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Review

Framework for assessing and mitigating the impacts of offshore wind energy development on marine birds

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ABSTRACT

Offshore wind energy development (OWED) is rapidly expanding globally and has the potential to contribute significantly to renewable energy portfolios. However, development of infrastructure in the marine environment presents risks to wildlife. Marine birds in particular have life history traits that amplify population impacts from displacement and collision with offshore wind infrastructure. Here, we present a broadly applicable framework to assess and mitigate the impacts of OWED on marine birds. We outline existing techniques to quantify impact via monitoring and modeling (e.g., collision risk models, population viability analysis), and present a robust mitigation framework to avoid, minimize, or compensate for OWED impacts. Our framework addresses impacts within the context of multiple stressors across multiple wind energy developments. We also present technological and methodological approaches that can improve impact estimation and mitigation. We highlight compensatory mitigation as a tool that can be incorporated into regulatory frameworks to mitigate impacts that cannot be avoided or minimized via siting decisions or alterations to OWED infrastructure or operation. Our framework is

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intended as a globally-relevant approach for assessing and mitigating OWED impacts on marine birds that may be adapted to existing regulatory frameworks in regions with existing or planned OWED.

1. Introduction

Offshore wind energy development (OWED) is a critical component of global renewable energy strategies to reduce carbon dioxide emissions. As of the end of 2021, global offshore wind energy projects exceeded 300 gigawatts, and the U.S. has a federal goal to install 30 gigawatts of offshore energy by 2030 (Musial et al., 2021). However, while OWED is rapidly expanding globally (Rogelj et al., 2016), it poses risks to wildlife. Effective assessment and mitigation of OWED-related wildlife impacts are critical for sustainable development and operation of OWED (Perveen et al., 2014). This will only become more important as emerging floating turbine technology is deployed, enabling development in previously inaccessible offshore areas (Bento and Fontes, 2019).

Marine birds, defined here as birds that feed in the marine environment (i.e. loons, grebes, sea ducks, phalaropes, and seabirds, Young

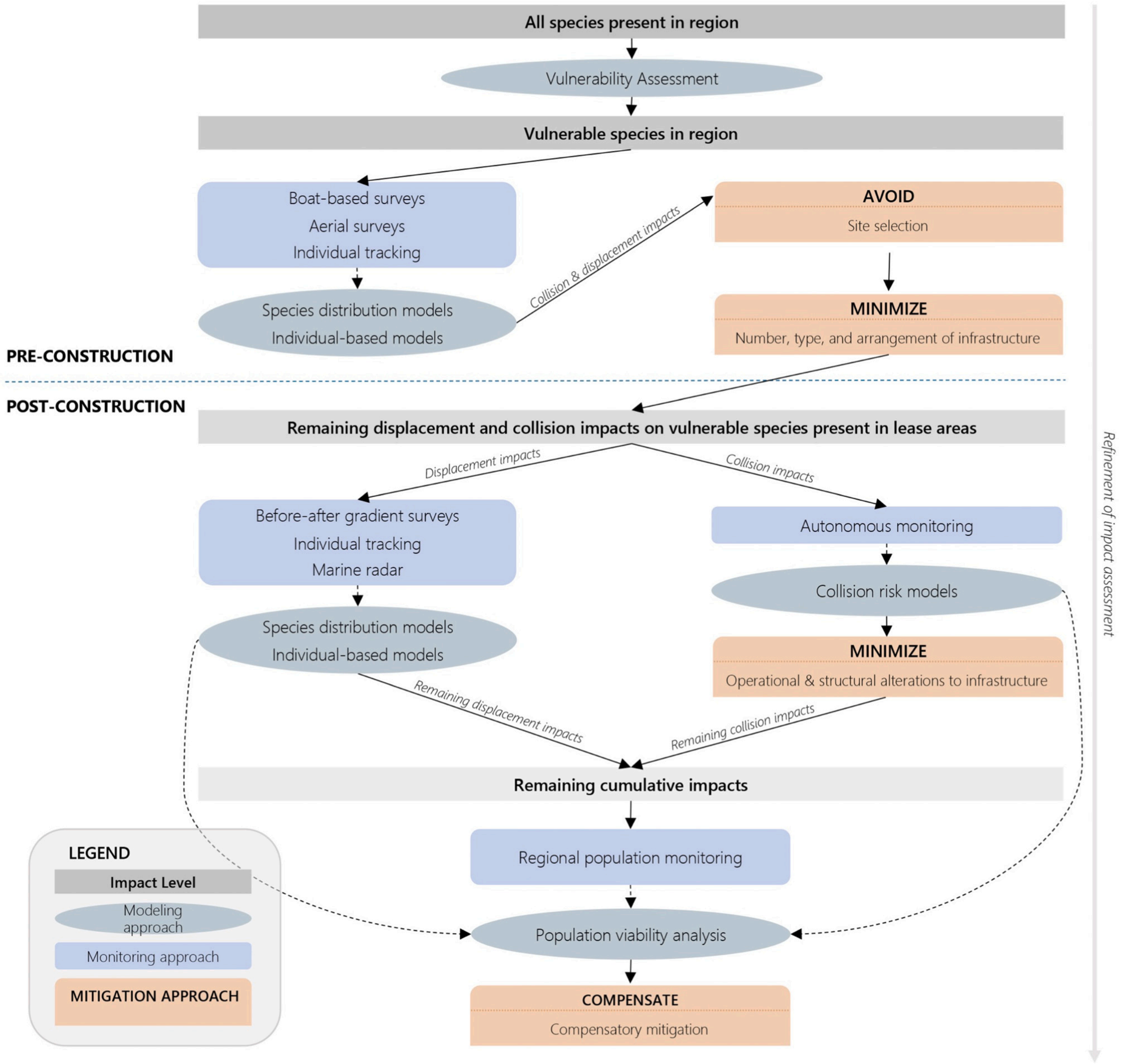

Fig. 1. Flowchart of approaches for assessment and mitigation of impacts for marine birds in a region under consideration for and/or following development of offshore wind energy infrastructure. Dotted lines indicate where outputs inform subsequent modeling approaches. This flowchart describes the steps useful to quantify impacts, however, in many cases the mitigation approaches described may be most effectively implemented as precautions prior to the collection of data necessary to fully validate models. Though population viability analysis is shown here as a post-construction step, we note that population modeling is the product of long-term data collection which must also occur pre-development and development. See text for discussion of the varying levels of development and/or certainty in the monitoring, modeling, and mitigation approaches included (e.g., the efficacy of impact minimization via operational alterations to wind turbines is not yet well tested in the marine environment).

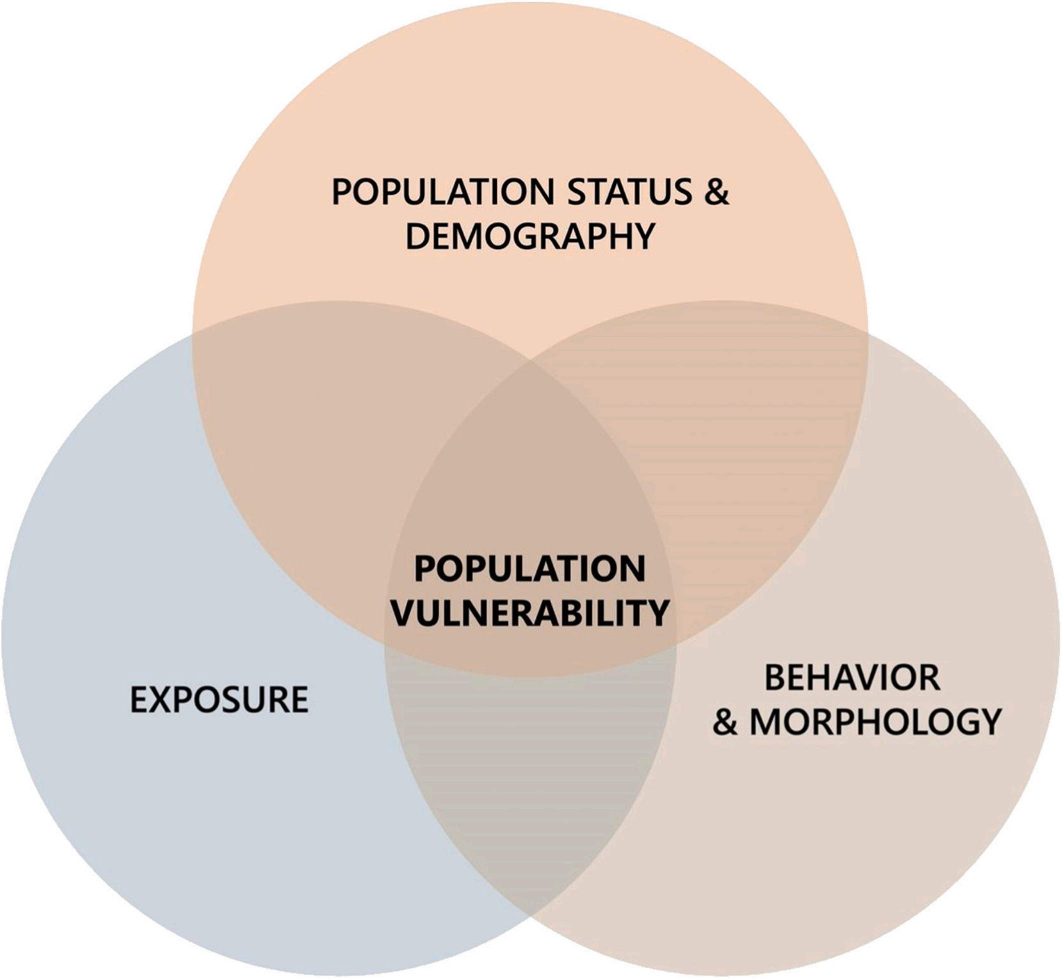

Fig. 2. Marine bird vulnerability to collision with or displacement from OWED can be broken into three components: population status and demography, exposure, and behavior and morphology. Population status and demography include a species' population size, adult survival and reproduction, and conservation threat status (Kelsey et al., 2018). Exposure is the species' spatial and temporal co-occurrence with OWEDs, maintenance, and infrastructure. Behavior and morphology, specifically flight behavior and morphology, are characteristics that contribute to a species' collision vulnerability (i.e., nocturnal and diurnal flight activity, avoidance behavior, and flight height); displacement vulnerability is a function of avoidance behavior and habitat flexibility (Kelsey et al., 2018).

and VanderWerf, 2022), are among the most threatened groups of marine organisms (Dias et al., 2019), and are impacted by invasive species, overexploitation, climate change, fisheries bycatch, and pollution (Boersma et al., 2001; Croxall et al., 2012; Dias et al., 2019; Rodríguez et al., 2017). Marine birds can be adversely affected by OWED through displacement due to avoidance or habitat alteration, or through direct mortality due to collision (Goodale and Milman, 2016; Hamer et al., 2014; Langhamer, 2012; Lieber et al., 2021; Linley et al., 2007; van Berkel et al., 2020; Voous, 1961). Population-level impacts from anthropogenic activities are amplified by marine bird life history characteristics including late maturation and low fecundity (Sandvik and Erikstad, 2008). Additionally, most marine birds are central place foragers during the breeding season and are therefore particularly vulnerable to stressors located in the vicinity of their nesting colonies (e.g., Schreiber and Burger, 2001).

Assessing and mitigating impacts to marine birds is imperative for sustainable construction and operation of OWED (Brabant et al., 2015; Busch and Garthe, 2017). Even if impacts of individual turbines or facilities are minor, the cumulative impacts of multiple turbines and wind energy facilities over time, have the potential to cause population declines (Goodale and Milman, 2016). Here, we review existing research and management approaches and present a broadly applicable framework to assess and mitigate the impacts of OWED on marine birds. We define mitigation as efforts to avoid, minimize and/or compensate for environmental impacts. To maximize the conservation utility of this framework and leverage previous work, we focus on approaches to model, monitor, and mitigate collision and displacement-related OWED impacts in the context of multiple stressors across multiple wind energy developments. Changes to physical and biological habitats, including changes in oceanographic conditions, the addition of new perching and roosting habitats in offshore areas, the potential for increased foraging opportunities due to "reef effects" around new benthic structures (Glarou et al., 2020; Goodale and Stenhouse, 2016), and changes to food web dynamics and prey populations, are not discussed here.

Quantification and mitigation of population-level impacts of OWED on marine birds requires: 1) information on vulnerability of marine bird species to displacement and collision, 2) estimation of displacement and collision impacts on demographic rates, 3) translation of demographic factors to impacts on population trajectories, 4) identification of feasible options to avoid, minimize, or compensate for these population impacts, and 5) sustained monitoring of impact and mitigation outcomes. Monitoring is essential to inform and validate models to predict avian distributions, calculate mortality, and estimate individual and population level impacts. In addition, monitoring informs adaptive management by quantifying the efficacy of mitigation. Here, we review current monitoring and modeling best practices, highlight areas requiring further development for evaluating displacement and collision impacts, and explore potential mitigation approaches.

A well-developed hierarchy for mitigating environmental impacts of OWED on marine birds includes: 1) strategic siting to *avoid* high-use areas for vulnerable populations 2) *minimization* of impacts through temporal or structural alterations to infrastructure and operation, and 3), *compensation* for impacts that cannot be avoided (Arnett and May, 2016; Kiesecker et al., 2010). We emphasize the importance of impact avoidance and minimization but recognize that it is almost certainly impossible to eliminate mortality and sublethal impacts. Therefore, we include a framework for compensatory mitigation as a feasible approach to addressing impacts that cannot be avoided or minimized (Fig. 1).

2. Vulnerability

Marine bird vulnerability assessments are an important first step when evaluating the impact of OWED on populations in a region. Luers (2005), defined vulnerability as the susceptibility of a population to damage. As such, a population's vulnerability to perturbation is a function of its population status and demography, exposure, and behavior and morphology (Fig. 2). Population status and demography includes a species' population size, adult survival and reproduction, and conservation threat status (Kelsey et al., 2018). Exposure is the species' spatial and temporal co-occurrence with OWED, maintenance, and infrastructure. Characteristics, including flight behavior and morphology, contribute to a species' vulnerability. Species vulnerability can further be broken into two components: displacement vulnerability and collision vulnerability (Goodale and Stenhouse, 2016). Displacement vulnerability is driven by a species' behavioral reactions when exposed to OWED (e.g., attraction, avoidance, habitat flexibility). Collision vulnerability is thought to be driven by species-specific flight behaviors (e.g., flight altitude, speed, maneuverability) that influence the likelihood of collision with OWED infrastructure (Furness et al., 2013).

Based on the parameters outlined above, avian vulnerability indices for displacement and collision were developed for Europe (Desholm, 2009; Furness et al., 2013; Garthe and Hüppop, 2004), the east coast of the US (Robinson Willmott et al., 2013) and the marine region off the west coast of the US (Kelsey et al., 2018). When the necessary behavioral, life-history or population data were missing for such assessments, proxies were considered with caution (e.g., data from another population or species) (Horswill et al., 2021; Zettler et al., 2013). These indices were built to be applicable to broad regions with diverse species assemblages, and thus did not incorporate assessment of exposure at the scale of an individual wind energy facility, though assessments of vulnerability could be evaluated with site-specific exposure data to assess risk at this scale. Avian vulnerability indices determine the species that are considered in vulnerability and environmental impact assessments and are valuable tools to identify focal species for further monitoring and mitigation efforts.

3. Displacement

We define displacement as partial or total avoidance of OWEDs (Drewitt and Langston, 2006). Displacement has different impacts on marine birds depending on the location of the OWED and the timing of the displacement (Busch and Garthe, 2017; Fox and Petersen, 2019). During the breeding season OWED close to breeding colonies may exclude birds from important foraging areas or commuting corridors (Fox et al., 2006), which can increase the energetic costs of foraging to parents and reduce reproductive output. Breeding-season impacts may be exacerbated for taxa with high flight costs (e.g., alcids). During the non-breeding seasons most marine birds range more widely and are more dispersed (Fort et al., 2012; Frederiksen et al., 2012). Nonetheless, displacement could impact species with specific habitat requirements (e.g., during flightless molting periods) or migratory pathways that overlap with OWEDs (Fox and Petersen, 2019; Newton, 2007). Although the effects of displacement due to a single wind park may be minor, as birds easily fly around a certain area and/or find their food elsewhere, effects of displacement will likely become more severe when a larger area becomes occupied by wind turbines, and birds can less easily compensate. Effects of displacement may also accumulate over time (e.g. subsequent year impacts of unfavorable conditions) (Daunt et al., 2020; Harrison et al., 2011). However, uncertainty remains regarding potential effects because 1) the turbine size, spatial arrangement, distance from shore, and anchoring technology of new developments are rapidly changing, and the degree of observed displacement at older wind farms may not predict effects at wind farms of more recent design, 2) surveys often have limited statistical power to detect changes (e.g., Maclean et al., 2013), 3) the influence of displacement on individual fitness is indirect, and thus can be difficult to measure, and 4) detailed information on prey distributions and availability is sparse or absent, making it hard to estimate effects of the loss of foraging habitat.

3.1. Monitoring

Monitoring to detect displacement can be conducted using a variety of approaches, with each method representing different tradeoffs in spatial and temporal resolutions, species identification capacity, and other factors. Visual surveys of displacement include boat- or aircraft-based human observers (Harwood et al., 2017) or digital aerial imagery (Buckland et al., 2012). Boat-based surveys can provide detailed behavioral and in-situ environmental covariate data, but are limited by weather, time of day favorable for surveys, survey duration, spatial extent, and difficulty accounting for avoidance or attraction behavior towards survey vessels (Hyrenbach, 2001; Mendel et al., 2019; Schwemmer et al., 2011). Digital aerial surveys have become common in relation to OWED because they are faster, safer, can be conducted at altitudes above the rotor-sweep zone of turbines, and produce a permanent record of sightings (Buckland et al., 2012). Digital aerial surveys may also provide better seabird abundance estimates than visual surveys in some cases (e.g., Buckland et al., 2012). Before-After Control-Impact (BACI) study designs, where an OWED area and an undeveloped "control" site are both surveyed before and after construction, generally suffer from low replication and certain a priori study design limitations, including difficulty with identifying an appropriate control site and an inability to adequately assess spatial heterogeneity in responses (Methratta, 2021). In seabirds, the use of BACI study design to examine seabird impacts have shown the need for multiple years of data (Maclean et al., 2013; Vanermen et al., 2015). Moreover, detection of BACI impacts the impacts of OWED to seabirds likely occur as gradients that attenuate with distance, further complicating their quantification. Thus, BACI designs have largely been replaced by Before-After Gradient (BAG) approaches that survey a proximity gradient in and around the OWED footprint. BAG designs provide greater inferential power (Methratta, 2021) but require larger survey areas (Ellis and Schneider, 1997).

Tracking individual birds can also be used to assess avoidance of OWED (Johnston et al., 2022). Unlike surveys, tracking provides data at night and during poor weather. For larger-bodied marine birds, additional sensors (barometers, accelerometers, etc.) can supplement spatial data (Largey et al., 2021) and record three-dimensional movement around turbines. Broader population inference from tracking data is limited by small sample sizes, high deployment costs, biases in deployment opportunities by sex or life history stage (Hazen et al., 2012), precision of spatial and altitude data from sensors, and low probability of individuals encountering OWEDs. Capture difficulties and the current technological limits of transmitter miniaturization can also limit tagging opportunities for some species (e.g., Evans et al., 2020; Sun et al., 2020; Vandenabeele et al., 2012).

Marine radar units have been used to assess migratory flux and flight parameters (such as height and speed) at terrestrial and OWEDs (Fijn et al., 2015; Largey et al., 2021). Although radars are constrained by weather and power requirements as well as their ability to provide species-specific data, they can be used in combination with other methods such as visual observation (Plonczkier and Simms, 2012) or digital aerial imaging (Niemi and Tanttu, 2020) to identify a subset of animals that are detected. Traditional marine radars can either provide two-dimensional horizontal movement data or monitor a narrow slice of vertical airspace (e.g., to acquire flight altitude and migratory flux data), but newer multi-radar systems have been deployed at OWED sites that can provide more detailed three-dimensional movement data and body size information (Urmy and Warren, 2017).

3.2. Modeling

Methods to quantify displacement impacts on marine bird populations are still being developed (Fox and Petersen, 2019; Mendel et al., 2019). A preliminary evaluation of displacement can be estimated using species distribution models (SDMs) that overlay seabird habitat locations with the spatial extent of potential OWED (e.g., Best and Halpin, 2019). With predictions of spatial density and consideration of behavior and life history from vulnerability assessments, the number of birds that have the potential to experience habitat loss due to displacement can be estimated (Busch and Garthe, 2017; van der Wal et al., 2018). Avoidance or displacement rates are best quantified by comparing pre- and post-construction densities for each species occurring in and around a wind farm area (Mendel et al., 2019; Peschko et al., 2020). Translating displacement into demographic impacts is difficult. Some studies have estimated mortality probabilities based on expert elicitation (Busch and Garthe, 2017; Leopold et al., 2014), which can then be used to estimate population-level mortalities and population-level impacts using population models (Soudijn et al., 2022).

Individual-based models incorporate the behavior of individual marine birds and allow for a more quantitative consideration of the impacts of displacement (Masden et al., 2010; Searle et al., 2014; van Kooten et al., 2019). Bioenergetic models and the changes in foraging habitat due to displacement from OWED can be used to estimate changes in energetic costs or energy intake arising from barrier effects or habitat loss. These bioenergetics models can be used to estimate changes in mortality during the nonbreeding (van Kooten et al., 2019) and breeding seasons (Searle et al., 2018, 2014; Warwick-Evans et al., 2016). Adult body mass at the end of the chick-rearing season can be related to the subsequent probability of survival (Daunt et al., 2020). However, models that simulate behavior are difficult to parameterize, requiring extensive baseline data on behavior and energetics, and therefore often contain considerable structural uncertainty, especially given limited synthesis of the relationships among environmental conditions, energetic costs, and demographic rates.

3.3. Mitigation

The primary approach to mitigate displacement impacts is to avoid areas with high densities of vulnerable marine birds. Site selection must accommodate trade-offs between potential impacts to wildlife and ecosystems, energy generation potential, technical limitations of turbine installation, and other human activities (e.g., fishing, shipping, tourism, and military activity, NYSERDA, 2022). The first stage of siting evaluates the areas where development is technically feasible, followed by a regional analysis of these other factors, including the habitat use of vulnerable marine birds within those areas (e.g., Johnston et al., 2015). Once development sites have been selected, reducing the intensity of construction and ongoing support vessel traffic, or adjusting the timing of activities to avoid coinciding with presence of vulnerable species may help minimize some displacement impact.

Species distribution models that link environmental covariates to at-sea survey data (Leirness et al., 2021; Nur et al., 2011), telemetry data (Krüger et al., 2018; Raine et al., 2021), or both are widely accepted for understanding the distribution and abundance of species to inform siting. These models typically use remotely-sensed environmental covariates and static habitat features to predict a continuous surface of species density or habitat use based on statistical associations with those oceanographic variables (Thorne et al., 2016). A variety of statistical approaches can be used, but regardless of the method, the sampling design requires careful consideration to ensure representative, useful model predictions (Fourcade et al., 2018; Jarnevich et al., 2015; Mason et al., 2018). A Bayesian approach may improve predictions by allowing incorporation of spatial and temporal dependencies (Pennino et al., 2017; Vilela et al., 2016). To accurately predict distribution at sea, these models rely on extensive empirical datasets of marine bird distribution and abundance across broad geographic areas, seasons, and years (Briggs et al., 1987; Mason et al., 2007).

Siting based on models developed for a subset of species may create unanticipated impacts by shifting risk to unmodeled species (Redfern et al., 2013). On the other hand, including too many species may dilute the weight of key vulnerable species (e.g., species with high collision/displacement risk or conservation concern) in the final planning process (Welch et al., 2020). Single-species model predictions can be combined into multi-species assessments that account for measures of abundance (Nur et al., 2011), diversity (Block et al., 2011; Davies et al., 2021; Yurkowski et al., 2019), or proportion of populations affected by different site selection scenarios (Goodale et al., 2019). In a multi-species combination approach, individual species can be weighted according to vulnerability (e.g., Kelsey et al., 2018). Model validation is vital to ensure predictive accuracy and ecological relevance (Allouche et al., 2006), and expert review can further help identify model failures and improve performance (Reside et al., 2019; Seoane et al., 2005). Spatial cross-validation is important to understand predictions at the edge of a species range or expansion into new areas (Hao et al., 2020; Smith et al., 2021). Temporal cross-validation is valuable when considering real-time, seasonal forecasting, or longer-term climate predictions (Rapacciuolo et al., 2014; Roberts et al., 2017).

Marine bird distributions vary substantially across seasons (Leirness et al., 2021; Peschko et al., 2020; Thaxter et al., 2015; Winship et al., 2018) and years (Goyert et al., 2016; Santora et al., 2017). Models that explicitly account for both intra- and inter-annual variability allow for assessments of potential impacts across multiple temporal scales (i.e., year-to-year trends while accounting for seasonal cycles). Models can be stratified by season, or explicitly include fine-scale intra-annual variability (i.e., Virgili et al., 2017). Where possible, interannual variability and climate change can be incorporated to account for predicted future interactions with OWED. Combining predictions from multiple temporal scales could help evaluate overall impact of OWED. However, annual predictions can dilute the importance of areas that are highly used for short time periods (i.e., stopover sites during migration). Geostatistical tools such as kernel density, maximum curvature (Cleasby et al., 2020; O'Brien et al., 2017), and Getis-Ord Gi* (Cleasby et al., 2020; Rockwood et al., 2020) can help address this short-coming when applied across multiple temporal scales. However, these methods can deliver quite different results even when applied to the same marine bird distribution datasets, and the appropriate analytical approach must be carefully selected for the specific research question of interest (Sussman et al., 2019). If data on the distribution of both a marine bird and its prey are available, spatial metrics (e.g., Carroll et al., 2019) can help identify foraging areas where species are particularly susceptible to displacement (Rockwood et al., 2020). Ultimately, incorporating more direct habitat metrics such as variability and persistence of key habitat qualities (e.g., prey availability) can improve site-specific risk assessment processes (Mannocci et al., 2017; Suryan et al., 2012).

4. Collision

On land, ~95% of birds flying near wind energy developments do not approach close enough to risk collision (Allison et al., 2019). Offshore, research in Europe has shown that marine birds may suffer direct mortality from collisions with wind energy infrastructure (Drewitt and Langston, 2006; Fox et al., 2006; Seoane et al., 2005; Skov et al., 2018). Marine birds can be abundant in regions of OWED and have flight characteristics (flight speed, height, maneuverability) that make them vulnerable to collision with turbine blades (Kelsey et al., 2018). Terrestrial wind energy infrastructure has been shown to lead to mortality in several seabird species in Hawaii (e.g., tropicbirds, shearwaters, and frigatebirds; USFWS unpublished data). For Northern Gannets, avoidance rates of entire wind farms (macro-avoidance) were estimated at ~64 %, and avoidance of individual turbines (micro-avoidance) at ~99 % (Refisch et al., 2014). However, while avoidance rates and correction factors have been estimated for some species (e.g., Furness et al., 2018; Lane et al., 2020), they are unknown for the majority of marine bird species. The need to better understand the impact of individual mortality from collision on long-term population viability is critical, especially as population-level impacts of adult mortality are amplified by marine bird life history characteristics (Sandvik and Erikstad, 2008). Though individual facilities may cause little additional adult mortality, the scale of proposed buildout in many regions with significant marine bird populations will make it essential to consider cumulative impacts throughout a region (Royal Society for the Protection of Birds, 2022).

4.1. Monitoring

In wind energy impact assessments for terrestrial birds, there are well-established methods for quantifying collision rates based on systematic searches around infrastructure and application of correction factors to account for imperfect detection and scavenger activity (Allison et al., 2019; Huso, 2011). Offshore, estimating mortality using a similar approach is not practical because carcasses are removed from the collision area by sinking, scavenging, wind, currents, and waves. Few studies have measured collision rates empirically (but see Skov et al., 2018). Thus, collision risk generally is estimated using collision risk models (CRMs).

Direct observation, autonomous monitoring (e.g., photography, video, acoustic, radar), and tracking methods can be used to examine individual interactions with wind infrastructure. Tracking and radar data can inform CRMs but may not be able to validate outputs. There are a range of sensor-based technologies in development, generally designed for deployment on or inside of turbine blades. These are often designed to detect collisions visually (e.g., camera systems pointed at turbine blades to observe collisions, or outwards from the tower to detect falling carcasses) or via vibrations in turbine blades caused by collision events (Collier et al., 2012; Hu and Albertani, 2021; May et al., 2012). These systems incorporate multiple technologies to provide different types of data on immediate collision avoidance behavior, collision events, and species identification (e.g., Hu et al., 2018). These new technologies will be essential for measuring marine bird/OWED interactions and assessing the frequency of collisions to help validate CRMs.

4.2. Modeling

CRMs are mathematical models that incorporate empirical data on OWED characteristics, the density of birds using the proposed area, and flight behavior to estimate collisions. Model outputs are highly sensitive to input parameters (Chamberlain et al., 2006; Masden et al., 2021). Inputs are values related to turbine infrastructure and operation, including turbine layout, dimensions, and rotor speeds; and those related to birds, including flight speed, flight height, avoidance behavior, and morphometrics. CRMs tend to be most sensitive to the parameters related to bird behavior (Masden and Cook, 2016). Results have highlighted the sensitivity of CRMs to assumptions around species avoidance behavior (Chamberlain et al., 2006; Masden et al., 2021). As a result, there has been considerable focus on studies that reduce this uncertainty, either through reviewing and collating data from existing OWEDs (e.g., Cook et al., 2018), or through novel data collection methodologies (e.g., Skov et al., 2018) to quantify micro-avoidance rates. More recently, analyses have highlighted the importance of additional input parameters, including flight height and speed (Masden et al., 2021).

CRMs are typically parameterized with generic flight height and speed values from multiple sites and species using boat-based data (Alerstam et al., 2007; Johnston et al., 2014; McGregor et al., 2018). These generic values are subject to significant uncertainty. For example, actual flight-speed data show temporal, spatial, and behavioral variability (Fijn and Gyimesi, 2018; Masden et al., 2021). Accounting for these differences a priori when generating model outputs can be important for resource managers because they can have significant implications for permitting decisions (Masden et al., 2021). A wide range of technologies (e.g., GPS tags (Ross-Smith et al., 2016), altimeters (Cleasby et al., 2015), LiDAR (Cook et al., 2018), radar (Fijn et al., 2015), and optical rangefinders (Borkenhagen et al., 2018; Harwood et al., 2018)) are available for measuring both flight height and speed to improve model input accuracy (Largey et al., 2021).

CRMs typically output an estimated annual collision rate for a single OWED site. These site-specific estimates may include birds from multiple colonies, sexes, and age classes, though some marine bird species have sex differences in foraging distributions (Stauss et al., 2012), and analysis of wind turbine collision fatalities in at least one species has indicated sex-biased mortality during breeding (Stienen et al., 2008). Consequently, it is important to apportion predicted collisions to the appropriate breeding colonies to properly account for potential mortality across metapopulations. Refined estimates can then be used within population models to assess the population level consequences of these collisions (e.g., Cook and Robinson, 2017).

Model transparency is critical because CRM outputs can have significant policy ramifications (Broadbent and Nixon, 2019; "Reclaiming motions in the petitions by the Royal Society for the Protection of Birds against the scottish ministers and (first) Inch Cape Offshore Ltd; (second) Neart Na Gaoithe Offshore Wind Ltd; and (third) Seagreen Wind Energy Ltd for judicial review, 2017). Comparing outputs from multiple CRMs can provide a more conservative estimate of the range of collision impacts. However, few studies have attempted to compare outputs from different models (though see Kleyheeg-Hartman et al., 2018) in part due to a general lack of publicly available data and code to recreate and run models (Masden and Cook, 2016).

4.3. Mitigation

Minimizing the probability of collision with OWED requires consideration of: 1) structural design, layout, and operational schedule, 2) the behavior of vulnerable species, and 3) environmental conditions during encounters (Arnett and May, 2016). Data on effective measures to minimize collision with OWED are limited and most measures described here are derived from terrestrial examples. There is limited evidence for the application of terrestrially derived collision mitigation solutions to the marine environment, creating a need to develop and evaluate approaches to risk minimization for marine applications.

Although visual stimuli presented by wind turbines and multi-turbine developments likely induce avoidance among some marine birds, it is unclear which visual cues are most important, how such responses affect life history parameters (survival, reproduction), and how response might attenuate with repeated exposure. The size, number, orientation, and spacing of turbines may be important, though evidence is mixed (Arnett and May, 2016). Although not independent of turbine size, slower rotor and blade tip speeds have been associated with lower mortality, perhaps in part due to the relationship between rotation speed, blade visibility, and individual avoidance behaviors (Marques et al., 2014).

The efficacy of turbine shutdown or curtailment during key times as a minimization approach is poorly understood. On land, one of the few studies to examine non-directed curtailment found it to be ineffective for reducing mortality among most bird species, though there was some evidence of possible efficacy for some raptor species (Smallwood and Bell, 2020). There is good evidence that targeted curtailment (e.g., shutdown of specific turbines when species of interest are detected nearby) can be effective for some raptor species (Arnett and May, 2016; McClure et al., 2021). For highly threatened species, human observers and automated detection technologies have been used to shut down turbines when species of special conservation concern approach (Allison et al., 2019).

Active deterrence and alterations to turbine visibility may have limited capacity to reduce collisions. Many birds have limited frontal binocular fields of view and tend to have downward-focused vision while foraging (Martin, 2011). Nonetheless, some measures have been proposed for terrestrial wind energy developments to increase turbine visibility. These include using distinguishing patterns and colors such as black-and-white bands, a single black blade, or blades painted with UV reflective colors (Defingou et al., 2019; Marques et al., 2014; May et al., 2020). The efficacy of these measures depends on species' sensitivity to the stimuli. There is some evidence that active deterrence techniques such as acoustic deterrence may reduce raptor collision risk; however, habituation of birds to the stimuli often reduces efficacy and these techniques have not been tested in marine environments (Allison et al., 2019). There are substantial gaps in knowledge regarding the degrees of efficacy and habituation that may occur for different deterrent technologies, bird taxa, and deployment situations (Enos et al., 2021).

Birds can be attracted to lights, resulting in collision, disorientation, and exhaustion (Defingou et al., 2019; Kerlinger et al., 2010). Evidence from lighted offshore research platforms indicates that collision risk with infrastructure in the offshore environment may be greatly increased for nocturnal migrants during periods of reduced visibility and poor weather when there is substantial sustained lighting (Hüppop et al., 2006). During OWED construction and maintenance, deck and navigation lighting is common. During operation, shipping and aviation safety lighting is required. Some nocturnally active marine birds exhibit spectra-specific avoidance behavior when exposed to artificial light (Syposz et al., 2021). However, light attraction is a greater risk and trying to deter some birds with light could possibly result in greater risk to other species. It is therefore best practice to reduce the amount and duration of lighting on OWED. Good practices include minimizing deck lighting, ensuring that light sources are shaded and directed downward, and avoiding broad-spectrum lights whenever possible (Defingou et al., 2019). For aviation and communications lighting, terrestrial studies have shown that bird fatalities are significantly reduced by installing flashing rather than steadily illuminated lights (Gehring et al., 2009; Kerlinger et al., 2010). Aviation light impacts can be further minimized by illuminating lights only when the adjacent airspace is occupied. On German installations, this reduces aviation lighting by over 99 % (Defingou et al., 2019). This type of technology appears likely to be required for commercial-scale OWEDs in the U.S. (BOEM, 2021a, 2021b). Roosting opportunities can be limited through structural design and deterrence, including installation of anti-perching infrastructure, although it is unclear if perching behavior increases collisions.

5. Cumulative impacts

Cumulative impacts from multiple OWEDs can be additive or greater than the sum of individual impacts (Masden et al., 2010). To fully understand the consequences of OWED on seabirds it is essential to understand the impact on populations, which requires estimates of OWED impacts on demographic rates (Sandvik and Erikstad, 2008). However, OWED impacts may be manifested within the context of cumulative impacts across multiple developments within the species' ranges as well as other natural and anthropogenic stressors (Goodale et al., 2019; Horswill et al., 2022). In the United States, the National Environmental Policy Act requires the consideration of the cumulative impacts to the environment, and the Environmental Impact Assessment Directive of the European Union likewise requires assessment of cumulative impacts (Masden et al., 2010). To adequately assess cumulative impacts of wind energy development on a marine bird species, we must understand the: 1) range of OWED impacts and how these affect demographic rates (e.g., mortality, decreased reproductive output, immigration, emigration), 2) expected scale of the industry at full buildout (e.g. number of developments, number of turbines), 3) proportion of population or species impacted, and 4) the impact of other stressors on demographic rates (e.g., introduced species, fisheries bycatch, shipping, climate change). For seabirds, Population Viability Analysis (hereafter PVA) has been used to assess multiple impacts to populations from human and natural stressors (Horswill et al., 2022), and can also be used for modeling cumulative impacts. However, demographic rates are often highly variable, and it may be difficult to detect OWED impacts on these parameters (Clark, 2003; Horswill et al., 2022).

Generally, cumulative impact assessments are conducted at the individual project level by developers and regulators but are likely more informative when all potential developments are considered for a region (Masden et al., 2010). This approach may require that the cumulative assessment be conducted by a regulatory body, as was done for the Vineyard Wind 1 supplemental environmental impact assessment (BOEM, 2020), rather than individual developers, and would provide the ability to pool resources among projects to facilitate data acquisition needed for cumulative impact assessment, monitoring, and mitigation. Masden et al. (2010) point out the lack of rigor and consistency across many assessments of cumulative impacts of wind energy developments and have proposed a framework that accounts for the full scope of actions, impacts, and scales of development (also see Willsteed et al., 2018). Such a framework would be useful for creating a robust process for assessing the cumulative impacts of wind energy development that provides transparency for both developers and regulators. In addition, due to natural variability in demographic rates and uncertainty in linking stressors explicitly to demographic rates, a precautionary approach is generally used (Miller et al., 2019). Mitigation of OWED impacts within the context of other stressors can be complicated, but compensatory mitigation (discussed in following section) provides a feasible and precautionary approach to compensating for cumulative effects.

5.1. *Monitoring*

Assessment of demographic parameters and population abundance trends (generally at breeding sites) are essential for assessing population viability and the cumulative impacts of OWED and other stressors on species or populations thought to be at risk from OWED. However, direct measurement of demographic and population trends may be costly, invasive, or difficult. In addition, such measurements may be difficult for non-colonial species or species with breeding colonies in locations that are difficult to access or not well-identified. Off-site monitoring is most likely to produce useful results when 1) historical demographic data are available, 2) measurements of demographic and population trends are relatively easy to obtain, and 3) monitoring approaches are standardized, and data are made publicly available, such that data from small-scale studies can be aggregated to examine cumulative impacts.

It is important to directly measure changes in population sizes of species that are highly threatened or suffer from severely reduced population sizes as a method to monitoring change when feasible. However, population size is often a relatively insensitive measure of changes to populations due to time lags between demographic impacts and population responses (particularly for long-lived marine birds with delayed age of first reproduction). Thus, it can also be useful and more feasible to empirically measure changes in demographic parameters that indicate changes in fitness (e.g., reproductive success, adult, or juvenile survival rates) (e.g., Maclean et al., 2007; Searle et al., 2022). For colonial-breeding marine birds, demographic data and population trends can be monitored at accessible breeding sites. However, it is important to recognize that demographic rates and population trends are naturally variable, making it difficult to differentiate any observed changes in survival due to individual OWED impacts from other factors such as natural variability, fisheries, disturbance, or predation (Cook and Robinson, 2017).

5.2. Modeling

Population modeling provides a rigorous statistical framework for translating the multiple impacts of OWED and other stressors on individuals into population or species-level impacts (Beissinger and McCullough, 2002; Soulé, 1986). Population viability analysis (PVA) is a set of conceptual and computational tools widely used to estimate future population trajectories and extinction risk. PVAs underpin ornithological OWED assessments and are considered best practice for understanding the population-level consequences of predicted impacts on marine birds (Horswill et al., 2022; Searle et al., 2022). PVAs can be used to forecast future population trajectories under baseline conditions, in the presence of individual OWED sites, or in the presence of cumulative sites throughout a region. In addition, PVAs can be used to examine trajectories that include multiple additional cumulative stressors, including fisheries bycatch, invasive species impacts, and climate change effects (e.g., Freeman et al., 2014; Maclean et al., 2007; Ruiz et al., 2021).

Several reviews of appropriate PVA model structure and parameter specification for marine birds considering OWED have been conducted (Cook and Robinson, 2017; Freeman et al., 2014; Horswill and Robinson, 2015; Maclean et al., 2007; Potiek et al., 2022; Searle et al., 2020; Trinder and Furness, 2015). These reviews identified varying methods depending upon the focus of the study, life history characteristics of the focal species, and/or availability of data at focal colonies. Most PVAs focusing on marine birds have used matrix population models to evaluate OWED impacts (Caswell, 2006), which provide a flexible, unifying statistical framework for linking impact to demography and abundance. For any form of PVA, including population models, input data on demographic rates are essential, particularly breeding success and age-specific survival. PVA best practice involves leveraging inference from multiple data sources, including data on breeding success, mark-resighting data on survival, population abundance counts, and integrated population modeling methods to estimate population demographic parameters with uncertainty (Freeman et al., 2014; Jitlal et al., 2017; Searle et al., 2020). It is also essential to use model calibration and validation techniques to develop robust PVAs. By running PVA models retrospectively, predicted trends can be compared against the observed trends seen in the population abundance data.

PVAs provide a data-based approach to quantify the magnitude of the impact of additional mortality due to collisions and/or displacement, generally by comparing estimated population trajectories in the impacted vs. unimpacted scenario. Such comparisons often are required in environmental impact assessments for OWED (Cook and Robinson, 2017). To compare impacted and unimpacted scenarios at the population level, PVAs require estimations of OWED impacts to key demographic parameters, and a mechanism for establishing connectivity between focal OWEDs and affected seabird populations. Outputs of models that produce these estimates (e.g., CRMs) are typically OWED-specific. Empirically measured or model-derived marine bird abundance and demographic estimates should underpin these models. Unfortunately, local or regional estimates for demographic parameters, particularly adult and immature survival, are lacking in many marine bird species, especially among non-colonial breeders. In addition, marine birds are generally colonial breeders that often nest in dense colonies across multiple islands (i.e., a meta-population) with potentially different demographic parameters. These data limitations introduce considerable uncertainty, affects model outputs (Searle et al., 2020), and may make PVAs infeasible for some species. PVA parameter sensitivity analysis can help identify where model inputs should be refined (e.g., Donovan et al., 2017).

It is important that impacted species are partitioned into distinct populations (often individual breeding colonies) or meta-populations via the process of apportioning (assigning birds seen at sea to focal populations or breeding colonies). Apportioning is critical for accurately determining the long-term trajectories of affected species. Large-scale collection of GPS tracking data from multiple breeding colonies and multiple species over several years provides robust and defensible methods for apportioning populations (Searle et al., 2020). Unfortunately, GPS tracking is only possible for a limited subset of species and excludes taxa that cannot be feasibly, safely, and reliably tracked (Wilson and McMahon, 2006). Where GPS tracking is infeasible, at-sea survey data have been used to develop decay-distance equations during the breeding season (NatureScot, 2018) and Biologically Defined Minimum Population Scales during the non-breeding season (Furness, 2015) to apportion birds to distinct populations, colonies, and broad regions. Although these techniques provide estimates and may contain biologically unrealistic assumptions, these data are more readily available over large areas and may include much longer temporal periods than tracking data. In the non-breeding season, marine birds can be more far ranging, which complicates apportioning. Satellite or GPS tracking may be used for some marine bird species over long enough timescales to cover both breeding and non-breeding periods (Buckingham et al., 2022; Duckworth et al., 2022; Heinänen et al., 2020). However, for many species of concern, such tags are not available due to geographical, size or weight restrictions. In these species, geolocation data collected using small, long-lasting light-level data loggers can be used for apportioning outside of the breeding season (Rayner et al., 2011), although this method can have relatively large spatial uncertainties (~100–200 km; Merkel et al., 2016).

Thus far, PVA-based assessments of OWED impacts to marine birds primarily have used static estimates for demographic parameters. However, there is growing evidence that additional factors (e.g. density dependent processes or climate-driven changes) are strongly shaping PVA outputs (e.g., Horswill et al., 2022; Searle et al., 2022). As a result, PVAs may need to be developed that incorporate predicted dynamic, pressure-driven changes among key demographic parameters. In the absence of empirical data, expert elicitation of estimated impact of severe pressures on demographic rates of focal populations could be used in PVAs to explore interactions between potential climate-driven changes and impacts from OWED on population trends. It will be necessary to develop alternative approaches for risk assessment of populations where sufficient data collection to inform PVAs isn't feasible or timely to inform OWED (Horswill et al., 2022).

6. Compensatory mitigation

Compensatory mitigation, or "offsetting", is the step in a mitigation hierarchy that facilitates net positive impacts of development (Moilanen and Kotiaho, 2021). Compensatory mitigation compensates for impacts that cannot be avoided or minimized (Arnett and May, 2016; Kiesecker et al., 2010) by funding reduction of alternate threats to populations away from the site of the direct focal impacts. For example, under the U. S. Bald and Golden Eagle Protection Act, terrestrial wind energy developments may compensate for eagle collisions that can't be prevented via avoidance and minimization measures at the wind energy facility by funding retrofits to existing power lines that reduce electrocution-related eagle mortality (U.S. Fish and Wildlife Service, 2013). Compensatory approaches can facilitate effective mitigation for an array of impacts. Such approaches are regularly applied to mitigate habitat loss, for example, and compensatory mitigation has been suggested as a viable approach to seabird conservation in the context of offsetting seabird bycatch in marine fisheries (Wilcox and Donlan, 2007).

While it is essential to utilize avoidance and minimization approaches to reduce OWED impacts, limitations on feasible mitigations with each approach will make elimination of impact impossible with these techniques alone. Compensatory mitigation can be used to offset residual OWED impacts to achieve no net loss or even net gain of marine bird populations (Bennett et al., 2017), and may be the best approach to prevent cumulative impacts from causing population declines across regional and international scales. Based on experience from Europe and the United Kingdom, a strategically coordinated approach to compensatory mitigation can work well for addressing OWED impacts to marine birds (Hooper et al., 2021).

Anthropogenic threats to marine birds, while numerous, are relatively well known (Dias et al., 2019; Spatz et al., 2014). Some of these threats have proven solutions that provide significant population benefit (Brooke et al., 2018; Jones et al., 2008; Spatz et al., 2017), and thus may be good candidates for compensatory mitigation actions. Because marine birds are far-ranging and often migrate across ocean basins, they may interact with offshore wind energy facilities at great distances from locations where compensatory mitigation actions may be most effective, potentially including multiple international jurisdictions (Beal et al., 2021; Wolf et al., 2006). For this reason, enactment of compensatory mitigation plans should be considered on broad regional scales. Compensatory measures should be selected for maximum efficacy on a species-by-species basis. Well-tested conservation measures for marine birds include:

- Invasive species removal at breeding colonies. Invasive predator removal at breeding sites can reduce adult mortality and increase reproductive success in marine birds (Brooke et al., 2018). The tools and efficacy of predator removal are well established; globally, there have been 1550 eradication attempts on 998 islands, with an 88 % success rate (Spatz et al., 2022).
- Establishment of new colonies in biosecure areas through social attraction and/or translocation. This approach will be most viable as compensation for OWED impacts in instances where the breeding colonies of species impacted by OWED are under alternate threats (e.g., human development, sea level rise). Site selection for colony creation should prioritize predator-free islands over fenced areas because predator-proof exclosures require long-term maintenance and periodic replacement. Nesting sites can be further protected by establishing formal protected areas and actively reducing disturbance and by managing threats (Spatz et al., 2017; Wolf et al., 2006).
- Fisheries bycatch reduction (Croxall et al., 2012). Fisheries bycatch is a primary conservation concern for many marine birds, and reduction is feasible and highly effective (Anderson et al., 2011). By supporting the costs and implementation of regulatory changes and implementing bycatch reduction techniques, impacts could be reduced to negligible levels for some species (Avery et al., 2017; Beal et al., 2021; Bull, 2007; Good et al., 2020).

PVAs should be used to model changes in population size under different management scenarios and select compensatory mitigation plans for affected species that will boost populations sufficiently to offset estimations of OWED impacts. Monitoring will also be necessary to validate PVA predictions. The approaches outlined above may not be effective for all species affected by OWED (e.g., non-colonial species), in which cases alternate compensation measures should be explored and monitored to ensure efficacy of new approaches.

7. Discussion

Reduction of global climate change impacts is essential for conservation of marine ecosystems, and offshore wind energy will be a critical element of plans to meet global goals to reduce carbon dioxide emissions. However, the immediate impacts of OWED remain difficult to predict, quantify, and mitigate. Marine bird populations face an array of threats, and many species are of significant conservation concern. It will therefore be critical to quantify the additional impacts of OWED in the context of cumulative risks to ascertain the long-term viability of populations and effects of direct conservation efforts.

Current data limitations require managers and regulators to contend with significant uncertainty around quantification of impacts. For example, although CRMs have been used to evaluate potential impacts on species in Biological Assessments that are listed on the U.S. Endangered Species Act (BOEM, 2021c, 2021d), results are generally not included in construction and operation environmental risk assessments due to uncertainty in validating model outputs. Ongoing collection of data and development of new technology to validate models and reduce model uncertainty are essential. However, the rate of new development of OWED necessitates timely implementation of risk mitigation frameworks in the face of this uncertainty. Models should therefore be used to provide precautionary estimates of marine bird impacts as starting points for mitigation plans that may be further refined as data becomes increasingly available. Where these precautionary estimates of impact are significant and necessitate extensive mitigation, additional emphasis may be placed on collection of data to refine estimates.

Avoidance of impact is a critical first approach in an effective impact mitigation hierarchy. Strategic siting of OWEDs may allow avoidance of impacts in high-use areas for marine birds. However, site selection considerations must not only include reduction of impacts to marine birds, but also balance tradeoffs with infrastructure requirements, other wildlife impacts, and stakeholder conflicts. Alterations to turbine layout, infrastructure, and operational procedures may also be important elements of a comprehensive impact avoidance framework. However, these techniques are not yet well tested in the marine environment, and even if shown to be effective, may be difficult, expensive, or impossible to retroactively implement for existing OWEDs. Therefore, a compensatory mitigation strategy will be an important addition to these measures. Determinations of appropriate levels of compensation remain challenging, given difficulties quantifying the population-level impacts of collision and displacement, and collaborative processes will be needed to inform this process.

Regulatory agencies are encouraged to find mechanisms that compel developers to undertake scale-appropriate mitigation that includes off-site compensatory mitigation even when there is uncertainty regarding OWED impacts to vulnerable populations (Goodale and Milman, 2016). Refining management recommendations will require regional efforts by responsible agencies to compile data on cumulative impacts, population trajectories, and other demographic data needed to predict species-level impacts and to develop effective, comprehensive compensatory mitigation plans (Goodale and Milman, 2016). It can often be more cost effective to combine compensatory mitigation resources among several projects to fund one larger, permanent restoration action. Such comprehensive plans may be funded and implemented through a conservation banking approach, where the comprehensive plan is supported by multiple project developers and resource managers within a region. Mitigation banking has been successfully applied in a broad range of biodiversity conservation applications by international government agencies and private industry (Carreras Gamarra and Toombs, 2017; Gelcich et al., 2017).

In the United States, there will be significant OWED, with a projected 30 GW installed by 2030 (Musial et al., 2021). For non-listed marine bird species in US waters, the Migratory Bird Treaty Act will serve as the primary legal regulator of incidental take from OWED. A framework similar to that proposed here has been used successfully in the US to regulate and respond to incidental take of Bald and Golden Eagles from onshore wind energy facilities (U.S. Fish and Wildlife Service, 2013). This includes the consideration of impacts at a regional scale and in the context of other threats to eagle populations. Mitigation banking and in-lieu fee programs are used by regulators to compensate for incidental eagle take following construction of terrestrial wind energy facilities. Implementation of a similar regulatory framework for mitigation of marine bird impacts due to OWED will be essential in the United States as the industry progresses.

A successful framework to assess and mitigate the impacts of OWED on marine birds has the potential to result in a win-win: development of

Table 1
Offshore wind energy development impact assessment and mitigation approaches to be utilized following broad-scale vulnerability assessment for species in a region, and recommendations for further development of methodology and technology.

	Displacement impacts	Collision impacts	Cumulative impacts
Monitor	Boat-based surveys Aerial surveys Individual tracking Radar Before-After Gradient surveys	Autonomous monitoring: Radar Passive acoustic Photogrammetry and video Autonomous collision detection Individual tracking	Offsite population monitoring to assess vital rates and movement within metapopulations
Model	Species Distribution Models Individual Based Models	Species Distribution Models Collision Risk Models (CRMs)	Population Viability Analyses
Mitigation type	Avoid Minimize	Avoid Minimize	Compensate
Mitigation approach	Site Selection	Site selection Site-specific infrastructure and operational alterations	Compensatory Mitigation
Recommendations	Resolve challenges inherent in displacement modeling approaches related to the difficulty of translating the direct and indirect impacts of displacement into changes in demographic rates.	Develop technologies and methodologies to record collision incidents in the offshore environment. Validate CRM structures using confirmation of collision incidents to ensure inclusion of the right parameters to predict risk and accurately value the relative importance of each parameter. Investigate the efficacy of deterrents, curtailment, and other operational impact minimization options for marine birds.	Integrate compensatory mitigation and conservation banking options into existing regulatory frameworks and facilitate compensatory mitigation projects at scales equal to the cumulative impact of planned projects. Share access to model code to ensure transparency in assessments and to resolve concerns surrounding uncertainty and variability of available input parameters that may decrease confidence in model predictions. Identify and resolve model and data limitations where possible.

essential renewable energy infrastructure and conservation of vulnerable marine bird populations. Key elements include transparent, feasible and rigorous impact assessment, monitoring, and mitigation. We also highlight some elements of the mitigation framework that will need to be addressed to facilitate the implementation of the framework (Table 1). An adaptive management approach to monitoring mitigations will assure their efficacy in addressing impacts. Finally, a precautionary approach, especially in the face of monitoring and modeling uncertainty, will provide incentives for the industry to improve monitoring and modeling methodologies to reduce these uncertainties to the benefit of marine birds.

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Declaration of competing interest

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

Data availability

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