productivity-exposure (Level 2) assessment for seven offshore regions around Australia and for the areas currently designated for OWF development. Input parameters in the Level 2 assessment included life-history, movement, behaviour and physical habitat attributes. These attributes were assessed for direct and indirect impacts to provide a vulnerability rating. At a regional level, electromagnetic fields and secondary entanglement were identified as the main potentially negative impacts, whereas altered food chains, increased food availability through artificial structure and protection from fishing interactions were identified as potentially positive impacts. At the level of OWF designated zones, electromagnetic fields, habitat alteration, barriers to movement and secondary entanglement were identified as the key potential negative impacts. Species-specific research and impact mitigation may be required for higher-risk species, such as the great hammerhead and the oceanic whitetip, in addition to medium-risk species including the scallop hammerhead and white shark. For medium and high-risk species that range over large areas including shelf waters, assessing distribution overlap with proposed OWF areas was identified as a priority for further research. More generally, we provide a framework to assess the impacts of OWFs on sharks and rays and identify priorities for future research.

Keywords Productivity, Exposure, EMF, Movement, Continental shelf

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1.Introduction

Global wind resources vastly exceed energy demand and wind turbines are at the forefront of the decarbonisation transition (Pryor et al., 2020). Large-scale installation of wind turbines and transmission infrastructure in the sea as offshore wind farms (OWFs) takes advantage of stronger and more consistent winds than are available on land (Bergström et al., 2014). However, the construction and operation of OWFs can have ecological consequences including impacts on species distribution, movement and behaviour, many of which are unknown for rays and sharks (Abramic et al., 2022; Bangley et al., 2020; Farr et al., 2021; Manz, 2021). Recent work in France comparing movement of tagged benthic sharks and the addition of artificial habitat from OWF structure over soft sediment benthos suggests OWF may provide potential shelter and food resources for the small-spotted catshark (*Scyliorhinus canicula*), altering the sharks behaviour (Labourgade et al., 2024). Conversely, OWFs may attract sharks and rays and thereby alter local ecosystem structure and predator-prey dynamics (Harris et al., 2025; Hermans et al., 2025; Watson et al., 2024).

Environmental impacts of new offshore windfarm projects are addressed in the planning stage through an environmental impact assessment (EIA) and can involve complex, interagency and cross-jurisdiction regulatory processes (NOPSEMA, 2022; DCCEEW, 2023). The lengthy environmental compliance process of up to a decade has been recognised as a significant impediment to offshore wind development in the USA (Best and Halpin, 2019). The novelty of the offshore wind farm impact pathways in new regions poses a challenge for environmental regulators, who manage uncertainties by advocating a conservative approach and by issuing guidance on key environmental receptors (e.g. DCCEEW, 2022; 2023). Amongst the lessons learnt from now 35 years of experience with the offshore wind industry in Europe, however, is the need to address impacts at the population level and to consider cumulative impacts at an appropriate spatial scale (Bailey et al., 2014; van Geel et al., 2025).

The Ecological Risk Assessment (ERA) approach that is commonly used to guide conservation and management decision-making for fisheries agencies, is a structured and hierarchical approach to assess impacts in data-limited situations (Gallagher et al., 2012; Hobday et al., 2011). The biological information required for this approach increases through the hierarchy to a fully quantitative population assessment (Hobday et al., 2011). ERA also provides a framework for a semi-quantitative calculation of hazard (Fletcher 2005; Gallagher et al., 2012; Robbins et al., 2017) and has been used to assess regional impacts of bycatch and climate change on sharks and fisheries species (e.g. Chin et al., 2010; Gallagher et al., 2012). ERAs may therefore have value in supplementing an EIA in data-limited circumstances, such as assessing risk to species that have not yet been exposed to windfarms (e.g. Reid et al., 2023).

Although impacts of OWFs on species such as birds and marine mammals are relatively well understood in regions such as the North Sea (Bailey et al., 2014; Puts et al., 2023), there are very few data available globally on the impacts of OWFs on sharks and rays. In Australia, there is substantial overlap between the 6 areas prioritised for OWF development by the Commonwealth Government, and habitat for shark species listed as threatened under Australian legislation (DCCEEW, 2023; NOPSEMA, 2022b; 2024). Yet no risk assessments have been undertaken on the impacts of OWFs on sharks or other elasmobranchs in Australian waters, despite their global conservation significance both in terms of endemic species and 'lifeboat' species (Last and Stevens, 2009; Kyne et al., 2021). Lifeboat shark species are defined by their ecological resilience and relative abundance in Australia amid declining global shark populations, making them critical components of conservation strategies aimed at sustaining shark diversity and ecosystem health (Kyne et al., 2021).

Globally, studies have generally only considered the potential electromagnetic field (EMF) effects of windfarms on sharks, and spatial overlap or displacement of benthic species distributions which have recently suggested to vary considerably with life history stage and species ecology (e.g. Gay, 2012; Hermans et al., 2024; Preziosi et al., 2024). These studies, however, have been mostly undertaken in Europe where the shark assemblages vary significantly from Australian waters. In the Unted States, Preziosi et al., (2024) recently used an ERA approach to characterize risk from EMF for marine life (especially sharks). The authors assessed specific exposure and potential hazards associated with OWF structures. The ERA approach is especially relevant to assessing the impacts of OWF installation in new regions where the species present may not have been exposed to OWFs before, and hence data on impacts are scarce. An example of this is an ERA that was recently undertaken to predict and assess the impacts of OWFs on birds in Australia (Reid et al., 2023). Following these examples, ERA can form the basis to understand shark response to OWF.

Although ERAs assessing interactions with OWF for sharks and rays are lacking, in Australia they have been well developed for fishing effects and climate change (Chin et al., 2010; Heupel et al., 2018; Hobday et al., 2011; Kyne et al., 2021). Assessments of interactions of benthic sharks and short fin mako sharks with OWFs in the Northern Hemisphere have also been undertaken (Gay, 2012; Gill and Kimber, 2005; Hermes et al., 2024; Manz, 2021). Interestingly, Manz (2021) found no influence of OWF on habitat use of pelagic mako sharks. For a risk assessment, the likelihood or risk of exposure to these hazards for sharks for example, is quantifiable, where risk is defined as the likelihood of something happening that will have an undesirable outcome within a certain time (Burgman, 2005; Gallagher et al., 2012). These ecological risk assessments generally follow the three-tiered approach developed by Hobday et al., (2011), where Level 1 examines the distribution of species in relation to risks providing qualitative measures of the scale, intensity and consequence of any interactions. Level 2 provides a semi-quantitative productivity-susceptibility analysis to highlight high-risk species of concern. Finally, Level 3 provides a highly quantitative, model-based analysis for species identified as being at high risk in the level 1 and 2 analyses.

OWFs have different potential effects among species, depending on their likelihood of interaction with the turbines and associated transmission infrastructure, in addition to individual species sensitivities. The impacts of OWFs on sharks and rays could also vary between the construction and operational phases of OWFs (Bailey et al., 2014), as is exemplified by marine mammals, where the impacts of most concern are noise from pile driving and increased vessel traffic during the construction phase (Bailey et al., 2014; Puts et al., 2023).

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In order to fully inform risk assessments and support decision making around OWFs, potential positive impact and indirect pathways should also be considered for sharks and rays (Puts et al., 2023; Reyier et al., 2023). For example, infrastructure for OWFs may act as artificial reefs that attract and sustain prey species (Raoux et al., 2017; Mavraki et al., 2021; Labourgade et al. 2024), and exclusion zones around turbines may act as a de-facto marine reserves that protect against fishing (Ashley et al., 2014; Birt et al., 2024).

This is particularly pertinent as sharks play important functional roles through top-down control of coastal and oceanic ecosystem function and structure and have some of the latest maturity, longest gestation times, highest levels of maternal investment, very low population growth rates and weak density-dependant juvenile survivorship (Dedman et al. 2024; Dulvy et al., 2017; Heithaus et al., 2012). These characteristics render them intrinsically sensitive to fishing pressure driven by the global trade to meet the Asian demand for shark fin soup and squalene, as well as declines in habitat suitability (Clarke et al., 2006; Dulvey et al., 2017; Orlov et al., 2024) and climate (Chin et al., 2010; Heupel et al., 2018; Werry et al., 2018). Moreover, many shark species undertake extensive oceanic and continental scale movements, which are influenced by varied biological (e.g. resources need) and environmental drivers (e.g. temperature cues, upwelling events) (Block et al., 2011; Espinoza et al., 2014; Heupel et al., 2015; Huveneers et al., 2021). These large-scale movements complicate conservation and management efforts as their spatial ecology can overlap with a range of potential stressors, including OWF (e.g. mako sharks, *Isurus oxyrinchus*, in the Northern Hemisphere, Manz, 2021; megafauna migratory pathways overlapping with increasing shipping traffic, Sequeira et al., 2025; and Wright et al., 2020). Additionally, considering the extent of connectivity between stocks is necessary for assessing extent of risk and ensuring sustainable protection measures for threatened sharks (Huveneers et al., 2021; Watson et al., 2024).

Here we develop the first offshore wind farm ecological risk assessment framework for Australian sharks and rays. Specifically, we first identify species likely to be at risk using a semi-quantitative productivity-exposure analysis. We then rank the vulnerability of at-risk species to OWF using a precautionary approach and information available for each potential impact and impact pathway. Finally, we use these results to identify knowledge gaps and priorities for further research.

2. Materials and Methods

Our overall approach was to first identify species that may be impacted by OWFs (Level 1 ERA), under the plausible ‘worst case scenario’ (Hobday et al., 2011). These species progressed through to the Level 2 semi-quantitative productivity/sensitivity-exposure analysis, which aimed to identify species of highest risk (Figure 1, as explained below). Finally, we assessed the potential vulnerability for each species within each region, based on a review of the scientific literature (*sensu* Chin et al., 2010, Kyne et al., 2021).

The Level 2 ERA is traditionally based on the distance from the origin to the point described by productivity (P) and susceptibility (S) (Gallagher et al., 2012; Reid et al., 2023; Williams et al., 2011). In the context of fisheries, susceptibility is directly quantifiable as the product of availability, encounter,

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selectivity and mortality (Walker, 2005), reflecting the likelihood of an animal encountering a net coupled with the likely outcome of that interaction. In contrast, the consequence of an interaction between a shark or ray with an OWF (or associated activities/infrastructure) is far less certain. We have therefore slightly modified the ERA approach and instead use a productivity-exposure matrix and incorporate an additional step of assessing direct and indirect impacts to explicitly account for uncertainties in the consequences of OWF exposure (E). This approach is much more detailed than a simple risk-consequence assessment but is not as comprehensive as a species-specific stock assessment or population model (Level 3 ERA, Hobday et al., 2007; 2011). In this study, exposure was quantified as varying levels of 'exposure' to OWF based on behavioural, life history and distribution characteristics of each species, such as habitat range, long-range movement, across-shelf movement, residency and depth preferences (see Figure 1).

Once variables and components of risk were identified and qualitatively ranked, Level 2 risk scores for each shark and ray species were then plotted in a productivity-exposure analysis (PEA) plot that corresponds to dividing the overall risk scores into three equal parts or thirds (Figure 2). The combined productivity and exposure scores thereby represent distinct risk categories: low risk (scores below 2.64), medium risk (scores between 2.64 and 3.18), and high risk (scores above 3.18). (Figure 2). This analysis was first done at the whole of Australia scale, prioritising the continental shelf where OWF development is considered to be the most feasible (e.g. Kalkarni and Edwards, 2022). Species with a risk score of 2 or greater were considered at high risk of impact from OWF. We then applied this approach on a finer scale by dividing the Australian Exclusive Economic Zone (EEZ) into seven subregions relevant to the management of marine resources and/or the biogeography of sharks and rays (Figure 3A), in order to provide a region-specific risk assessment for shark and ray interactions with OWF. Risk values may therefore vary for a species across the subregions depending on their extent of distribution, migration and lifecycle strategy, which may involve residency vs transitory behaviours in different subregions. A finer-scale OWF designated zones assessment (as per current designated zones 2025) was also done to provide a designated zone-specific assessment.

Finally, a component-integration matrix was used to determine a species-vulnerability rating (following Chin et al., 2010; Fletch, 2014; Kyne et al., 2021). The integration matrix describes the outcomes of each combination of productivity and exposure to derive the vulnerability of that shark or ray to OWF.

Figure 1 – Flow diagram of OWF ERA for shark and ray

2.1 Screening species to shortlist species potentially at risk: Level 1 ERA

An estimated 314 species of elasmobranchs (182 sharks and 132 rays) are thought to occur in Australian waters (Kyne et al., 2021). A precautionary first-pass Level 1 was undertaken on these species based on published assessments and expert opinion outlined in the Action Plan for Australian Sharks and Rays (herein termed "Australian Action Plan") (Kyne et al., 2021). The Australian Action Plan provides an extinction risk of all elasmobranchs occurring in Australian waters which in turn provides a benchmark from which changes in population and risk can be measured. The Australian Action Plan assessed extinction risk by applying the IUCN Red List Categories and Criteria at the national level providing an Australian (i.e. Australia only) Action Plan risk rating (Appendix A, Figure 1A). The IUCN Red List Categories and Criteria consider a series of thresholds to evaluate extinction risk based on population size reduction, geographic range, population size, or the probability of extinction and are assessed against the five Red List Criteria (Kyne et al., 2021). To qualify for one of the three threatened categories (Critically Endangered, Endangered or Vulnerable), a species had to meet a quantitative threshold for that category in any of the five criteria where the assessments of extinction risk considered all available information on a species' taxonomy, distribution, population status, habitat and ecology, major threats, use and trade, and conservation measures. The Australian Action Plan noted that the overall national Red List status of sharks in Australia is characterised by a relatively low level of extinction risk and a high level of secure species (Kyne et al., 2021). The Australian Action Plan identified 12% or 39 (22 shark and 17 ray species) of the 314 shark and ray species as threatened. Of the remaining species, 10% or 31 (18 sharks, 13 rays) were Near Threatened, 70% or 218 (123 sharks, 95 rays) were Least Concern, and 8% or 26 (19 sharks, 7 rays) as Data Deficient.

All species with legislative protection under the Commonwealth (EPBC Act) or state/territory legislation considered to be threatened under the Australian Action Plan Red List of Threatened Species, progressed to the Level 2 assessment. Many species considered threatened under the global IUCN Red List of Threatened Species are, in contrast, considered Near Threatened and Least Concern under the Australian Red List (Australian Action Plan) (Kyne et al., 2021). Consequently, most of these non-threatened species in Australia, are considered "lifeboat" species, which by definition are species for which heavy exploitation occurs that has caused population reduction outside of Australian waters, but which do not face comparable levels of threat in Australia (Kyne et al., 2021). Of 45 species (27 sharks, 18 rays) which are threatened globally, Kyne et al., (2021) assessed 18 species as Near Threatened and 27 species Least Concern in Australia (see Table 5, Kyne et al., 2021) (as of Red List update 2020.3 on 10 December 2020) as lifeboat species. Non-threatened shark and ray species were not included in our Level 1 – first pass ERA, (Appendix A, Figure 1A). Species listed under relevant international conventions (Convention on Migratory Species (CMS) and Convention on International Trade in Endangered Species of wild fauna and flora (CITES) were also noted. For example, the shortfin and longfin mako sharks, wedgefish, and guitarfish in Australia for which listing came into effect on 26 November 2019 (DCCEEW, 2023) (Appendix A). This initial list was then screened based on plausible likelihood of a species interacting with an offshore wind farm and considered the extent to which species transit through coastal and inshore regions as well as across shelf, offshore and open pelagic waters. The Endangered Maugean Skate, which is restricted to two remote estuaries in Tasmania, was included in the Level 1 analysis, but under consideration that there are no plans for OWF on west coast of Tasmanian (Awruch et al., 2021). Species that transit through coastal and inshore regions during annual migration or dispersive movements, were also considered. The number of species included reflects the large biogeographic scales involved across Australia and species that have the potential to interact with offshore wind farms. The taxonomy and nomenclature adopted by Kyne et al., (2021) was used in the species list.

Journal Pre-proof

2.2 Productivity-Exposure analysis: Level 2 ERA

The Level 2 ERA was based on the product of productivity and exposure, as outlined below.

2.2.1 Productivity

Productivity (P) was determined from the conservation status score (CS) and generation length (GL) (following Reid et al., 2023). CS scores were taken from the recent Australian Action Plan assessment of sharks and rays in Australia against the IUCN Red List criteria (Simpfendorfer et al., 2019; Kyne et al., 2021). The CS assessment for most species considers population sizes, trend and threats, which are in turn linked to life history traits related to productivity, such as reproductive strategy and fecundity. Species were ranked from 1 to 5, where a species assessed as Least Concern was assigned a rank of 1, and a species assessed as Critically Endangered was assigned the highest rank of 5 (Table 1). The Action Plan scores were considered to be more representative of current extinction risk than legislative listings for many sharks and rays (but see Appendix A, Figure 1A and 2A for legislative listings).

Table 1: Conservation Status (CS) listing and corresponding score for shark ray species based on the Action Plan for Australian Sharks and Rays.

A simple estimate of Generation Length (GL) for each species was used from the Australian Action Plan (Kyne et al., 2021), which only requires female age-at-maturity and maximum age where;

GL = ((maximum age – age-at-maturity)/2)) + age-at-maturity

The Australian Action Plan noted that in species where female age-at-maturity and maximum age were lacking, GL was estimated using age data available for closely related species. GL were scored according to Table 2.

Table 2: Generation Length (GL) listing for shark ray species based on the Australian National Plan of Action.

Productivity (P) was then calculated as:

$$P = \frac{(CS\ x\ 1.5) + GL}{2}$$

Where the weighting factor of 1.5 takes the species productivity criteria inherent to CS assessments (following Reid et al., 2023).

2.2.2 Exposure

'Exposure' (E) represents the extent to which a given species is likely to interact with an OWF and was assessed as the potential for spatial-temporal overlap between a species and the likely location

Journal Pre-proof

of an OWF (refer to Appendix 3A for this outline). This was enumerated by the following parameters for each species:

1. Habitat range (HR),
2. Distribution across Australian waters (D),
3. Upper depth (UD) and lower depth (LD),
4. Long-range movement (LRM),
5. Across shelf movement (ASM),
6. Seasonality (SEAS), and
7. Residency index (RI).

2.2.2.1 Habitat range (HR)

HR categories followed those defined by Chin et. al., (2010), Heupel et al., (2018) and the Australian Action Plan (Kyne et al., 2021), which describe the primary broad habitat(s) that a species occurs in, without specific detail of substrata. The following habitat affinities were assessed: (1) rivers; (2) estuaries, defined as the tidal transition habitat between river and marine environments; (3) continental shelf, which is the marine area of continental Australia from the inshore coastal zone to ~200 m depth (i.e. the 'shelf break' or 'shelf edge' leading to the continental slope); (4) the continental slope, incorporating the steep slope from the continental shelf edge (~200 m) to ~2,000 to 2,250 m depth on the abyssal plain; and (5) pelagic open oceanic waters off the continental shelf.

Habitats were assigned scores on a scale of 1 to 5 (Table 3), where the continental shelf was ranked with the highest score, which reflects the current Australian Government policy of prioritising areas of the continental shelf more than 10 km from the coast for development of OWFs. The next highest score was assigned to the pelagic environment, because evidence suggests highly pelagic species may use shelf areas to pup (for example, pelagic short fin mako pregnant female occurs over shallow shelf areas, see Corrigan et al., 2015), highlighting the connectivity between shelf and the pelagic zone in relation to OWF in 16 to 60 m depths. For species known to occur in more than one habitat, we took the average of scores across all habitats that the species occurred in (Table 3). We considered species that feed in estuarine areas as well as wholly marine species, as most euryhaline sharks have a lifecycle component that involves coastal and shelf as well as riverine and estuarine habitat-use, e.g. bull shark, *Carcharhinus leucas* (Smoothey et al., 2023; Werry et al., 2011), endangered speartooth, *Glyphis* spp. (Patterson et al., 2022; Peverall et al., 2006) and sawfish (Peverell, 2005).

Table 3: Habitat Range (HR) listing for shark and ray species known occurrence.

2.2.2.2 Distribution (D)

Broad-scale distribution was based on the number of states (or territories) that the species is known to occur across and was again scaled from 1 to 5 (Table 4), where ‘5’ represented a species occurring in only one state/territory and ‘1’ represented a species that occurs in more than 4 states/territories. Distributional data were taken from the Australian Action Plan (Kyne et al., 2021) and Last and Stevens (2009).

Table 4: Distribution (D) listing for shark and ray species known occurrence. State refers to a state or territory in Australia.

2.2.2.3 Upper Depth (UD) and Lower Depth (LD)

This describes the upper depth (i.e. closer to the surface) and lower depth (i.e. deeper) that a species is known to occur in (e.g. Andrzejaczek et al., 2022). For each, this was scored separately on a scale of 1–5 (as in Table 5). While the full depth range may not be completely defined for many poorly known species, especially for species with only a few known specimens, understanding depth range is important for assessing risk as it provides information on the degree of overlap with OWF activities. Globally, as floating OWFs become more commercially feasible they may be increasingly being located in deeper waters further from the coast, with priority areas (declared areas) for some OWFs in Australia in areas up to 180 m deep. However, in Australia many wind turbines are projected to occur in shallower waters. Species occupying in deep depths in areas off the continental shelf may be less exposed to OWFs compared to those occupying shallow depths if they are pelagic. We note that species could still be exposed to risks at depth from the mooring structure of floating turbines.

Table 5: Upper Depth (UD) and Lower Depth (LD) score categories for shark and ray species known occurrence.

2.2.2.4 Long range movement (LRM)

Shark and rays have a high diversity of movement patterns, ranging from high-site fidelity and limited movements for some rays and benthic species, to large sharks that range over 1,000’s of km. Species that are unable to travel large distances or that have high-site fidelity are likely to be less able to avoid OWF and associated impacts than more mobile species. We considered the extent of known movement or migrations, termed long range movement (LRM). Based on literature review, expert opinion and the Australian Action Plan (Kyne et al., 2021; Last and Stevens, 2009), each species distribution was scored on a scale of 1–5 as in Table 6, where a low LRM represents a species with a small home range and a high LRM represents species that range over a large area. Hence, a species with a lower LRM rank is less able to move away from an OWF than a species with a higher LRM rank.

Journal Pre-proof

Table 6: Long range movement (LRM) score categories for shark and ray species known occurrence.

2.2.2.5 Across shelf movement (ASM)

We further considered across shelf movement (ASM) of shark and ray species. This is because a species
that regularly moves across the inshore-offshore gradient of the continental shelf (for example to feed) is expected to interact with OWFs more often than species with other movement patterns. Species that have known occurrence in the continental shelf and adjoining inshore and pelagic habitats were assumed to have ASM. Species across shelf movement and occurrence was scored on a scale of 1–5 as in Table 7. A precautionary approach was taken for ASM scoring as this parameter is considered of significant relevance to species overlap with OWF in Australia. ASM was assumed to be 5 for data deficient species.

Specific data on across shelf co-occurrence patterns for many large sharks are lacking but are important for interpreting how offshore infrastructure may influence shark assemblage patterns, particularly for species of conservation concern.

Table 7: Across shelf movement (ASM) score categories for shark and ray species.

2.2.2.6 Seasonality (SEAS)

Exposure of sharks and rays to potential risks from OWFs is determined by both spatial and temporal overlap. Seasonality refers to patterns of shark or ray presence or movement that vary predictably with the seasons or times of the year and reflects temporal variation in habitat use, often linked to factors like water temperature, food availability, or reproductive cycles. We assessed seasonality because sharks may show *seasonal* residency by spending certain seasons in a particular area (e.g., summering or breeding grounds) and moving to different locations or habitats in other seasons. We accounted for seasonality (SEAS) or seasonal preferences for locations or latitudes by scoring each species on a scale of 1–5 as in Table 8, which represented seasonal occurrence in shelf habitat where OWFs occur.

Table 8: Seasonality (SEAS) score categories for shark and ray species.

2.2.2.7 Residency Index (RI)

Some shark and ray species that display extensive migrations also display extended residency in small defined areas for periods independent of season (e.g. tiger sharks in the Coral Sea, see Werry et al., 2014). At the other extreme, some species demonstrate fine-scale site fidelity and year-round residency (e.g. the Maugean skate) (Appert et al., 2023). Residency refers to an individual shark or ray exhibiting largely uninterrupted occupancy of a limited area for a specified period of time and measures how consistently they remain in or regularly return to a specific habitat or site over days, weeks, or longer and can be viewed separate from seasonality. Residency is often quantified with a residency index (RI). RI represents the proportion of time or number of days a shark is detected in a given area without extended absences. Each species residency was scored on a scale of 1–5 as in Table 9.

Table 9: Residency Index (RI) score categories for shark and ray species.

The spatio-temporal extent of exposure for a given species and their likelihood to interact with an OWF was therefore defined as the following, where:

$$Exposure\ (E) = ((HR + D)/2 + (UD + LD)/2) + ((LRM + ASM + SEAS + RI)/4)$$

2.2.2.8 Overall Risk Scores

Productivity and exposure scores were then standardised and overall risk scores were then calculated as the Euclidean distance from the plot of productivity and exposure (Figure 2) (following Williams et al., 2011), using the following formula:

$R = ((P-X0)^2 + (E-Y0)^2)^{1/2}$ where $X0$ and $Y0$ are the x and y origin coordinates, R is risk, P is productivity and E is exposure.

This method divides the plot into equal thirds. Scores in the upper third of all possible scores (risk value >3.18) are classified as high risk, values in middle third of possible scores (2.64 < risk value < 3.18) are medium risk. Values in in the lower third of possible scores (risk value < 2.64) are classified as low risk.

2.3 Subregional zonation and designated OWF zones

To outline the occurrence of sharks and rays from the level 2 productivity-exposure analysis at subregional Australia and designated OWF zones, the Australian Economic Exclusive Zone (EEZ) was first divided into seven subregional zones based on adjacent state or territory waters (Figure 3A). Although large shark species, for example, occur along the West Australian coast and move between tropical and temperate regions (often driven by the Leeuwin current), we used a delineation of the EEZ off Western Australia divided at approximately 25.5º S to reflect the general differences in species assemblages between the northern and southern areas of the state (Figure 3A). We combined Tasmania and Victoria into a single region to reflect the similarities in shark and ray species composition across the Bass Strait, and the migration and dispersive movement of sharks throughout the region (e.g. white shark, *Carcharodon carcharias*) (Burke et al., 2025; Hillary et al., 2018; Spaet et al., 2020). We excluded green sawfish from South Australia, which was based on a single historical extralimital record (one record off Glenelg in 1936 in the Atlas of Living Australia). Finally, the six designated OWF zones for Offshore wind farms (DEECCW, 2023) in Australia were then assessed to confirm occurrence of sharks and rays from the level 2 productivity-exposure analysis. These designated OWF zones were, 1. Bunbury in Southwestern Australia, 2. Southern Ocean, Victoria, 3.

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Gippsland, Victoria, 4. Bass Strait, Tasmania, 5. Illawarra, New South Wales, and 6. Hunter, New South Wales (Figure 3B).

2.4 Level 2 ERA-extension: Component integration matrix to determine species vulnerability rating

Species ranked as moderate to high risk in the Level 2 ERA were then assessed by region for vulnerability to direct and indirect physical environmental factors. Vulnerability was ranked from High, Medium to Low using a component-risk matrix adapted from Chin et al., (2010), Fletch (2015) and Williams et al., (2011). We also included a Data Deficiency category where a species with low data availability were placed one level up, from low to medium, following the precautionary principle (Hobday et al., 2007). A register of potential impacts to sharks and rays were collated from the scientific literature (Bailey et al., 2014; Carroll and Harvey-Carroll 2023; Copping et al., 2022; Halouani et al., 2020) and is presented in Appendix B. Potential vulnerabilities of sharks and rays to each risk were then rated as direct or indirect based on a literature review (Supplementary A, Figure 5A and Supplementary B online material).

2.4.1 Direct Impacts

Direct hazards assessed included impacts such as, electromagnetic fields (EMF), noise, increased light, turbine and vessel collision risk, habitat alternation, barriers to movement and release of contaminants from seabed sediments as key environmental concerns (Appendix B).

2.4.2 Indirect Impacts

Additionally, indirect hazards assessed included impacts such as alteration in the ecological processes of ocean current and upwelling, food web impacts through alterations to food chains, shifts in prey availability influencing shark and ray dietary breadth/trophic specialty, secondary entanglement from rope, ghost nets and fishing gears and changes in fishing pressure (Appendix B).

3. Results

A total of 314 species were included in this ERA. Of these species, 39 progressed to the Level 2 assessment (Figure 2)(Supplementary A, Figure 1A). Productivity-exposure scores varied from low to high (Figure 2).

3.1 High-risk species productivity-exposure scores

Of the 39 species that progressed to the Level 2 assessment, eight of these species had high productivity-exposure scores, and included the oceanic whitetip shark, dwarf and green sawfish, the great hammerhead, the coastal stingaree, estuary stingray, the northern river shark and the maugean skate. The highest scores were assigned to the dwarf and green sawfish, followed by the coastal stingaree, estuary stingray, northern rivershark and the oceanic whitetip (Figure 2 and 4). In total, 11 species of sharks and rays had moderate scores and the remaining 10 species had low scores

Journal Pre-proof

(Figure 2). Of these low-score species, we applied the precautionary principle for species considered just below the medium-level score of 2.64, in acknowledgement of uncertainties in productivity and/or exposure estimates. This included the spotted shovelnose ray, bigeye thresher, harrisons dogfish, winghead hammerhead, shortfin mako, longfin mako and the eastern angelshark (Figure 2 and 4). In total, 39 species were included in the further analysis with the Level 2 ERA-extension also undertaken separately for each subregion and 29 species in the designated OWF zones (Figures 4 and 5)(Appendix A, Figure 5A).

3.2 Occurrence across subregions

Occurrence of shark and ray species of risk to OWF varied across the seven subregions. Queensland had 28 species, New South Wales had 30 species, Victoria/Tasmania had 16 species, South Australia had 14 species, NorthWestern Australia had 21 species, Southern Western Australia had 19 species and Northern Territory had 21 species. Victoria/Tasmania had 1 species of high risk, the Oceanic White tip, and South Australia no species identified with high risk to OWF (Figure 4A). South Australia had the least number of species at risk and all other regions had species with high, medium and “borderline” medium risk.

Species ranked as moderate to high risk, that have habitat overlapping with areas currently designated for OWF development, include the great hammerhead, estuary stingray, whitefin swell shark, scallop hammerhead, school shark, Harrison’s dogfish and the greeneye spurdog (Figure 4B). Medium risk species occurring across current designated OWF areas included the grey nurse shark and the white shark. Other species are not considered likely to be present in OWF areas include the speartooth shark and the green sawfish. Number of species occurring in designated priority areas for offshore wind including the following, where 1. Bunbury, SouthWestern Australia, had 14 species. 2. Southern Ocean, Victoria, had 15 species. 3. Gippsland, Victoria, had 13 species. 4. Bass Strait, Tasmania, had 14 species. 5. Illawarra, New South Wales had 23 species and 6. Hunter, New South Wales had 24 species (Figure 4B).

3.3 Level 2 ERA-extension shark and ray vulnerability and risk characterisation

The Level 2 extension component integration matrix identified several direct and indirect vulnerabilities of high and medium-risk shark and ray species to OWF. These risks varied across subregions and specific vulnerability (Figure 5). Most direct vulnerabilities were considered low overall, whereas most indirect vulnerabilities were medium risk.

3.3.1 Vulnerability to direct impacts

Electromagnetic fields that may or may not act as interference or a deterrent to access OWF areas and to force sharks to move away were ranked as medium overall across the subregional and designated OWF zones (Figure 5 and 6). The number of species with vulnerability to EMF were greatest in the Northwestern Australia, the Northern Territory and Queensland subregional zones and in the Illawarra and Hunter designated OWF zones. Medium vulnerability for barrier to movement was evident for shark and ray species across all designated OWF zones, but not at the subregional level.

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Potential medium vulnerability to habitat alteration was evident across all OWF designated zones but was largely driven by species in those zones on the east coast of Australia (Figure 5 and 6).

3.3.2 Vulnerability to indirect impacts

Indirect vulnerabilities of upwelling and currents, prey availability and secondary entanglement were identified as medium for sharks and rays across both subregional and OWF designated zones. Food chain alteration was low to medium, whereas reduced fishing pressure was considered a medium to high indirect vulnerability for potential positive benefits for shark and ray OWF interactions (Figure 5 and 6).

4.Discussion

Our decision-making framework to both define hazards and to assess species responses using the hierarchical approach of ERAs and precautionary approach to uncertainty (adapted from Fletcher 2005; Gallagher et al., 2012; Hobday et al., 2011; Robbins et al., 2017) is especially appropriate for assessment of impacts in data-limited situations for many sharks and rays. This is because ERAs have a much more structured approach to deal with uncertainties than is required for EIAs in Australia, and ERAs are therefore less likely to overlook the potential for environmental impacts when data is very scarce. Of our initial set of 39 species of concern, 8 species were assessed as high risk based on productivity-exposure, 12 species were assessed to be of moderate risk and 7 species were of borderline medium-low risk. Furthermore, our ERA approach provides an important first step for assessing the environmental impacts of OWFs at multiple scales for the 39 species shark and ray species considered to be potentially at-risk in Australia. Our ERA also highlights knowledge gaps and priorities for future research to support informed EIAs and monitoring.

At the subregional level in Australia, we identified areas with highest numbers of shark and ray species of concern were Queensland, northwestern Australia and the Northern Territory. This was largely driven by the potential exposure of high-risk threatened species such as the green and dwarf sawfish, hammerhead sharks and *Glyphis* spp. There are no current plans to develop windfarms in these areas, owing to predominately poor wind conditions for offshore wind farms across northern Australia compared to southern Australia. However, there are some notable exceptions such as Cape York in Queensland and central Western Australia (Figure 3A), where wind conditions suggest that OWFs be considered feasible in the future. If this is the case, EIAs will need to consider potential impacts on these shark and ray species in addition to other conservation values in the region. Furthermore, shark and ray species undergoing extensive coastal and oceanic migrations, may interact with more than one subregional and designated OWF zone boundary, and may therefore be exposed to the cumulative impact of windfarms at a scale not traditionally considered in EIAs. Species-specific monitoring and movement studies for such species considered to be at higher risk

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(e.g. the oceanic whitetip and hammerhead shark species) may be required to understand whether they overlap with more than one designated OWF zone.

Most benthic shark and ray EIAs for OWFs have only considered potential EMF effects and spatial displacement of benthic species distributions (e.g. Gay, 2012; Hermans et al., 2024;2025) and have focussed mostly on European waters where the shark assemblages are much less diverse and abundant to Australian waters. Elasmobranchs in Australian waters are both nationally and globally significant in terms of the variety of endemic species and the presence of many lifeboat species that are threatened with extinction elsewhere (Kyne et al., 2021; Last and Stevens, 2009). Assessment of migratory and threatened shark species was identified as a priority research area for offshore renewable energy areas by Australia's lead management agency for offshore energy (NOPSEMA, 2024). Hence, consideration of the potential impact of OWFs on hitherto largely ignored elasmobranchs should be a focus in future EIAs and in decision making by environmental regulators. Until these impacts of planned OWFs on these largely data-deficient species are much better understood, we advise a precautionary ERA approach as presented in this study.

4.1 Data deficiencies and leveraging existing data

Whilst data deficiency is a limitation to informed risk management for many shark and ray species in Australia, there is a growing body of literature providing insight into large shark movement and habitat use in Australian waters. This data can be leveraged to predict and understand impacts from the emerging OWF industry. Numerous species of large sharks utilise specific continental shelf depth contours (such as, but not limited to, the 60 to 120 m depth) for latitudinal migrations between coastal, shelf and oceanic habitats (e.g. dusky whaler, *Carcharhinus obscurus*, Huveneers et al., 2021; white sharks, *C. carcharias,* Spaet et al., 2022; tiger sharks, *Galeocerdo cuvier*, Lipscommbe et al., 2020 and Werry et al., 2014; whale sharks, *Rhincodon typus*, Norman et al., 2016; Grey nurse sharks, *Carcharias taurus*, Otway and Ellis, 2011; and manta rays, *Mobula alfredi*, Jaine et al., 2014). These studies provide important insight into potential overlap with OWF footprints and associated habitat change for wide ranging species. For example, for the white shark, movement and life history has been extensively studied on the east coast of Australia via satellite and acoustic telemetry (Bruce and Bradford 2012; Spaet et al., 2020; 2022; Werry et al., 2012). As a result, varying modes of behaviour, shifting between well-defined short-term residency patches and long-range migration, have been identified across life-history stages and these data have been leverage in the species exposure assessment for this ERA.

In Australian east coast waters, two key juvenile nursery areas have been identified for white sharks, one off Port Stephens/Hawks Nest in NSW and another off 90-Mile Beach in Victoria. Juvenile white sharks alternate between long-range latitudinal migrations and short-term residency in these defined nearshore beach-zone nurseries (Bruce and Bradford 2012). Both nursery areas are in close proximity to proposed OWF footprints, raising the potential for impacts on the entire east coast population (Bruce and Bradford 2012; Spaet et al., 2020, 2022; Werry et al., 2012). Considering juvenile white sharks make repeated, short-term across shelf movements from the inshore nursery to the outer shelf edge to utilise productive prey patches from shelf upwelling (Bruce and Bradford 2010; Hillary et al. 2018; Spaet et al., 2022; Werry et al., 2012), they will face the choice of navigating through OWF or avoiding OWF areas. Avoiding OWFs could be energetically costly for sharks and rays, given the proposed spatial scale of declared OWF areas (up to 1,900 km^2) and potential for multiple projects to be developed within close proximities.

Additionally, some shark and rays have very limited distributions, sometimes with high site-fidelity (Last and Stevens 2009), such as the grey nurse shark (Otway and Ellis, 2011), and drastically reduced populations from fishing pressure, such as the Australian longnose skate, *Dentiraja confusa*, endemic to southeastern Australia (Kyne and Sherman, 2023). OWF footprint impacts on these species may be more acute, particularly if they lead to less favourable habitat conditions forcing species to look elsewhere for more suitable habitat that may or may not be available (Lear et al., 2024; Kyne et al., 2021). As further understanding of shark biology and life history becomes available, positive and negative effects of OWF may be better identified with corresponding shifts in risk to sharks. The short fin mako, *Isurus oxyrinchus*, while an oceanic species for example, may require shelf habitats for pupping (see Corrigan et al., 2015) and juveniles have seasonal incursions into shelf areas which may play more important roles than previously understood, increasing their projected interaction with OWF footprints. Furthermore, some species ranked as potentially at risk in this study are considered to be especially data-deficient, such as the basking shark, *Cetorhinus maximus*, and the longfin mako, *Isurus paucus*. It is also worth considering the potential global conservation implications for species in significant decline in other areas around the globe but are at healthy population levels in Australia, operating as lifeboat species (e.g. see Kyne et al., 2021).

Finally, the Maugean skate, *Zearaja maugeana*, also has life history characteristics that suggested they could be at risk from OWFs, even though the actual exposure of the species to OWFs is likely to be extremely low because of their restricted distribution in two estuaries in western Tasmania, where there are currently no plans for windfarm development. That said, if future research indicates the species has population connectivity to nearshore habitats, or if future windfarms are planned in nearshore/estuarine regions, then potential impacts to the species will need to be considered.

4.2 Electromagnetic field (EMF)

Our ERA identified electromagnetic fields (EMF) as a key direct impact of medium risk for sharks and rays (Appendix A, Figure 5A; Figure 5 and 6). This is because transmission cables and subsea infrastructure that transports generated electricity produce electromagnetic fields may have potential impacts of EMF on sharks that are largely unknown. The development of offshore wind energy infrastructure will modify oceanic habitats and result in networks of high-voltage submarine cables to transport electricity back to shore (Bicknell et al., 2025; Hermans et al., 2024; 2025). Determining the thresholds of EMF that will not interfere with pelagic or benthic sharks and rays is necessary. This is because sharks use electromagnetic signals to detect prey, to help navigate during migration and to orient themselves to return to a specific location (Andersen et al., 2017; Hutchinson et al., 2020; Keller et al., 2021; Meyer et al., 2005). This is particularly pertinent for some shark species as electromagnetic fields could also disturb migration patterns by interfering with their capacity to orientate themselves in relation to earth's magnetic field, such as the scallop hammerhead, *Sphyrna lewini*, for example. This species is hypothesised to use their sense of the Earth's geomagnetic field to help navigate during migrations (Andersen et al., 2017; Bergström et al., 2014; Klimley 1993). Additionally, EMF has been found to increase exploratory behaviour in little skates, which typically have small home ranges (Hutchinson et. al., 2020). Burying the cables under the seabed may help to mitigate impacts of EMF on sharks and rays (Bergström et al., 2014; Gay 2012). Further, it will not be possible to bury all transmission cables in the case of floating offshore windfarms, hence shielding is likely to be required. Shielding, however, is understood to not necessarily reduce impacts on sharks and rays, hence alternant mitigation methods may need to be determined (Hermans et al., 2024; 2025). If electromagnetic fields mimic the bio-electric fields produced by prey, sharks and rays could forage in unproductive areas or overlook prey. Additionally, if underwater transmission cables alter the local geomagnetic landscape, navigational barriers to sharks and rays may occur or cause migrating sharks and rays to veer off course or avoid areas altogether. The impacts of EMF on sharks and rays should be priority for future research (Kimley et al., 2021). Infield experiments using sharks and rays tagged with acoustic, biologging and satellite tags will enable better insight into how species respond to EMF by tracking their movements and behaviour in overlapping acoustic arrays in areas of underwater power cables. This approach is particularly pertinent for hammerheads, grey nurse and white sharks in the Australia context as these species are considered at risk and there is a growing body of data on their movement, migration and habitat requirements (Spaet et al., 2020; Otway and Ellis, 2011).

4.3 Habitat alteration

Habitat alteration was identified as medium to low risk to sharks and rays in the designated OWF zones, but not at the subregional scale (Figure 6). Alteration to habitat may have positive or negative effects on shark and ray populations. For example, recent work looking at the interaction of artificial reefs and the movement of white sharks along the east coast of Australia hypothesised minimal influence on white shark aggregation (Becker et al., 2024). Additionally, both artificial and natural structures (such as seamounts) have been shown to be favourable short-term residency locations for whale sharks on the west coast of Australia (D'Antonio et al., 2025). Further, OWF could act as de-facto marine reserves, providing protection against overlap with fishing pressures and these factors need to be considered for assessing the risks to sharks (Puts et al., 2023; Reyier et al., 2023; Wang et al., 2022). Concomitantly, OWF may also benefit the local ecosystem by acting as artificial reefs increasing available habitat for schooling fish and inadvertedly providing predictable prey sources for sharks (Mavraki et al., 2021; Raoux et al., 2017). The potential impact of physical structure on sharks and rays features prominently in recent guidelines and research strategies released by the environmental regulators of the industry in Australia (i.e. DCCEEW's key factor guidelines and NOPSEMMA's research strategy). Understanding these impacts at the OWF designated scale may be best determined with a before, during and after OWF establishment monitoring approach. Identifying shark and ray occurrence and behaviour via targeted surveys, such as baited and unbaited

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Journal Pre-proof

remote underwater video (BRUV and RUV) in pelagic and demersal habitats, spatial and temporal eDNA sampling (e.g. Hermens et al. 2024) and fine-scale tracking may help answer these questions. It should also be noted that current legislation for OWF in Australia stipulates that infrastructure must be removed at the end of project life (20-30 years). Hence, the potential direct and indirect impacts of the removal of in-water structure and reversal of fisheries exclusions during the decommissioning phase should be considered in EIAs.

4.4 Barriers to movement

Our ERA identified barriers to movement as a direct impact of medium risk for sharks and rays in the OWF designated zones (Figure 6). Physical structures that can impede the movement of sharks and rays between important habitats or migrations of important lifecycle stages (e.g. across shelf and along shelf migrations) require careful consideration. This is particularly important as movements and migrations connect the habitats of sharks and rays both horizontally, temporally, and integrate energy flows at large spatial scales. OWF and associated infrastructure could impede normal movement patterns because of their physical presence, or through an indirect impact such as shark and ray species avoiding the area, changing their normal movement patterns to visit the area for foraging or collective impacts on ecological processes, biological connectivity and habitat quality (Lubitz et al., 2024). Understanding how and if barriers impede shark and ray movement would be best better determined through understanding both established movement and migratory patterns and corridors and the fine-scale response of species at the scale of an OWF footprint. In the Australian context, the white shark and the grey nurse shark have considered movement data, especially on the east coast of Australia, and could be used as model species to test hypotheses on OWF barriers to movement.

4.5 Upwelling and Currents

Our ERA identified changes in currents and upwelling as an indirect impact of medium risk for sharks and rays at the subregional scale (Figure 5 and Appendix A, Figure 5A). Modelling studies in the North Sea have suggested that the wind wake effect of OWFs can affect hydrodynamical conditions by reducing current velocities and decreasing dissolved oxygen (Daewel et al., 2022). This could have both indirect (e.g. prey field) and direct impacts with impacts for species across the shelf. Current velocities may be altered and act as a means to influence movement and in some cases may provide significant barriers to movement (DiSanto 2024). Shifts in intensity and severity of rising cold upwelling currents can have significant impact on sharks, including death in extremes (Lubitz et al., 2024). Large sharks have been documented making significant movements away from shelf areas in response to significant shifts in current velocities, including active avoidance, which can lead to reshaping the patterns of species and distribution (DiSanto 2024; Lubitz et al., 2024). These climate-based shifts in ocean dynamics may be further exacerbated on a fine scale from OWF infrastructure with potential to alter shark and ray migratory routes, movement corridors and the viability of preferred habitat. Research focussed on understanding movements and drivers of shark and ray species in relation to hydrology and pulse events such as upwelling should be prioritised. This could be achieved with relating spatial and temporal trends in shark and ray tracking data and modelled in relation to both wide-scale physical parameters and fine-scale hydrology measured with acoustic dopplers.

4.6 Food chain alteration

Food chain alteration was identified as an indirect impact of medium to low risk for sharks and rays at the subregional scale and a medium risk for the OWF designated zones (Figure 5 and 6, Appendix A, Figure 5A). Movement is critical to the life-history of sharks, enabling important ontogenetic shifts to exploit different prey sources and to regulate food chains (e.g. Werry et al., 2011). Sharks and rays move to find and take advantage of food supplies, avoid conspecifics, reduce competition and maximise fitness. Concomitantly, sexual segregation drives important regional and fine-scale patterns for many populations (Mucientes et al., 2009). Alterations in food chain may may have significant impacts on Australian shark and ray populations because the structural and functional effects to ecosystems extend in space and time, impacting species differently throughout their life cycles. The positive or negative effects of alterations to food chains from OWF structures must be assessed at those larger spatiotemporal scales and these may be achieved through both combined stable isotopes and movement analysis of both predators and prey, as well conventional survey techniques such remote underwater video (RUV) surveys (Degraer et al., 2020; Werry et al., 2011).

4.7 Prey Availability

Highly specialized sharks and ray species may not be able to exploit alternative prey groups should their preferred prey become unavailable. Trophic specificity/dietary breadth is therefore a measure of indirect impacts of OWFs on sharks and rays. Our ERA identified prey availability as an indirect impact of medium to low risk for sharks and rays at the subregional scale (Figure 5). In the past. the major focus of concerns for this phase of offshore wind farms has been seabird mortality caused by collision with the moving turbine blades and seabird displacement from key habitats because of avoidance responses (Bailey et al., 2014; Reid et al., 2023). In turn, these impacts can affect birds migrating through the area as well as those that breed or forage in the vicinity. While seabird mortality may provide opportunistic nutrition sources for sharks (Romano et al., 2022), the impact of these stressors on sharks needs to be quantified to be able to predict the risk of OWFs to key oceanic apex predators (Nopsema, 2023). Increased fish biomass around OWF structures influence predators and is likely to have positive effects for whale sharks and white sharks (Bicknell et al., 2025; D'Antonio et al., 2025). for the duration of the operational life of offshore windfarms (20-30 years).

4.8 Secondary entanglement

Secondary entanglement through drifting fishing equipment, ghost nets, ropes and fishing line may pose a significant risk to sharks and rays. This was identified as a medium indirect risk at the scale of both the subregional and designated OWF zone. The cabling and mooring systems associated with floating windfarms presents a risk of entanglement to marine fauna including large sharks (Maxwell et al., 2022). This has been termed primary entanglement, whereas secondary entanglement represents the risk of animals entangling in other materials entangled in cables, such as fishing gear or debris (Maxwell et al., 2022: Parton et al. 2019). When this material becomes entangled around OWF structure and cables, the risk imposed for entanglement of species moving through these areas is unknown, and would depend on the OWF location, the potential quantity of drifting secondary entanglement material, across-shelf currents and the period of time megafauna remain within these structures. Quantifying the type and extent of secondary entanglement material should be a priority at each OWF footprint.

4.9 Reduced fishing pressure

Both globally and within Australia, sharks and rays are, and have historically been, faced with extensive fishing pressure, both as targeted species and as bycatch (Dulvy et al., 2021). In our ERA, we identified reduced fishing pressure as medium to high positive impact for sharks and rays (Figure 5 and 6). In the context of OWF, sharks and rays typically have area-use distributions greater than the footprint of an OWF development. For shark and ray species that exhibit relatively high site fidelity within a development area, they may migrate outside the impacted area for feeding or breeding. Identifying these important habitats is essential for offsetting the loss of available habitat to OWF. Additionally, OWF may act as defacto Marine Protected Areas (MPAs), providing protection against overlap with fishing pressures sharks (Puts et al., 2023; Reyier et al., 2023; Wang et al., 2022). This is because of reduced fishing pressures in OWF, assuming these areas are not opened to fishing. The potential positive benefits of OWF zones to shark and ray populations could be tested through conventional presence and abundance surveys done before, during and after OWF development.

4.10 Noise

While noise was identified as low risk to sharks and rays in the Level 2-extension, an established body of evidence suggest the construction phase of OWF is likely to have the greatest impact for other noise-sensitive species, especially if pile driving is used (Bailey et al., 2014; Puts et al., 2023). Although noise with the hearing range of sharks can be produced from initial site investigations (e.g. drilling and seabed seismic investigations) and from operation of the turbines themselves, pile driving can potentially cause hearing impediment or displace individuals (Bergström et al., 2014; Casper et al., 2012; Kulkarni et al., 2022). The opposite may also be true for lower sound source levels, which could also initially attract larger sharks to an area, probably as a predator investigation response (Chapuis et al., 2019; Hermans et al., 2025; Mickle et al., 2020). Noise abatement systems and alternative construction approaches to piling are now available (Bergström et al., 2014; Maxwell et al., 2022).

The sound produced by operational windfarms (mainly < 1 kHz, Tougaard et al, 2020) also overlaps with the hearing sensitivity of most sharks and rays, is mostly from 25 Hz to 1.5 kHz, peaking between 200 to 600 Hz (Mickle and Higgs 2021; Mickel et al., 2020). Whale sharks in particular are highly responsive to long wavelength, low frequency, sounds (Martin 2007). A simple multi-turbine model demonstrates that cumulative noise levels from wind farm operation could be elevated up to a few kilometres from a wind farm under very low ambient noise conditions (Tougaard et al., 2020). Even though the noise levels radiating from individual turbines are low, the combined contribution of multiple turbines becomes important at larger distances from the wind farm, especially for locations with low ambient noise (Tougaard et al., 2020), however most OWFs designated zones in Australia are situated in “noisy” environmental conditions (Figure 3).

4.11 Priorities for future research

Multi-species movement assessments will be increasingly important, not just within the footprint of the OWF, but also in the context of the wider and “whole of lifecycle” for key shark and ray species. Complex inter and intra-species interactions can have spatial and temporal influences on species assemblage patterns (e.g. see Clua et al., 2014). For high-risk species that range over large areas including shelf waters, assessing distribution overlap with proposed OWF areas was identified as a priority for further research. Considerable movement data is already available for some of these species in Australian waters, but more information is required for less data-rich species, such as the oceanic whitetip, basking shark, mako shark, scallop and great hammerhead shark and manta rays. Sexual segregation patterns are also an important consideration as impacts on key parts of a species lifecycle strategy may cause bottleneck consequences with flow-on effects to the larger population. For example, whale sharks are typified by mostly young males seasonally occurring in large, predictable concentrations in shelf habitats. OWF impacts driving male whale sharks to avoid, or alternatively be attracted to, key feeding sites may have significant implications for populations of conservation significance (D’Antonio et al., 2025). Careful planning, however, could enable these potential impacts to be mitigated and provide positive scenarios for balancing the needs of humans as well as key wildlife species. Experimental design should consider not only the extent of a shark or ray species movements, but also the key drivers, important habitats, and these should be considered in light of a fine-scale approach to habitat use (such as acoustic receiver arrays) in proposed OWF footprints. This will require well planned multi-monitoring methods and multi-tagging technology approaches (e.g. Werry et al., 2014). In the Australian context, taking advantage of extensive country wide tagging (several 100’s of individual sharks) with long-term acoustic tags (up to 10yrs+) of the protected white shark, could enable this large shark species to be developed as a model species for testing scenarios of species response to OWF development.

Furthermore, with increasing technology advances, deeper water OWF and the ability to deploy OWF on shelf edges is progressing. Monitoring methods and technological advancements for deep water sharks should therefore be a future consideration for OWF monitoring and assessment programs. This is particularly pertinent as this group of sharks and rays is data deficient in the Australian region. In addition, recent collations of available catch data, however, suggest deep water sharks are at risk of irreversible defaunation due to overfishing (Finucci et al., 2024). We further suggest embracing emerging technologies, such as eDNA (see Boussarie et al., 2018) to gain an overview of shark assemblage and occurrence patterns, both spatially and temporally for OWF footprints (e.g. Hermans et al., 2024). eDNA can increase the detection for cryptic shark species and is particularly powerful when combined with other survey methods and qPCR (Boussarie et al., 2018).

4.12 Limitations of the semi-quantitative Level 2 ERA

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ERA provides a robust method particularly for assessing species that are data deficient. However, it is not a replacement for targeted research to support evidence-based decision-making. Movement studies, for example, however, provide a powerful method for understanding habitat function and connectiveness for sharks and rays. Movement studies are also important to determine the appropriate scale for assessing impacts to sharks and rays from OWF development

ERA also often depends on expert opinion to guide ERA scoring for data limited species, and these scores may change as better and more detailed data on shark and ray species become available. The strength of this approach is that it can iteratively lead to more robust assessments as more data becomes available, but the reliance on expert opinion the potential subjectivity that this may introduce for data limited species also needs to be recognized.

Further, ERA stems from fisheries management and research, and hence does not directly align with environmental legislation. However, incorporating the ERA approach into the overarching EIA framework is likely to supplement and improve the rigor of impact assessments for wide ranging and data-limited marine species.

4.13 Conclusion

Our ERA for assessing the impacts of OWF on sharks and rays identified increased electromagnetic fields as the key direct impact for consideration for 31 sharks identified at medium to high risk from OWF and understanding this impact and the efficacy of shielding as a mitigation requires immediate attention (Klimley et al., 2021). OWF may also represent potential barriers to movement (Wilms et al., 2023). Alterations to upwelling and currents, changes in prey availability, secondary entanglement and food chain alteration were identified as key indirect impacts to 39 sharks and rays from OWF. The key positive benefit to sharks and rays was predicted to be reduced fishing pressure within and around the turbine array (from vessel exclusion), coupled with the likely increased food resources for sharks associated with hard structure for feeding (D'Antonio et al., 2025; Wilms et al., 2023). These impacts are likely to persist for the operational life of windfarms, which is likely to be 20-30 years, because current license conditions in Australia mandate removal of all infrastructure at the end of operational life of the windfarm. To this end, pre-decommissioning surveys of sharks and rays are likely to be required, and it may be worth considering design and decommissioning options that involve leaving some in-water structure in place.

Cross-shelf movements, ontogenetic shifts in habitat that depend on the utilisation of shelf areas, large home ranges and migration pathways and the restricted range of some shark and ray species (e.g. skates) are life-history traits that make sharks and rays vulnerable to OWF impacts. Shedding further light on these movement patterns would support sustainable development of the industry to balance the needs for a rapid transition to renewable energy and the trophic and habitat requirements of protected and iconic species of sharks and rays. More information on movement and residency patterns of data-deficient sharks and rays will also be fundamental for establishing sensitive environmental windows and avoiding impacts on sharks and rays during the construction and decommissioning phases. A coordinated approach to shark and ray monitoring and research for

Australian OWFs would ideally not just focus on the priority threatened species but would also use this opportunity to better understand data-deficient species.

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Graphical Abstract

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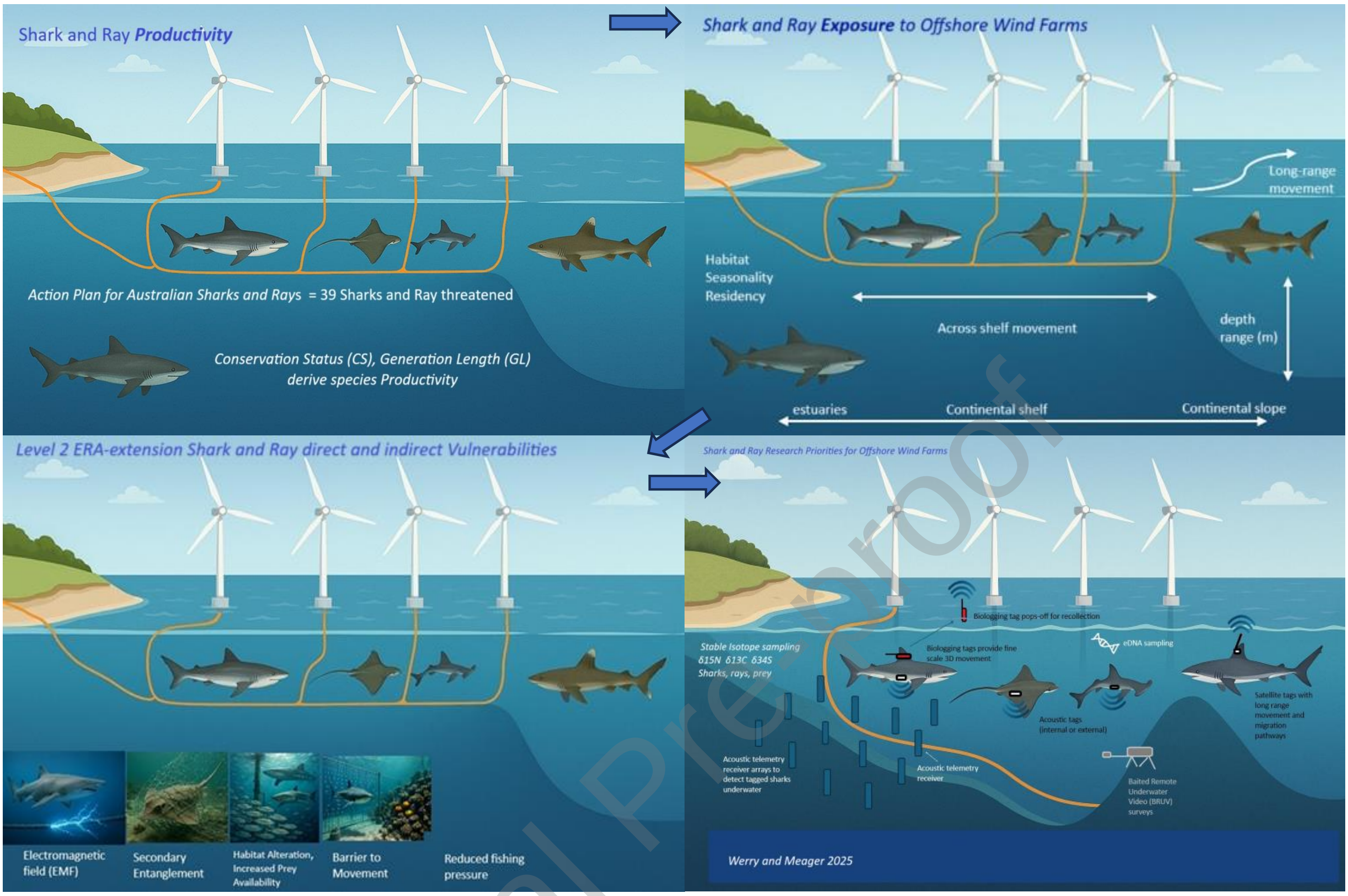

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Figures for Werry and Meager 2025

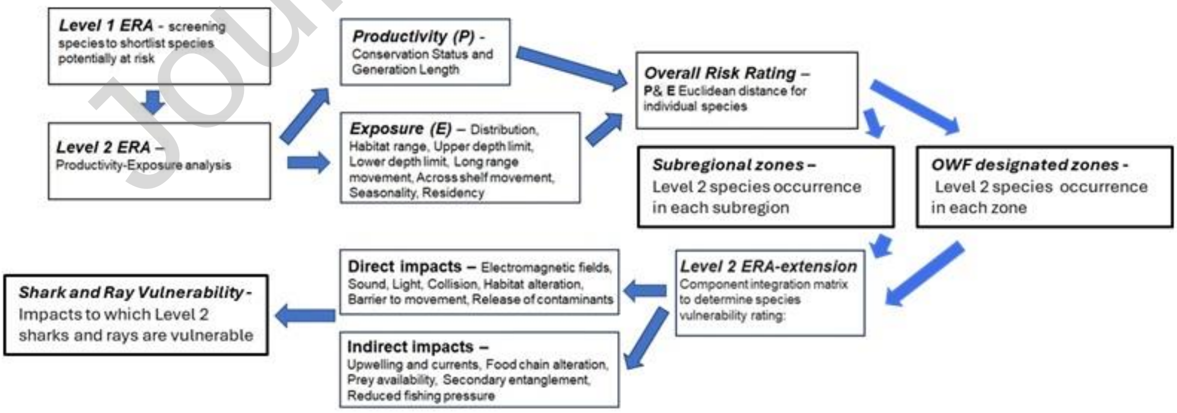

Figure 1 – Flow Diagram of Offshore Wind Farms Environmental Risk Assessment for shark and ray

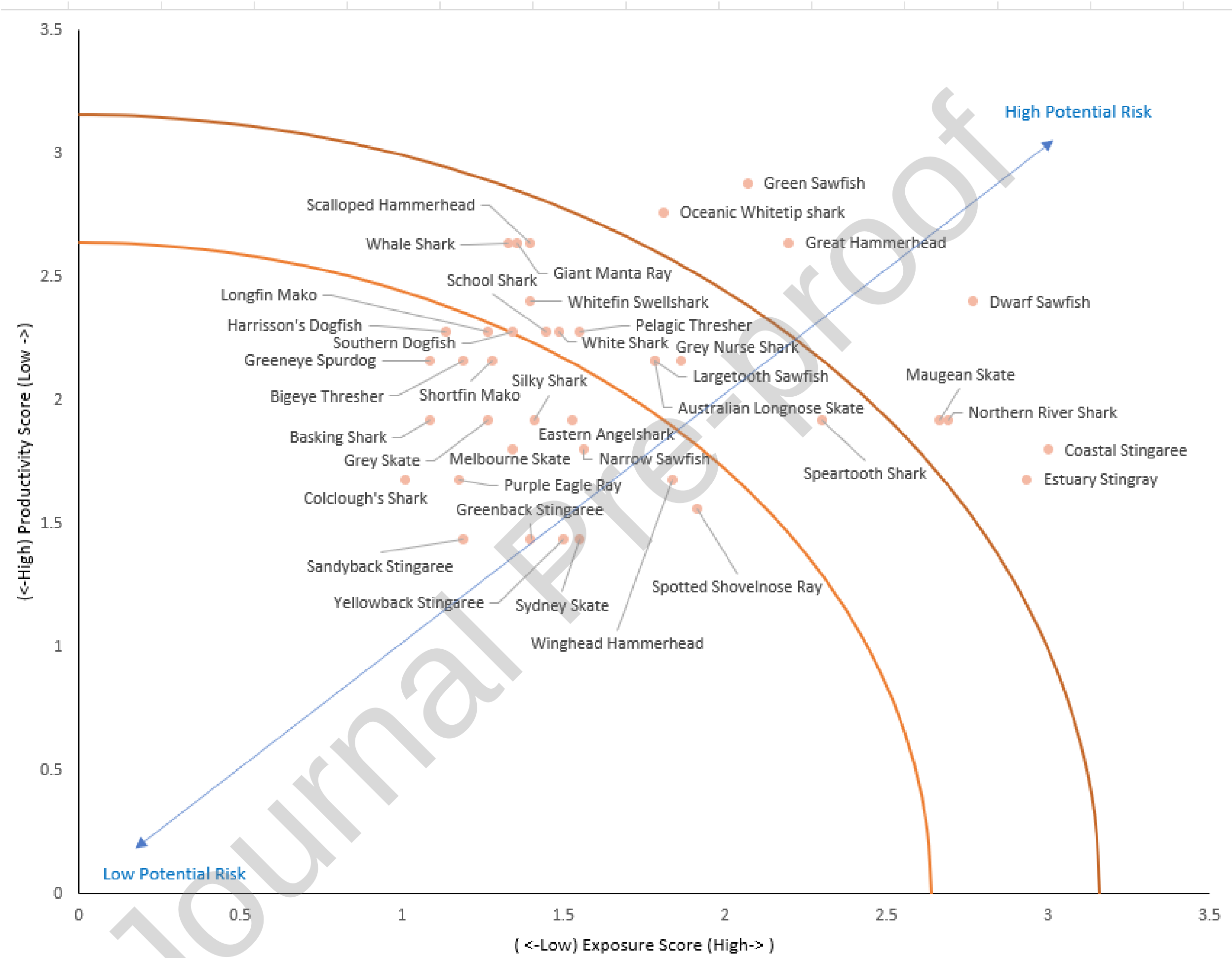

Figure 2 Normalised productivity-exposure analysis (PEA) plot illustrates the relationship between productivity (P) and exposure (E) for 39 sharks and rays with increasing risk of impact from Offshore Wind Farms from left to right. This method divides the plot into equal thirds. Scores in the upper third of all possible scores (risk value >3.18) are classified as high risk, values in middle third of possible scores (2.64 < risk value < 3.18) are medium risk. Values in in the lower third of possible scores (risk value < 2.64) are classified as low risk. Arcs represent high (3.18), medium (2.64) and low risk.

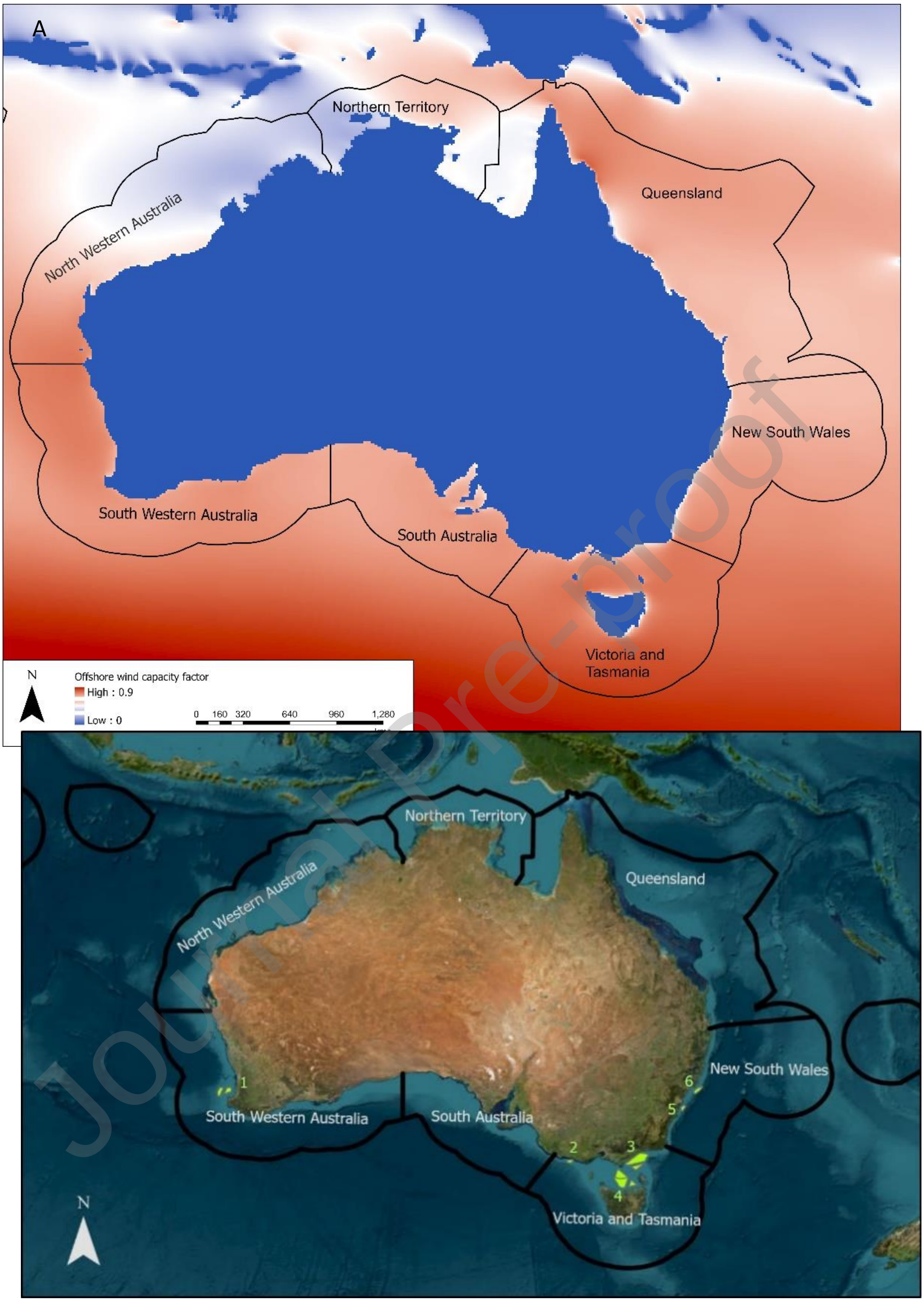

Figure 3 (A) Seven subregional zones for assessment of shark and ray vulnerability to impacts from Offshore Wind Farm areas in Australia. Shading indicates the offshore wind capacity factor where red indicates highest and blue the lowest. Designated wind zones for Offshore wind farms are shown in (B) and include: 1. Bunbury, Southwestern Australia, 2. Southern Ocean, Victoria, 3. Gippsland, Victoria, 4. Bass Strait, Tasmania, 5. Illawarra, New South Wales, 6. Hunter, New South Wales.

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(A) Species name	Common name	QLD	NSW	Vic Tas	SA	SWA	NWA	NT
Carcharhinus longimanus	Oceanic Whitetip shark							
Glyphis garricki	Northern River Shark							
Hemitrygon fluviorum	Estuary Stingray							
Pristis clavata	Dwarf Sawfish							
Pristis zijsron	Green Sawfish							
Sphyrna makarran	Great Hammerhead							
Urolophys orarius	Coastal Stingaree							
Zearaja maugeana	Maugean Skate							
Alopias pelagicus	Pelagic Thresher							
Carcharias taurus	Grey Nurse Shark							
Carcharodon carcharias	White Shark							
Centrophorus zeehaani	Southern Dogfish							
Cephaloscyllium albipinnum	Whitefin Swellshark							
Dentiraja confusa	Australian Longnose Skate							
Galeorhinus galeus	School Shark							
Glyphis glyphis	Speartooth Shark							
Mobula birostris	Giant Manta Ray							
Pristis microdon	Largetooth Sawfish							
Rhincodon typus	Whale Shark							
Sphyrna lewini	Scalloped Hammerhead							
Aptychotrema timorensis	Spotted Shovelnose Ray							
Aptychotrema timorensis	Bigeye Thresher							
Centrophorus harrissoni	Harrisson's Dogfish							
Eusphyra blochii	Winghead Hammerhead							
Isurus oxyrinchus	Shortfin Mako							
Isurus paucus	Longfin Mako							
Squatina albipunctata	Eastern Angelshark							
Anoxypristis cuspidata	Narrow Sawfish							
Carcharhinus falciformis	Silky Shark							
Cetorhinus maximus	Basking Shark							
Dentiraja australis	Sydney Skate							
Depturus canutus	Grey Skate							
Myliobatis hamlyni	Purple Eagle Ray							
Spiniraja whitleyi	Melbourne Skate							
Squalus chloroculus	Greeneye Spurdog							
Urolophus sufflavus	Yellowback Stingaree							
Urolophus viridis	Greenback Stingaree							
Brachaelurus colcloughi	Colclough's Shark							
Urolophus bucculentus	Sandyback Stingaree							

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(B) Species name	Common name	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Pristis zijsron	Green Sawfish						
Sphyrna makarran	Great Hammerhead						
Hemitrygon fluviorum	Estuary Stingray						
Carcharhinus longimanus	Oceanic Whitetip shark						
Sphyrna lewini	Scalloped Hammerhead						
Mobula birostris	Giant Manta Ray						
Rhincodon typus	Whale Shark						
Carcharias taurus	Grey Nurse Shark						
Dentiraja confusa	Australian Longnose Skate						
Pristis microdon	Largetooth Sawfish						
Cephaloscyllium albipinnum	Whitefin Swellshark						
Carcharodon carcharias	White Shark						
Galeorhinus galeus	School Shark						
Centrophorus zeehaani	Southern Dogfish						
Isurus paucus	Longfin Mako						
Centrophorus harrissoni	Harrisson's Dogfish						
Isurus oxyrinchus	Shortfin Mako						
Aptychotrema timorensis	Bigeye Thresher						
Squatina albipunctata	Eastern Angelshark						
Squalus chloroculus	Greeneye Spurdog						
Carcharhinus falciformis	Silky Shark						
Depturus canutus	Grey Skate						
Spiniraja whitleyi	Melbourne Skate						
Cetorhinus maximus	Basking Shark						
Dentiraja australis	Sydney Skate						
Urolophus sufflavus	Yellowback Stingaree						
Myliobatis hamlyni	Purple Eagle Ray						
Urolophus viridis	Greenback Stingaree						
Urolophus bucculentus	Sandyback Stingaree						

Figure 4 (A) Occurrence of 39 shark and ray species, ranked by productivity-exposure score, across the seven subregional zones (Figure 3A) and (B) occurrence of 29 shark and ray species ranked by productivity-exposure score across the six OWF designated wind zones of 1. Bunbury, Southwestern Australia, 2. Southern Ocean, Victoria, 3. Gippsland, Victoria, 4. Bass Strait, Tasmania, 5. Illawarra, New South Wales, 6. Hunter, New South Wales. (Figure 3B). The pink colour refers to species with high productivity-exposure risk, yellow for medium risk and light yellow for borderline medium risk. Light green for borderline medium-low risk and dark green for low risk. The red bars indicate species are expected to occur in this subregion or OWF designated zones.

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Figure 5. Level 2 extension component integration matrix to determine species level of impact risk on 39 shark and ray species for OWF from component rankings with their relative occurrence in the subregional zones of OWF. Numbers indicate the number of species in each category. Overall vulnerability is the mean across state categories. the table considers the vulnerability (as L, M, H). Species identified across the areas were taken from figure 4A for all of Australia.

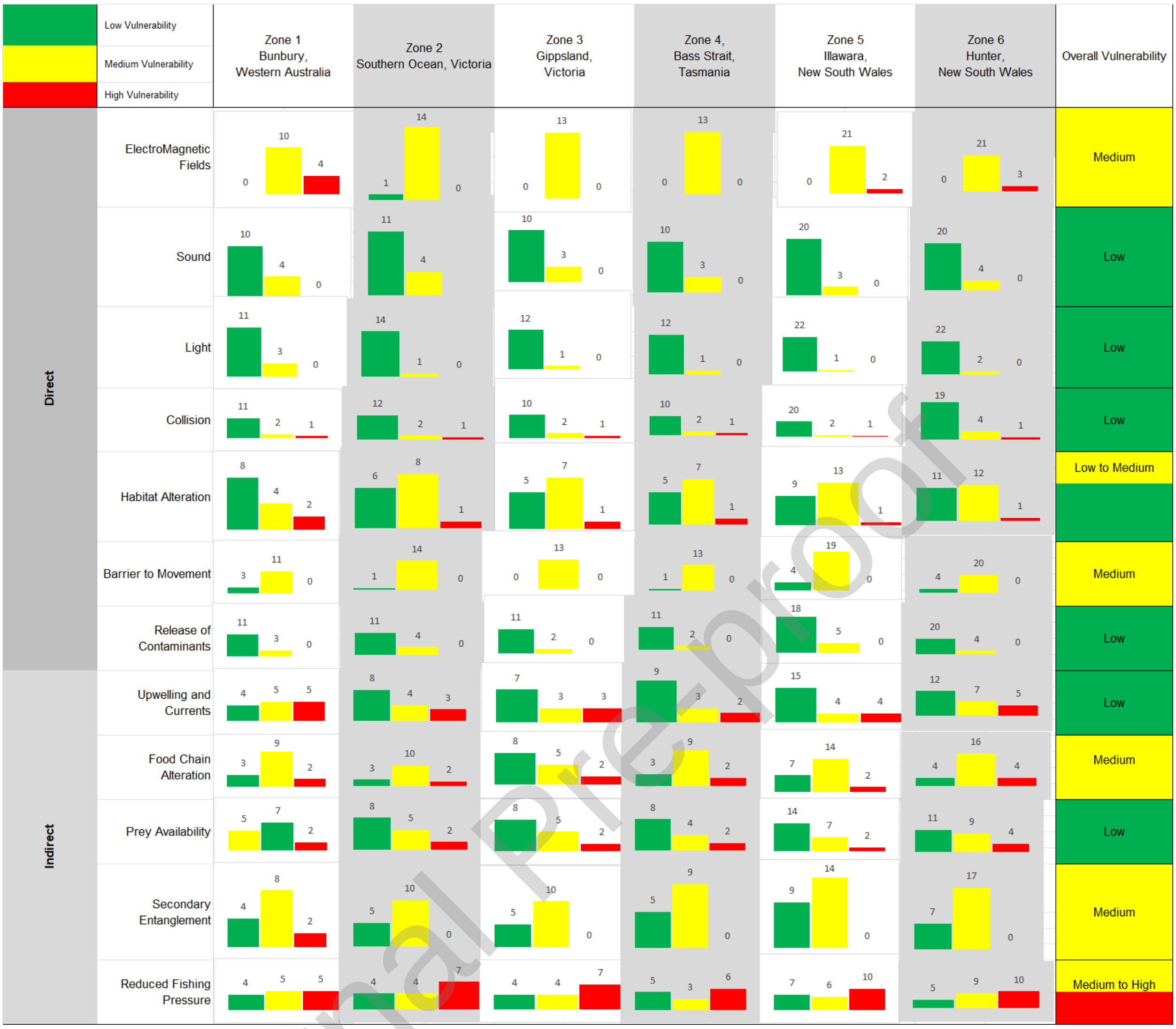

Figure 6. Level 2 extension component integration matrix for direct and indirect vulnerabilities for species only occurring in each OWF designated zone (1 to 6). The Level 2 extension for the individual zones to determine the species level of impact risk on 29 shark and ray species for OWF from component rankings with their relative occurrence in the zones of OWF (Figure 4B). Numbers indicate the number of species in each category. Overall vulnerability is the mean across state categories. the table considers the vulnerability (as L, M, H). Species identified across the areas were taken from figure 4 and only included if their known distribution overlapped with the six designated OWF zones. (1) Bunbury, Southwestern Australia, (2). Southern Ocean, Victoria, (3). Gippsland, Victoria, (4). Bass Strait, Tasmania, (5). Illawarra, New South Wales, (6). Hunter, New South Wales.

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Tables

Table 1 : Conservation Status (CS) listing and corresponding score for shark ray species based on the Australian National Plan of Action.

Action Plan	Conservation Status Score
Least Concern (LC)	1
Near-Threatened (NT)	2
Vulnerable (V)	3
Endangered (E)	4
Critically Endangered (CR)	5

Table 2 : Generation Length (GL) listing for shark ray species based on the Australian National Plan of Action.

Generation Length	Generation Length Score
<5 years	1
≥5 and <10 years	2
≥10 and ≤15 years	3
>15 and ≤20 years	4
>20 years	5

Table 3 : Habitat Range (HR) listing for shark and ray species known occurrence.

Habitat Range	Score
River	1
Estuaries	2
Continental shelf	5
Continental slope	3
Pelagic	4

Table 4 : Distribution (D) listing for shark and ray species known occurrence. State refers to a state or territory.

Distribution	Score
1 state	5
2 states	4
3 states	3
4 states	2
> 4 states	1

Table 5 : Upper (UD) and lower depth (LD) score categories for shark and ray species known occurrence.

Depth (upper range)	score	Depth (lower range)	score
0 to 20 m	5	0 to 20 m	5
20 to 60 m	4	20 to 60 m	4
60 to 100 m	3	60 to 100 m	3
100 to 200 m	2	100 to 200 m	2

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> 200 m	1	> 200 m	1

Table 6 : Long range movement (LRM) score categories for shark and ray species known occurrence.

(LRM) long-range movement/migration	score
> 5000 km	1
> 1000 km	2
> 500 km	3
> 100 km	4
never	5

Table 7 : Across shelf movement (ASM) score categories for shark and ray species.

(ASM) Across shelf movement	score
never	1
infrequent north-south coastal migrations occur at different distances offshore	2
seasonal (once a year)	3
frequent direct inshore-offshore movement	4
unknown	5

Table 8 : Seasonality (SEAS) score categories for shark and ray species.

(SEAS) Seasonality	Score
infrequent (less than once a year)	1
present in 1 season/ yr	2
present in 2 season/ yr	3
present in 3 season/ yr	4
present All year	5

Table 9 : Residency Index (RI)) score categories for shark and ray species.

(RI) Residency Index	Score
completely transitory	1
minimal (app. 1 month)	2
alternates between residency and transitory	3
year round	4
unknown	5

Author contributions: CRediT

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Declaration of interests

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

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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