Offshore Wind and Aerofauna: Avoidance Remains the Best Bet Amid Limited Mitigation Evidence

Julia Gulka[1], Steve Knapp[1], Anna Soccorsi[1], Stephanie Avery-Gomm[2], Paul Knaga[3], and Kathryn A. Williams[1]

[1] *Biodiversity Research Institute, 276 Canco Road, Portland Maine, 04013 USA*
[2] *Environment and Climate Change Canada, Science and Technology Branch, Wildlife and Landscape Science Directorate, 1125 Colonel By Drive, Ottawa, Ontario, K1S 5B6*
[3] *Environment and Climate Change Canada, Canadian Wildlife Service, 45 Alderney Dr Dartmouth NS B2Y 2N6*

Corresponding Author: Stephanie Avery-Gomm, Stephanie.Avery-Gomm@ec.gc.ca

ABSTRACT

Offshore wind energy (OSW) development is a vital strategy for reducing global reliance on fossil fuels but also poses environmental challenges that require mitigation. A diversity of approaches exist for mitigating (e.g., avoiding, minimizing, or compensating for) the effects of OSW development on aerofauna (birds and bats), but little is known about the effectiveness of many of these approaches. To address this knowledge gap, we reviewed the scientific and gray literature to evaluate the evidence base for proposed mitigation approaches for OSW and aerofauna. Given limited data from the OSW sector, we included studies from other industries where relevant (e.g., terrestrial wind energy, offshore oil and gas industry, other maritime and terrestrial industries). Of a total of 211 mitigation approaches relevant to OSW that were described in 183 source documents, most approaches focused on minimization, with far fewer addressing avoidance or compensation. Sixty-one percent (128 approaches) had no evidence of being tested in the reviewed literature. Of the 83 mitigation approaches that were field tested or implemented, we found evidence of effectiveness for only 41 approaches. This included approaches tested and implemented in other industry contexts; however, specific to the OSW sector, we found evidence of effectiveness for only 10 approaches. Consequently, 86% of all the mitigation approaches identified in this review lacked any evidence of effectiveness. For birds, minimization approaches related to lighting (e.g., reducing artificial light, avoiding white and steady-burning lights) were the most tested and effective methods for reducing maladaptive attraction and collisions. For bats, minimization approaches involving adjustments to turbine operations (e.g., curtailment and feathering of turbine blades) were most tested and effective methods for reducing collisions. Given the limited evidence of effectiveness for most approaches, dedicated testing of mitigation measures is urgently needed to mitigate the environmental challenges posed by the OSW industry. Until such evidence becomes available, avoidance of effects (via careful siting of industrial activity and related measures) remains the single best available option for mitigating impacts to aerofauna. To fully address the effects of OSW development on aerofauna, compensation and offset strategies should also be further explored.

Résumé

Le développement de l'Énergie Éolienne Extracôtière (EEE)est une stratégie vitale pour réduire la dépendance mondiale aux énergies fossiles, mais il pose des défis environnementaux qui nécessitent des mesures d'atténuation. Il existe une diversité d'approches pour atténuer (e.g. éviter, minimiser ou compenser) les effets du développement de l'EEE sur les oiseaux et les chauves-souris (aérofaune), mais l'efficacité de nombreuses de ces approches est encore peu connue. Pour combler ces lacunes, nous avons passé en revue la littérature scientifique et la littérature grise afin d'évaluer les données probantes concernant les mesures d'atténuation proposées pour l'EEE et l'aérofaune. Étant donné la quantité limitée d'information disponible dans le domaine de l'EEE, nous avons inclus des études d'autres industries lorsque cela était pertinent (e.g., l'énergie éolienne terrestre, l'industrie pétrolière et gazière extracôtière et d'autres industries maritimes et terrestres). Sur un total de 211 approches d'atténuation pertinentes pour l'EEE, décrites dans 183 documents sources, la plupart des approches se concentraient sur la minimisation, avec beaucoup moins d'approches portant sur l'évitement ou la compensation. Soixante-et-un pourcent (128 approches) des approches proposées dans cette revue ne semblent pas avoir été testées.. Parmi les 83 approches d'atténuation qui ont été testées sur le terrain ou mises en œuvre, nous avons trouvé des preuves de leur efficacité pour seulement 41 approches. Ceci comprend les tests et la mise en œuvre dans d'autres scénarios industriels que l'EEE; cependant, spécifiquement pour le secteur de l'EEE, nous avons trouvé des preuves d'efficacité pour 10 approches. Par conséquent, 86 % des approches d'atténuation identifiées dans cette revue de la littérature n'étaient appuyées par aucune preuve d'efficacité. Chez les oiseaux, les approches de minimisation liées à l'éclairage (e.g., réduction de la lumière artificielle, éviter les lumières blanches et fixes) étaient les méthodes les plus couramment testées et les plus efficaces pour réduire l'attraction et les collisions. Chez les chauves-souris, les approches de minimisation impliquant la modification du fonctionnement des turbines (e.g., réduction de la vitesse de rotation ou mise en drapeau des hélices) étaient les méthodes les plus couramment testées et les plus efficaces pour réduire les collisions. Étant donné les preuves limitées d'efficacité pour la plupart des approches, des tests dédiés sur les mesures d'atténuation sont urgemment nécessaires afin d'atténuer les défis environnementaux posés par l'industrie de l'EEE. Jusqu'à ce que de telles preuves soient disponibles, l'évitement des effets (via un choix judicieux des sites d'implantation des activités industrielles et la mise en place de mesures connexes pour éviter les effets sur la faune et ses habitats) reste la meilleure option disponible pour atténuer les impacts sur l'aérofaune. Pour atténuer pleinement les effets du développement de l'EEE sur l'aérofaune, des stratégies de compensation devraient également être étudiées plus en détail.

KEYWORDS

Avoidance, aerofauna, effectiveness, minimization, mitigation, offshore wind energy development, review

Offshore wind energy (OSW) development is a vital strategy for reducing global reliance on fossil fuels but also poses environmental challenges that require mitigation (Peste et al. 2015). Many bird and bat ("aerofauna") species worldwide are in decline and are protected at state, provincial, federal, or international levels (Dias et al. 2019, Frick et al. 2020, Neate-Clegg et al. 2020). Within this context, it is critical to consider the potential effects of OSW developments on these aerofauna. There are three main types of effects to aerofauna from OSW development: collisions, behavior change (e.g., avoidance, attraction), and habitat-mediated change (e.g., changes in prey; Williams et al. 2024). Although our scientific understanding of the scale of these effects varies widely and significant gaps remain, several comprehensive reviews have synthesized the current state of knowledge on how OSW development effects birds and bats (Marques et al. 2014, Goodale and Stenhouse 2016, Fox and Petersen 2019, Solick and Newman 2021, Lamb et al. 2024, Williams et al. 2024). These reviews highlight pathways of effects that can inform mitigation strategies. Currently, a variety of mitigation measures are used by the OSW industry, but there is limited information about the effectiveness of many approaches to effectively mitigate the effects of developments on birds and bats.

Overview of offshore wind effects to aerofauna

Collisions of birds and bats with wind turbines is one of the primary mechanisms by which wind facilities – both onshore and offshore – have the potential to directly influence population size. Collisions may result from the long-term presence of OSW infrastructure (e.g., turbines and substations) in marine environments, as well as changes in wildlife behavior (e.g., attraction) or habitat-mediated changes (e.g., increased prey near turbines). Collisions of migrating birds (e.g., songbirds, raptors) are well documented at onshore facilities (Allison et al. 2019) and concerns over high mortality levels, particularly for migratory bats, has driven significant efforts to monitor and mitigate collision risks in the onshore wind industry (e.g., Adams et al. 2021, Whitby et al. 2021). Offshore, monitoring collisions is far more challenging; carcass searches, a key detection method onshore, are largely impossible in the marine environment. Existing evidence, while limited, suggests that collisions of marine birds with OSW

facilities in Europe (documented via direct observation and camera systems) appear to be much rarer than in terrestrial contexts (Skov et al. 2018, Tjørnløv et al. 2023), though the extent of this phenomenon remains poorly documented. To address monitoring limitations, collision risk models are often employed to predict effects to bird species of interest at individual wind farms and to inform potential mitigation measures (Cook et al. 2025). However, the effectiveness of these strategies in the OSW context remains unclear, underscoring the need to critically evaluate existing approaches and identify those capable of effectively mitigating injury and mortality risks for birds and bats.

Behavioral responses can include avoidance, attraction, and displacement of animals from their ideal distributions due to the presence of structures and associated vessels (Williams et al. 2024). Behavioral change has been documented for a range of marine bird species at offshore wind facilities in Europe, with the type and degree of attraction or avoidance depending on many factors including species, facility location and design (Dierschke et al. 2016, Lamb et al. 2024). Attraction may be due to increased opportunities for perching and roosting (Dierschke et al. 2016), lighting on turbines and substations (Rebke et al. 2019), or habitat-mediated change (e.g., increased prey; Russell et al. 2014). In general, lighting on offshore wind turbines, vessels, and substations has been identified as a potential risk to aerofauna, (Williams et al. 2024). Some species of birds may be attracted to and disoriented by artificial light at night, particularly during migration; this can lead to death via collisions or exhaustion (as they circle the light source for long periods; Montevecchi 2006, Burt et al. 2023). Though less commonly reported, artificial light may also cause avoidance in some species of seabirds (Syposz et al. 2021). For bats, artificial lighting is an attractant, in part due to the attraction of insects on which bats feed (Stone et al. 2015), although at least one study suggests that lighting of onshore turbines does not affect bat mortality rates (Johnson et al. 2003).

Avoidance of individual turbines within the wind farm footprint (meso-avoidance), and avoidance of the entire offshore wind facility (macro-avoidance) with resultant changes in distributions (e.g.,

displacement) may relate to the presence of the offshore wind facility infrastructure itself, or associated activities, such as vessel traffic (Cook et al. 2018). Behavioral response may also be a result of sound during construction or operations or electromagnetic fields and other sensory changes (e.g., heat or vibration), most of which occur underwater at OSW facilities.

Another way OSW developments affects aerofauna is through changes in the physical environment and/or resource availability (i.e., habitat-mediated effects). There are multiple stressors that may influence aerofauna (particularly marine birds) around offshore wind facilities via changes in water quality, community alteration, introduction of invasive species, scouring, and bottom disturbance. In addition, the presence of the structures themselves may lead to changes in resources (e.g., artificial reef effect; Degraer et al., 2020). All of these may lead to changes in the physical environment that individuals experience, and may also influence the distribution, abundance, and structure of prey communities.

The mitigation hierarchy

Mitigation of effects such as those posed to aerofauna by the OSW industry is guided by the well-established mitigation hierarchy, which prioritizes measures that avoid potential effects altogether as the most effective strategy, followed by minimization of unavoidable effects, and finally, compensation for residual effects that cannot be avoided or minimized (Council on Environmental Quality 2020). This hierarchy provides a structured framework for addressing the effects of anthropogenic activities, ensuring that efforts first aim to prevent harm before attempting to reduce or compensate for it. Hereafter, the term ‘mitigation’ is used to encompass all three steps of this hierarchy.

Avoidance measures are generally implemented during early planning phases of OSW development and typically involve siting decisions, such as locating wind energy areas, lease areas, or individual wind farms away from regions with high risks to aerofauna (Winiarski et al. 2014, Croll et al. 2022). Minimization primarily occurs during pre-construction and operational phases, and may include

153 adjustments to facility design (e.g., micro-siting, turbine size/height, lighting, perching deterrents) and
154 operational parameters (e.g., cut-in speeds at which turbines begin generating electricity). Compensation,
155 the final step, involves activities designed to offset effects that cannot be avoided or minimized, and may
156 include approaches such as creating habitat (e.g., new breeding, roosting, wintering sites) and improving
157 existing habitat through measures like invasive species removal or predator control (Wolf et al. 2006,
158 Croll et al. 2022, Spatz et al. 2022). Compensation aims to achieve net neutral or net positive outcomes
159 for affected populations and ecosystems (Kiesecker et al. 2010).
160
161 While various mitigation approaches have been proposed for the OSW developments, often drawing from
162 the terrestrial wind and offshore oil and gas industries, many mitigation measures remain untested in the
163 offshore wind context. Given the harsh and inaccessible nature of the offshore environment, it can be both
164 challenging and expensive to test mitigation strategies. Moreover, high environmental variability, often
165 coupled with low sample sizes for studies that are trying to measure change in these systems, create
166 challenges in achieving adequate statistical power to provide evidence of effectiveness (Maclean et al.
167 2013, Regional Synthesis Workgroup of the Environmental Technical Working Group 2023).
168 Additionally, wildlife species and their habitats may be affected by a range of effects and stressors, as
169 noted above, and the sensitivity and vulnerability of species varies in relation to a variety of factors, both
170 internal (e.g., demographics, life history), and external (e.g., facility layout, location). Consequently,
171 some mitigation measures have been implemented without sufficient evidence of their effectiveness,
172 potentially wasting resources and creating a false sense of confidence in their ability to reduce the effects
173 of OSW development.

174 **Study objectives**

175 The goal of this review is to assess the state of knowledge for mitigation for aerofauna in relation to OSW
176 development. Specifically, we compile an inventory of mitigation approaches that have been proposed for
177 use for OSW development across jurisdictions and draw insights from related industries given the nascent

178 state of the OSW sector in many regions. Our focus is on mitigation for aspects of OSW developments in
179 the marine environment (e.g., project footprint, cable and transit routes) as opposed to onshore aspects
180 (e.g., transmission interconnection), although some mitigation approaches may also apply to onshore
181 project components. In this study we summarize the weight of evidence supporting various mitigation
182 approaches, identify key knowledge gaps in our understanding, and propose criteria for prioritizing future
183 studies to examine the effectiveness of mitigation options for birds and bats in relation to OSW
184 development.

185 **METHODS**

186 To assess the state of knowledge of OSW development mitigation for aerofauna, we utilized the
187 Mitigation Practices Database Tool, an existing database of mitigation approaches relevant to wildlife,
188 fisheries, and OSW development. In part because information in the database only included literature
189 through 2018, we conducted an additional literature review to include additional sources, including more
190 recent relevant literature (2019-2023). This review (as well as the original database) drew from both the
191 peer-reviewed literature and gray literature, as 1) there is more evidence on OSW-wildlife effects and
192 related research available in the gray literature than the peer-reviewed literature, and 2) the gray literature
193 remains a main source of information to inform regulatory decision making (Szostek et al. 2024).

194 **Mitigation Practices Database**

195 In 2018-2019, the New York State Energy Research and Development Authority funded a desktop review
196 to aggregate and assess practices for minimization and avoidance of effects to fisheries and offshore
197 species (i.e., birds, bats, marine mammals, sea turtles, fish, and benthos) associated with all phases of
198 OSW development. This database, the Mitigation Practices Database (MPD) Tool
199 (https://www.nyetwg.com/mpd-tool), included sources relevant to aerofauna (n=107) that included peer-
200 reviewed and gray literature (e.g, agency reports, environmental assessments, technical guidance
201 documents) that were identified via Google Scholar (search terms: offshore wind + birds + mitigation;

offshore wind + bats + mitigation) and via an internal Biodiversity Research Institute Mendeley database (search terms: mitigation; mitigate; minimize). Additional sources were identified when cited by sources found with the search terms above and included where appropriate.

The structure of the database included information on the taxonomic group for which the mitigation was proposed or tested, the types of stressors and effects that were addressed, the phase of development, and evidence of effectiveness for the mitigation approach, among other information (Table 1). Effectiveness, in this context, was defined as the degree to which a mitigation approach was successful in producing the desired result, which assumes scientific rigor in data collection for such a conclusion.

Update to literature review

We conducted an additional literature review in 2024 to add sources not identified in the original database and to update information on mitigation approaches for aerofauna from 2019-2023. A series of literature searches were conducted (focusing primarily, though not exclusively, on sources from 2019-2023) using Google Scholar (search terms: bird+wind+mitigation; bat+wind+mitigat*; bat+wind+mitigat*+offshore; bird*+wind+mitigat*+offshore) and the Tethys Knowledge Base (Filters: Wind energy content + birds or bats; search term "mitigation"). These search methods were chosen to replicate the MPD Tool review process and ensure that key research texts from both the gray and published literature were included. The abstract or summary of each source was manually reviewed for initial relevance. If there was no mention of mitigation, avoidance, minimization, compensation, or offsetting, sources were deemed not relevant and were not reviewed further. The remaining sources were reviewed, and information was manually extracted following a similar structure to the MPD Tool, above. This initial filtering resulted in the identification of 129 additional sources, of which 73 were included in the literature review (the remaining 56 were deemed not relevant following a more in-depth review of the entire document). Combined with approaches from the MPD Tool, there were a total of 183 sources (n=111 peer reviewed, n= 72 gray literature). These sources focused on various industries, including offshore wind (n=76), terrestrial wind

227 (n=92), offshore oil and gas (n=15), other maritime industries (n=6), and generic or other industries (e.g.,

228 agriculture; n=35).

229

230 **Table 1.** Key types of information collated in review of mitigation options available for offshore wind
231 development for aerofauna, synthesized from the existing published and gray literature.

Type of Information	**Options**	**Definition**
Mitigation Category	Siting/Activity Restriction, Turbine Operation Parameters, Other Operations Parameters, Structure Configuration, Deterrence and Attraction Reduction, Lighting and Visibility, Compensation	High level categorization of mitigation approach
Resource	All Birds, All Bats, Marine Birds, Nocturnal Aerial Migrants	Functional species group for which mitigation approach is relevant, as defined in source document(s)
Stressors	Bottom Disturbance, Changes in Vessel Traffic, Light, Long-term Structures, Sound, Vibration, Water Quality Changes	External stimuli that can cause changes to the behavioral, physical, chemical, and/or biological characteristics of an organism or species, or the ecosystem inhabited by the organism/species
Potential Effects	Behavioral Disturbance, Displacement, Attraction, Habitat Fragmentation/Modification, Injury/Mortality, Community Alteration/Invasive Species	The changes to the behavioral, physical, chemical, and/or biological characteristics of an organism or species, or the ecosystem inhabited by the organism/species, due to stressors related to OSW development
Development Phase	Pre-construction, Construction, Operations and Maintenance, Decommissioning	Stage of offshore wind facility development/operation for which the approach is relevant, each of which encompass a number of activities and, as a result, may have different types of stressors
Industry Origin	Offshore Wind, Onshore Wind, Oil and Gas, Maritime, Generic/Other	Type of industry for which mitigation practice was suggested or implemented. Generic/Other used if unspecified or another industry (e.g., agriculture)
Mitigation Hierarchy	Avoidance, Minimization, Offset	Level of the mitigation hierarchy
Implementation Status	Not Implemented, Field Tested, Implemented, Implemented and Evidence of Effectiveness, Unknown	The degree to which the use or effectiveness of a mitigation practice was tested in the cited literature

232

Data synthesis

Mitigation approaches from the literature review update were synthesized with the original mitigation strategies included in the MPD Tool based on topical commonalities. For example, if a source from the updated literature review discussed the mitigation strategy 'paint turbine blades' and the same approach was already included in the MPD Tool, then data from the new source was synthesized with the original entry for that mitigation approach. However, if a new source identified a strategy not in the MPD Tool, it was added as a new mitigation approach. When examining the degree to which the various mitigation strategies have been tested for evidence of effectiveness, we summarized by source document rather than by mitigation approach, as an individual mitigation measure may have been suggested by multiple sources with various degrees of testing and evidence of effectiveness.

AVAILABLE MITIGATION APPROACHES

A broad range of mitigation approaches (n=211) were identified from the existing literature (n=183 sources; Appendix A-B), focusing on a variety of stressors, potential effects, and industries. There were 73 sources from the literature review update, of which 28 were incorporated into existing approaches in the MPD Tool, while 45 identified new approaches. There were a wider variety of mitigation approaches focused on birds (n=133) than bats (n=30), with some focused on both (n=48). About 15% of the total were specific to marine birds or nocturnal avian migrants, but most were relatively general. Despite the position in the mitigation hierarchy, minimization approaches were the most common (n=173), followed by avoidance (n=23), with the fewest compensation/offset-related approaches (n=14). Most mitigation approaches came at least in part from the onshore wind industry (66%), with about 45% focused on offshore/marine environments, including offshore oil and gas, offshore wind, and other maritime industries (Figure 1a); the remainder were "general" mitigation approaches that were either not suggested in relation to a specific type of industrial development, or for an industry not listed above (e.g., agricultural sector).

To aid in further summarization, we categorized mitigation approaches into 8 general categories within the mitigation hierarchy (Figure 1b): 1) avoidance measures (e.g., wind farm siting and seasonal restrictions/limitations on activities, other activity limitations; n=37), minimization measures involving 2) configuration of structures (e.g., wind farm layout, turbine size, n=28), 3) turbine operation parameters (e.g., curtailment, shutdown, feathering; n=38), 4) lighting to reduce attraction (n=31), 5) visibility and detection enhancement (n=12), 6) vessel operations and water quality (n=12), 7) deterrents and other attraction reduction measures (n=12), and finally, 8) compensation measures (n=15). The widest variety of suggested approaches was in the category of lighting and visibility enhancement (n=43), most of which were focused on birds (74%). The category of changes to turbine operations included the greatest number of bat-related approaches, mostly variations of curtailment, which is a key mitigation tool used for bats at onshore wind facilities (Adams et al. 2021, Whitby et al. 2021).

Almost three quarters of mitigation approaches (74%) focused on the presence of long-term structures (e.g., turbines, substations) as the primary stressor type, followed by lighting (23%) and changes in vessel traffic (14%; Figure 1c). The bulk of mitigation approaches focused on mitigating injury/mortality (85%) or behavioral disturbance (31%; Figure 1d). Within approaches focused on injury/mortality, half (51%) also focused on mitigating attraction.

Surprisingly, only 82 (39%) mitigation approaches were implemented or field tested in at least one source document (Figure 2). Of those 82 approaches, evidence of effectiveness was found for 39% - representing just 15% of all mitigation approaches identified in this review. Thus, 85% of mitigation approaches had no evidence of effectiveness based on the reviewed source documents, underscoring critical gaps in our understanding of appropriate mitigation measures. For the remaining 129 approaches (61%), it was clear that 19% had not been implemented or tested, while for the remaining 41% the implementation and testing status was unclear. Of the 82 mitigation approaches that were implemented or field tested, most

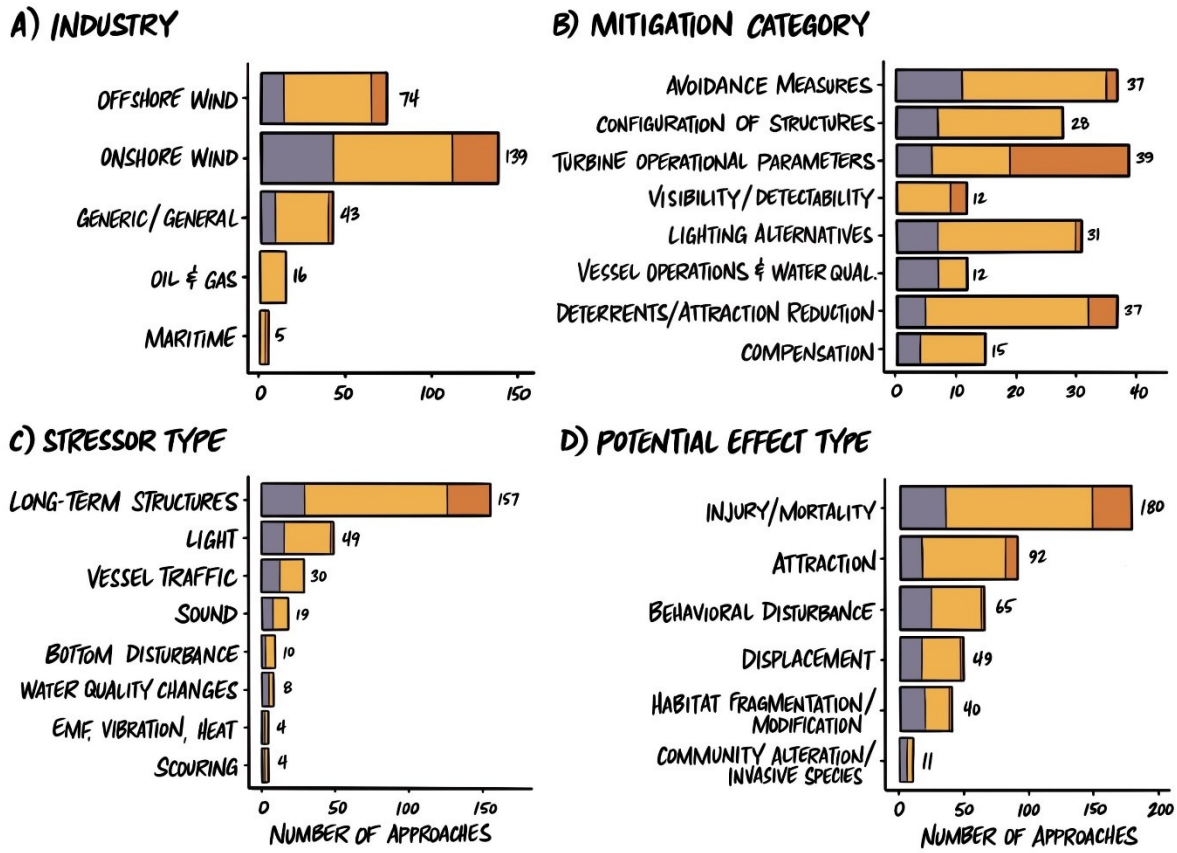

Figure 1. Number of mitigation approaches by general category (A), potential effect type (B), stressor (C), and industry (D). Mitigation approaches were directed towards birds (yellow), bats (orange), or both taxa (gray). Mitigation categories are mutually exclusive; however, each mitigation approach could be listed under multiple stressors, effects, and industries. Numbers indicate total approaches per category.

were primarily focused on birds, or on both birds and bats (74%), with fewer focused on bats alone (26%). Unsurprisingly, given the difficulties in testing mitigation approaches in the offshore environment, a slightly lower percentage of offshore-focused methods had been field tested or implemented (about 36%) as opposed to 41-50% of approaches targeted partially or wholly on terrestrial systems. Where mitigation approaches had been tested, it was typically at a small scale due to logistical difficulties, which led to small sample sizes and other issues that may make it difficult to scale up results to understand the likely influence of mitigation measures that are implemented more broadly. For the various mitigation approaches for aerofauna, we summarized results into the eight general categories of mitigation

approaches described above, and for each category, discuss the state of knowledge, level of testing and evidence of effectiveness, and key knowledge gaps. The order of mitigation approaches discussed below generally follows the mitigation hierarchy (avoid, minimize, compensate).

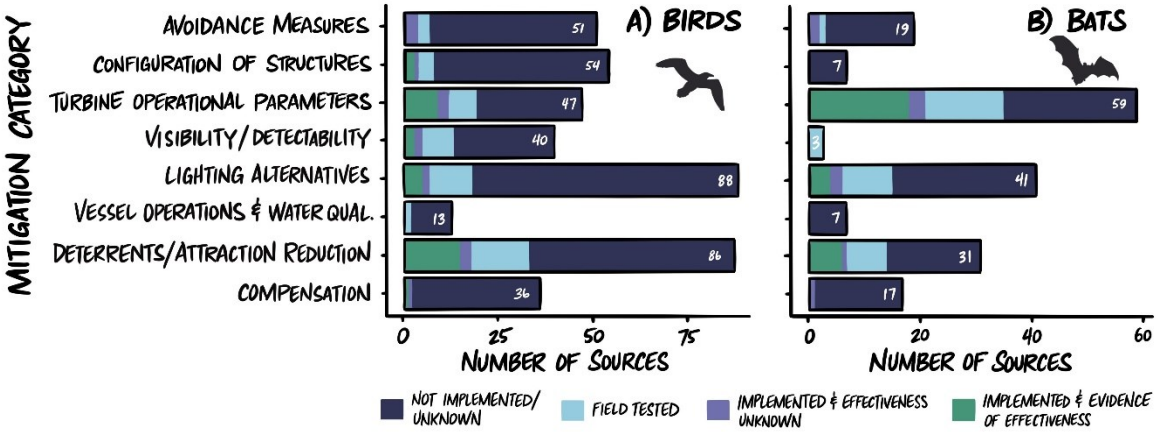

Figure 2. Number of sources by category for (A) birds and (B) bats for various mitigation approaches along with the level of testing and evidence for effectiveness (dark blue = mitigation approach was not implemented/tested in the source document or it was unclear whether it had been implemented; purple = mitigation approach had been field tested in the source document, but not implemented in a real-world situation; light blue = mitigation approach was implemented in a real-world situation, but it was either not tested to determine its effectiveness, or it was shown not to be effective; and green = mitigation approach was implemented and shown to be effective). Mitigation categories are mutually exclusive; however, if the same mitigation approach is discussed in multiple source documents within a category, it is represented multiple times in this figure (and may be classified into different effectiveness types, if the studies had differing results). Numbers indicate total number of sources per category.

Avoidance measures

Avoidance represents the first step in the mitigation hierarchy. Thirty-seven different mitigation approaches were suggested in 43 reviewed literature sources to avoid effects to aerofauna by 1) siting development activities away from important populations or habitats (n=15 approaches), 2) conducting development activities outside of important habitat use periods (e.g., seasonal restrictions; n=7 approaches), 3) limiting activities (for example, phasing construction activities to avoid higher-risk time periods; n=11), and 4) communication and engagement with stakeholders (n=4). The literature included preliminary or desktop-based assessment of effectiveness for only three of these proposed approaches in the avoidance category with an additional five implemented but no evidence of effectiveness reported.

Siting and spatial avoidance

Siting and other spatial-based avoidance approaches (n=15) included macro-siting (e.g., siting the entire wind farm away from important habitat use areas) and micro-siting (e.g., placing individual turbines and other infrastructure within a project footprint in such a way as to avoid key use areas (Allison et al. 2019). Important habitat use areas were defined in the literature in a variety of ways, including known bat maternity roosts and hibernacula (American Wind Wildlife Institute 2019, Reusch et al. 2022), avian breeding colonies and nesting areas (May et al. 2015, Defingou et al. 2019, Simmons et al. 2020), designated Important Bird Areas and other areas of high bird usage, e.g., with known natural concentrations of birds (Langston and Pullan 2003, Drewitt and Langston 2006, Lüdeke 2019), known feeding, staging, or loafing locations (Defingou et al. 2019, Lüdeke 2019, Thaxter et al. 2019), migratory and commuting pathways (Langston and Pullan 2003, Mockrin and Gravenmier 2012, Defingou et al. 2019, Lüdeke 2019), areas of high prey density (Watson et al. 2018), shallow waters and waters in proximity to shore (Williams et al. 2015, Goodale and Milman 2020, Lagerveld et al. 2023), sensitive habitats (Mockrin and Gravenmier 2012, Rydell et al. 2012), and undisturbed areas (Mockrin and Gravenmier 2012, Eshleman and Elmore 2013). Several literature sources suggested using specific types of data to help define these important habitat use areas, such as collision risk models, bat acoustic activity data, weather data, and weather radar data on aerofauna migration (Murgatroyd et al. 2021, Cohen et al. 2022, Gaultier et al. 2023). In addition to wind farm and turbine siting, other spatial avoidance approaches included the implementation of buffers and setbacks in the choice of location or for particular activities (Mockrin and Gravenmier 2012, Rydell et al. 2012, Eshleman and Elmore 2013).

Few approaches in this category were tested for effectiveness, though several studies used different types of avian movement data to inform model-based assessments of risk. For example, Goodale et al., (2019) conducted a model-based analysis of Northern Gannet (*Morus bassanus*) movements, and found that siting offshore wind projects away from shallow coastal waters could reduce gannet exposure to

development activities by avoiding key habitats. Likewise, Cohen et al. (2022) used weather radar data to assess putative collision risk based on stopover densities of migrants in the Great Lakes region of North America, and found that siting projects >20 km from coastlines would help to avoid this risk. Validation of these assessments, however, is lacking.

Temporal avoidance

In addition to spatial avoidance methods described above, several approaches focus on temporal avoidance (n=7), which involves scheduling disruptive activities to avoid sensitive life history periods and/or times of high habitat use. This includes scheduling construction activities and maintenance activities (including vessel and helicopter activity) to avoid the avian breeding season and other times of high bird or bat abundance, such as migratory or wintering periods (Cook et al., 2011; English et al., 2017; Eshleman and Elmore, 2013; Gartman et al., 2016; Langston, 2013; May et al., 2015; Mockrin and Gravenmier, 2012; USFWS, 2021; Vaissière et al., 2014; World Bank Group, 2015). Seasonal limitations on construction activities to mitigate effects on marine birds have been implemented in multiple sources related to OSW development. For example, construction was limited to March-October at the Burbo Bank offshore wind farm to protect wintering birds, and restricted from 16 December-March at Rhyl Flats to protect Common Scoter (English et al. 2017). Despite this implementation, the effectiveness of such measures was not reported.

Limiting activities

There are other types of activity limits that could be implemented for mitigation that relate to the spatial and temporal overlap of development activities and habitat for aerofauna (n=11). These include sequencing and phasing turbine installation and other construction activities (English et al. 2017), limiting construction of artificial breeding structures in proximity to development (Everaert and Stienen 2007), and co-locating equipment across projects (Drewitt and Langston 2008). Of the 11 strategies identified, two were implemented, three were not implemented, and for six strategies implementation status was

368 unknown. The two implemented strategies were for offshore wind in the UK. In one case, turbine
369 installation progressed from north to south over the course of a season to minimize the effect on a nearby
370 Little Tern (*Sternula albifrons*) colony (English et al. 2017); in the other example, a phased development
371 approach was applied, with the second phase only permitted once the developer demonstrated no
372 construction-related change to Red-throated Loon (*Gavia stellata*) habitat that would compromise
373 identified conservation objectives (English et al. 2017). Effectiveness of these avoidance-based
374 approaches was not reported.

375 *Engagement and communication*

376 While not exclusive to siting, approaches related to engagement and communication with stakeholders
377 (n=4) were identified as potential mitigation strategies. These approaches typically relate to early and
378 standardized engagement with stakeholders and state and federal agencies, particularly in regard to siting,
379 as a method of minimizing the potential for effects (USFWS, 2021). None of these strategies were tested
380 for effectiveness within the reviewed literature, likely because the majority of these strategies were
381 documented in guidance papers intended to provide planning assistance.

382 **Minimization measures**

383 Minimization represents the second step in the mitigation hierarchy, and approaches in this category were
384 by far the most abundance (n=159; 75%). Categories of minimization included configuration of structures
385 (n=28), changes to turbine operational parameters (n=39), lighting reduction (n=31), approaches to
386 increase visibility and detectability (n=12), deterrents and other attraction reduction methods (n=37), and
387 adjusting other operational parameters (n=12). Of the 159 approaches, 56% had some level of testing or
388 implementation, of which 42% showed evidence of effectiveness, primarily in the terrestrial context. For
389 birds, deterrents and other attraction reduction measures was the most tested and implemented
390 minimization category, with lighting and visibility enhancements and changes to turbine operations
391 parameters also having high rates of testing. Much of the testing of these types of mitigation approaches

occurred in relation to the onshore wind industry. For bat mitigation, approaches relating to turbine operation parameters (e.g., curtailment) had the highest testing rate and evidence of effectiveness, though lighting/visibility enhancement and deterrence/attraction reduction, also exhibited high rates of testing and effectiveness.

Configuration of structures

The configuration of offshore wind farms (and other anthropogenic infrastructure) has the potential to influence how aerofauna perceive these structures and therefore how they respond to and interact with them. Decisions on configuration occur during planning stages but often after macro-siting has already occurred (e.g., the general location of the facility has been determined). Mitigation strategies (n=28) in this category included adjusting the number of turbines, turbine layout (e.g., clustering, spacing), and turbine size (overall height, size of "air gap" below the lower edge of rotor-swept zone). Additional considerations related to clustering included leaving open migration corridors (Cook et al. 2011), leaving larger gaps between rows in the direction of prevailing winds (Tulp et al. 1999), and avoiding placing infrastructure within daily flight paths to foraging and breeding sites to ensure safe passage through or around the wind farm (Vaissière et al. 2014).

While most approaches lacked testing and evidence of effectiveness (n=21), four approaches were field tested and three were implemented with evidence of effectiveness for birds specifically in the terrestrial wind context. The effectiveness of altering turbine configuration and size to reduce mortality risk was variable, in part because "size" is a term used to describe multiple turbine characteristics, including overall height, distance between the surface of the water and the lower edge of the turbine blade (i.e., air gap), and rotor diameter (Garvin et al. 2024). Effectiveness also varied by species and by the combination of characteristics that were altered. Approaches in this category included increasing the air gap has been suggested to reduce mortality for marine birds that largely fly close to the water's surface and increasing turbine height to in turn reduce the total number of turbines needed to produce the same amount of

electricity to help reduce collision mortality. However, the ideal height is likely species and context specific. For example, multiple studies found that increasing turbine height helped to reduce raptor mortalities at onshore wind farms (Arnett and May 2016), including for Golden Eagles (*Aquila chrysaetos*; CEC 2002). However, the number of neotropical migrant mortalities was two orders of magnitude higher for 300m turbines compared with 90m towers (Crawford and Engstrom 2001). A recent study found rotor diameter was positively correlated with bird mortalities but not with bat mortality rates at terrestrial wind farms (Garvin et al. 2024).

Turbine operation parameters

Altering turbine operation parameters has been a large focus of mitigation efforts in the terrestrial wind industry. Potential mitigation approaches related to turbine operational parameters include 1) curtailment (n=26 approaches), 2) temporary shutdown (n=7 approaches), and 3) feathering (n=5 approaches). Curtailment involves raising the threshold for wind speed (also called cut-in speed) at which turbines begin to generate power. Below the cut-in speed, turbine blades spin but at much slower speeds, if at all (blades can be "feathered," or pitched to catch as little wind as possible; Adams et al. 2021).

One strategy was to implement turbine curtailment consistently at night (termed 'blanket curtailment'; Allison et al., 2019), though this approach leads to loss of energy production (Thurber et al. 2023). To address this concern, a range of other approaches have been suggested for implementing more targeted curtailment during periods of higher activity for aerofauna, as defined based on environmental conditions (e.g., a combination of low wind speeds and higher temperatures; see American Wind Wildlife Institute, 2019; Arnett and May, 2016; Sinclair and DeGeorge, 2016; Whitby et al., 2021), high risk periods of the year (e.g., migration; Hill et al., 2014; Smallwood and Bell, 2020), and/or the use of tools and technologies (e.g., radar, human observers, acoustic monitoring) to detect bats or birds within the vicinity of the turbine and trigger curtailment, often termed 'smart curtailment'.

We found strong evidence in the literature that curtailment was an effective mitigation strategy for bats in the onshore wind context. Multiple review papers suggested that across studies, a 50% reduction in bat mortality could be achieved by implementing cut-in speeds 1.5-3.0 m/s above normal (Garman et al. 2016). For example, a meta-analysis of bat curtailment studies in the Midwest and Mid-Atlantic regions of the United States found that a 5.0 m/s cut-in speed could reduce total bat mortalities across facilities by an average of 62% (Whitby et al. 2021). However, smart curtailment approaches have not yet been shown to be effective for many bat species (Hayes et al. 2023).

There is currently little or no evidence that blanket curtailment reduces mortalities for birds (Smallwood and Bell 2020). In general, the only studies with evidence of effectiveness utilized human observers to implement smart curtailment with a focus on raptors (Ferrer et al. 2022, Bennun et al. 2021). Evidence of the effectiveness of curtailment for other groups of birds was also generally lacking. Curtailment was mentioned in the literature as a potential mitigation strategy in the offshore environment for aerofauna, but this mitigation strategy remained untested in this context.

Similar to curtailment strategies, turbine shutdown strategies generally included temporary shutdown of turbines during periods of high activity, but in this case shutdown occurs regardless of wind and cut-in speeds. Periods of high activity can be determined based on timing (e.g., seasonal) or other environmental conditions or monitoring data (e.g., active monitoring or model predictions). These strategies came primarily from the onshore industry, and in most cases lacked evidence of effectiveness, though a review paper (Cook et al. 2011) suggested evidence of effectiveness for bats and Marbled Murrelets (*Brachyramphus marmoratus*).

Finally, mitigation strategies related to feathering included implementing partial or full feathering (pitching the turbine blades to 45 degrees or 90 degrees, respectively, to catch as little wind as possible when below the cut-in speed for energy generation). In some cases, feathering was targeted towards high

activity periods, it was primarily tested and implemented in the onshore wind industry. There was substantial evidence of effectiveness from multiple studies for bats onshore, either on its own or in combination with curtailment (Baerwald et al. 2009, Arnett and May 2016, American Wind Wildlife Institute 2019). As with curtailment, there was a lack of testing and evidence for the effectiveness of feathering as a mitigation measure for birds. There was also no testing or evidence of effectiveness in the offshore context.

Lighting to reduce attraction

There were 31 lighting-related mitigation approaches in the reviewed literature related to reducing attraction. Lighting-related mitigation approaches that were suggested in the literature included limiting the use of lighting (n=18) as well as altering various lighting characteristics such as color (n=6), visibility (n=2), flashing (n=3), and intensity (n=2) to reduce attraction.

Various approaches have been suggested related to reducing light sources offshore, including turning lights off when not in use, shielding lighting to only illuminate where needed (particularly down-shielding), and using on-demand lighting of various types (e.g., timers, heat sensors, motion sensors, ambient conditions; E-TWG Bird and Bat Specialist Committee 2020). Flood lighting was broadly acknowledged to be hazardous to migrating birds, and minimizing flood lighting particularly at night, in poor weather, and during migration was recommended (Gauthreaux and Belser 2006, E-TWG Bird and Bat Specialist Committee 2020). Methods to limit permanent lighting on offshore structures (as allowed by local safety regulations) was also a commonly suggested mitigation approach, including the use of Aircraft Detection Lighting Systems (ADLS) to ensure that aviation obstruction lights on turbine towers and nacelles were only lit when an aircraft was in the vicinity (Gartman et al. 2016). Using as few lights as possible - for example, only lighting the outer turbines in an array, and using as few lights as necessary to light each structure - was also suggested as a common-sense way to minimize the amount of artificial light to which wildlife were exposed (Mockrin and Gravenmier 2012). Triggering vessel navigation

lighting around turbine bases, rather than having such lighting operational during all periods of poor visibility (similarly to ADLS for towers/nacelles), was also suggested as a way to minimize light pollution (Rebke et al. 2019), though this approach is not been implemented in the source documents examined. Most of these lighting minimization approaches have not been tested or implemented, with the exception of a few studies from islands that found lighting reduction and down-shielding decreased attraction of tubenose seabirds breeding in the vicinity (Reed et al. 1985, Miles et al. 2010).

In addition to lighting reduction, the color spectrum of artificial lights was also a focus of minimization approaches. White light has been shown to attract birds more than other wavelengths of artificial light. The color that leads to the least amount of attraction, however, is still debated based on our literature review. A study using lampposts in the Netherlands, for example, found that 60-81% of nocturnally migrating birds were disoriented and attracted by white lights, while fewer birds were influenced by red (54%), green (12-27%), or blue (4-5%) lights (Poot et al. 2008). However, a field test in the terrestrial United States that pointed lights into the night sky found that white, blue, and green lights all attracted birds, while red light did not (Evans et al. 2007). Based on field testing, several studies suggested the use of red light offshore, including near Procellarid breeding colonies (Syposz et al. 2021) and at offshore wind farms in the North Sea (Rebke et al. 2019). While the available evidence clearly indicated that avoidance of the use of white lights helped to mitigate attraction in birds, the best alternative lighting color is still unresolved, and may depend on weather, taxon, and other variables. Much more limited data was available on bat responses to light color. A study on the coast of the Baltic Sea found that bat acoustic activity increased around red LED light as opposed to white (Voigt et al. 2018). However, high levels of bat activity around the white beams emitted by lighthouses has been noted for several decades (e.g., Cryan and Brown, 2007; Stantec Consulting Services Inc., 2016), and in a five-year study of bat mortalities at a terrestrial wind farm in the United States, Bennett and Hale (2014) found that synchronized, flashing red aviation lights did not increase bat mortality rates compared to unlit turbines.

Alteration of other lighting characteristics has also been suggested to minimize risk to birds, including the use of flashing lights and different light intensity. Flashing (but not strobing) light was found to reduce avian attraction relative to continuously burning light (Evans et al. 2007, Gehring et al. 2009, Kerlinger et al. 2010, Cook et al. 2011, Gartman et al. 2016) and has been widely recommended in both offshore and onshore contexts, though most testing of this approach occurred onshore. One meta-analysis of avian collision mortality from 30 terrestrial wind farms across North America found no significant difference between mortality rates at turbines with red flashing aviation safety lighting and turbines without lighting at the same wind farms (Kerlinger et al. 2010). The more the flash duration was reduced, and the longer the time interval between flashes, the better for reducing wildlife interactions. Flash synchronicity (e.g., across all turbines in a wind farm) has also been suggested to be important (Bennett and Hale 2014), along with using the minimum intensity required for safety or other purposes (e.g., (Syposz et al. 2021) and others). However, more research is needed on effectiveness of various lighting strategies to reduce attraction, particularly for bats.

Visibility and detectability enhancement

While in the instances described above, mitigation was focused on methods to reduce attraction to artificial light, there were some instances where lighting was proposed to increase visibility of structures to reduce potential for collision (n=12). Many of these approaches have been field tested for birds or bats (n=6) or implemented with evidence of effectiveness for birds (n=4), generally in terrestrial contexts. For example, Day et al. (2005) determined that flashing lights significantly reduced nighttime flight velocity, resulted in a spatial redistribution away from the island, and resulted in greater course change distances when visibility was good or during tailwinds for Eider species (*Somateria* sp.) in Alaska. For bats, Gorresen et al., (2015) illuminated trees with dim flickering UV light, which resulted in a reduction in Hawaiian hoary bat (*Lasiurus cinereus semotus*) activity levels despite an increase in insects (prey), though there was a high level of variation in results across turbines. However, a United States study of steady-burning dim ultraviolet (UV) light used to illuminate terrestrial wind turbines found no difference

in bat mortality rates between illuminated and unilluminated turbines (Cryan et al. 2022). In contrast, the use of ultraviolet light to illuminate electrical lines reduced avian collisions at those lines by 88% (Baasch et al. 2022). Previous studies suggested that UV light does not attract and disorient birds as much as longer wavelengths (e.g., as cited in Wiese et al. 2001), but additional data is needed on the utility of UV lights to illuminate obstacles.

Other visual mitigation strategies explored for aerofauna involved painting or texturizing turbine blades and towers to increase visibility of wind farm structures (Ahlén et al. 2007, Arnett and May 2016, American Wind Wildlife Institute 2019, Hein and Straw 2021). For bats, Long et al., (2011) determined that white and gray were among colors found to attract significantly more insects (e.g., prey for bats) than other colors tested. Bennett and Hale (2018) tested texturizing turbine towers to reduce attractiveness to bats, and while lab and flight cage experiments indicated potential effectiveness, initial field trials at terrestrial wind turbines were inconclusive (Hein and Straw 2021). Further testing of these visual and sensory-based mitigation approaches is required to determine potential effectiveness for bats, particularly in the offshore wind industry. For birds, painting turbine blades was field tested and demonstrated to be effective for several species. An experimental laboratory study on American Kestrels (*Falco sparverius*) indicated that painting a single turbine blade black may have reduced motion smear and could be effective for reducing bird collision risk (Hodos 2003). This strategy was further tested at a wind farm in Norway, in which May et al. (2020) found that painting one blade black significantly reduced the annual bird mortality rate by over 70% relative to neighboring unpainted turbines, with raptor mortalities experiencing the greatest reduction. Other research supported the importance of increasing contrast of turbine blades to improve bird's ability to detect rotating blades (Blary et al. 2023). Painting turbine foundations has also shown effectiveness for mitigating bird collisions (Gartman et al. 2016). A field study on Willow Ptarmigan (*Lagopus lagopus*) mortality rates found a 48.2% reduction in the annual number of recorded carcasses per search at turbine towers with painted bases relative to unpainted turbines (Stokke et al. 2020). As some birds have the ability to see in the UV spectrum, using UV-

570 reflective paint to increase turbine blade and tower visibility was also suggested. One paper
571 recommended, but did not test, the use of highly reflective achromatic patterns (black and white) that
572 extended across the full spectrum of incident light (Martin and Banks 2023). Although UV paint is an
573 established method for reducing bird strikes against windows (Marques et al. 2014, Defingou et al. 2019),
574 its effectiveness in onshore and offshore wind development has not been shown (Young et al. 2003).
575 While field testing of detectability approaches offers promise, more research is needed into effectiveness,
576 particularly in the offshore context.

577 *Vessel operations and water quality*

578 There are additional operational considerations (n=12 approaches) specific to marine industries focused
579 on vessels (n=6 approaches) and safety measures to ensure water quality (n=6 approaches). These
580 approaches were primarily relevant to marine birds and for a majority (n=10), the implementation status
581 was unknown or not implemented, while two vessel-related approaches in our literature review were field
582 tested. Six mitigation approaches related to vessel operation parameters including those aimed at reducing
583 bird disturbance by minimizing vessel speed and density, implementing setbacks from high-use areas
584 (i.e., breeding or foraging grounds), and using caution in low visibility conditions. Limiting vessel speed
585 and volume and adopting set-back distances were field tested as mitigation strategies in maritime
586 industries. For example, Bellefleur et al. (2009) determined that Marbled Murrelets required a minimum
587 buffer distance of 29 m between a boat and birds on the water to reduce disturbance such that 75% of the
588 studied population would be minimally affected. Additionally, Ronconi and St. Clair, (2002) found that
589 using a vessel setback distance of 600 m from shore with a speed limit of 25 km/h reduced Black
590 Guillemot (*Cepphus grylle*) flushing behavior to ~10%. At onshore wind farms, there has also been some
591 suggestion to manage vehicle volumes and remain particularly alert when visibility is poor to reduce
592 aerofauna collisions and disturbance (Mockrin and Gravenmier, 2012; USFWS, 2012), but this has not
593 yet been tested or implemented so far as we are aware. Additionally, no studies examined the
594 effectiveness of implementing vessel operation parameters for offshore wind development specifically.

595

596 Finally, there were five mitigation strategies tied to water quality from three sources, but none of these
597 mitigation strategies were tested for effectiveness. Potential strategies include implementing methods to
598 reduce potential changes in water quality (i.e., best management practices), following applicable
599 regulations, proper handling of toxic substances following appropriate federal and state measures, and
600 reducing the likelihood of invasive species introduction (USFWS, 2012).

601 *Deterrents and attraction reduction*

602 Deterrents and other methods to reduce attraction were by far the most common category of mitigation
603 approaches (n=37 approaches), with various methods suggested primarily in the terrestrial wind and
604 agricultural context. Of these, 17 had not been tested or implemented, another 11 were field tested, and 9
605 were implemented with evidence of effectiveness. While some industries distinguish between deterrents
606 and hazing devices, for the purposes of this review, we use 'deterrents' as an encompassing term to
607 include both. There are various types of deterrents aimed at scaring or otherwise repulsing individuals to
608 counteract attraction and in turn reduce collision risk. These act on various senses of individuals and
609 include acoustic (n=9), visual (n=6), physical (n=4), olfactory and chemical (n=2) deterrents, or some
610 combination of these (n=5). In addition, approaches to reduce attraction have been suggested that relate to
611 altering prey resources and habitat (n=11).
612

613 Ultrasonic deterrents (which jam the ability of bats to receive and interpret echolocation calls) have
614 shown some evidence of effectiveness for reducing bat mortality at onshore wind facilities (ONeil 2020,
615 Hein et al. 2021) and ripairan sites (Gilmour et al. 2020, 2021), but effectiveness may be location- and
616 species-specific. For example, one study at a terrestrial wind farm found that broadband ultrasound (20-
617 100 kHz) decreased bat mortality between 2-64%, but only significantly for hoary bat (*Lasiurus cinereus*)
618 and silver-haired bat (*Lasionycteris noctivagans*; Arnett et al., 2013). Schirmacher (2020) did not detect a
619 clear reduction in bat mortalities from the use of ultrasonic acoustic deterrents for any individual species,

including hoary bats, silver-haired bats, big brown bats (*Eptesicus fuscus*), and Eastern red bat (*Lasiurus borealis*). In fact, mortality of eastern red bat was estimated to be 1.3-4.2 times greater when deterrents were operational. Several studies tested the use of other electromagnetic radiation deterrents on bats with some evidence of success (Nicholls and Racey 2007, 2009). Despite some promising evidence in the terrestrial environment, ultrasonic and other auditory deterrents have not yet been tested in the offshore context.

In the case of birds, acoustic deterrents include two types, bioacoutic deterrents, which primarily involve the playback of recorded alarm or distress calls by the species to be deterred, and other acoustic deterrents that are generally loud noises used to scare birds. Both of which have been effectively used in agricultural and riparian settings (Enos et al. 2021), though effectiveness appears to vary by species, and habituation is common. Studies have shown that playing distress calls was an effective deterrent in agricultural contexts for both Black-crowned Night Herons (*Nycticorax nycticorax*) and Carrion Crow (*Corvus corone*) and for starlings in lab settings (Bomford and O'Brien 1990), though habituation was reported for starlings. In contrast, recorded alarm calls were ineffective at deterring Canada Geese (*Branta canadensis*) in recreational areas (Aguilera et al. 1991). Other studies have examined using loud noises (e.g., pyrotechnics, bangers, screamers, exploders) to deter birds from an area with varying effectiveness. For example, propane exploders reduced Red-winged Blackbird (*Agelaius phoeniceus*) damage to cornfields by 77%, with no evidence of habituation after 4 weeks (Conover 1984) and screamer shells reduced the number of geese in urban parks for up to 15 days (Aguilera et al. 1991). In contrast, response to pyrotechnics at a landfill site was species-specific, with a reduction in Herring Gull (*Larus argentatus*) numbers, but little response by crows and starlings (Curtis et al. 1993). In general, bird habituation to loud noises may limit deterrent effectiveness over longer time periods. Presenting sounds at random intervals, using a range of different sounds or moving them frequently, and supporting sounds with additional auditory or visual methods can help to increase long-term effectiveness (Bomford and O'Brien 1990, Gilsdorf et al. 2002). In the offshore environment there is more limited evidence regarding acoustic

646 deterrents, but aquatic hazing devices were ineffective at deterring waterbirds species, such as Greater and
647 Lesser Scaup (*Aythya affinis* and *A. marila*) and Surf Scoter (*Melanitta perspicillata*), from oil spills in
648 the San Francisco Bay (Whisson and Takekawa 2000). Other research suggested that using acoustic
649 whistle cues (2-4 kHz) may help birds hear turbine blades and avoid collision, but this strategy was not
650 tested (Dooling 2002). Lastly, ultrasonic acoustic deterrents were implemented as a strategy to deter birds
651 from perching at offshore platforms (Christensen-Dalsgaard et al. 2019), but there was minimal empirical
652 proof of their effectiveness (Defingou et al. 2019).
653
654 Visual deterrents are a common strategy used in agriculture and other terrestrial industries for birds (e.g.,
655 airports, landfills), and therefore many have been field tested and implemented in these settings. Visual
656 deterrents have included lasers, effigies, flagging, flickering light, unmanned aerial vehicles (UAVs),
657 automated detection systems, and paint. Lasers have deterred certain bird species, including roosting
658 Double-crested Cormorants (*Phalacrocorax auritus*) under low light conditions but were not consistently
659 effective across studies and did not disperse birds long distances (Glahn et al. 2000, Blackwell et al. 2002,
660 Sherman and Barras 2004). In maritime industries, automated laser systems were successfully used on
661 installations to deter gulls from large open areas such as helicopter landing platforms, and worked best in
662 low light conditions (Christensen-Dalsgaard et al. 2019). For offshore wind development, lasers were
663 identified as a potential mitigation method to minimize avian collision risk with turbines in the UK (Cook
664 et al. 2011), but this approach has not been tested in this context. Effigies, including scarecrows, hawk-
665 kites, and eye-spot balloons, have also been used as a visual stimulus to deter birds (Gilsdorf et al. 2002,
666 Arnett and May 2016, Enos et al. 2021). For example, Conover (1984) reported plastic kites imprinted
667 with a picture of a flying hawk reduced Red-winged Blackbird damage to cornfields by 83%, with no
668 habituation observed during the 4-week study period and Stickley and King (1993) found that the use of a
669 "Scary Man" pop-up inflatable effigy device proved effective in reducing Double-crested Cormorant
670 numbers on catfish ponds for 10-19 days.
671

Reflective materials have also been tested as a visual deterrence method for birds in terrestrial contexts, with some success deterring Herring Gulls from nesting colonies, but not loafing sites (Belant and Ickes 1997) and this approach was ineffective in reducing bird damage to agricultural fields, possibly due to habituation (Gilsdorf et al. 2002). Finally, UAVs, which include drones or remote-controlled helicopters, have been found to significantly reduce crop damage and bird abundances in several experiments on passerines in vineyards (Enos et al. 2021). For bats, a 3-week study indicated that a UAV deterrent significantly reduced bat activity in the relevant airspace of up to 700m above the UAV's flight altitude (Werber et al. 2023). There have not been any studies on the effectiveness of UAVs as deterrents in relation to onshore or offshore wind development.

Physical structural deterrents, such as wires, spikes, and netting, have been tested as a method to mitigate avian perching or roosting behavior on onshore and offshore wind turbines and other infrastructure, but their effectiveness was unknown (Curry and Kerlinger 1998, Clarke 2004, Cook et al. 2011). Available research suggested that physical deterrents may work best when installed on horizontal structures (i.e., staircases, railings) and be more effective for certain species, including raptors and gulls (Christensen-Dalsgaard et al. 2019). Decoy towers without functioning rotor blades, positioned at the end of turbine rows, were also tested as a potential method to deter raptor species from perching at an onshore wind facility, but effectiveness was not determined (Curry and Kerlinger 1998) and it is unclear to degree to which this might increase attraction to the general wind farm area (Smallwood and Karas 2009, Cook et al. 2011).

Several studies tested chemical deterrents (taste, olfactory, and tactile repellents) at landfills, crop fields, and other onshore areas with variable levels of effectiveness (Conover 1984, Curtis et al. 1993, Gilsdorf et al. 2002, Cook et al. 2011). In the offshore oil and gas industry, the use of 'Bird Free Gel', a sticky gel emitting UV light and a deterring smell and taste, was implemented on an offshore oil installation in the North Sea and used successfully in other areas to deter breeding Black-legged Kittiwakes (*Rissa*

tridactyla), gulls, and roosting pigeons (Christensen-Dalsgaard et al. 2019). However, other research noted that chemical repellents had little specificity to reducing offshore and onshore wind turbine collision risk, and their permanence over time may depend on terrain and weather conditions (Marques et al. 2014, May et al. 2015, Arnett and May 2016). In general, there was little evidence of effectiveness for any of these deterrents in the offshore context, and the level of effectiveness varied based on species, environmental conditions, and other factors.

In addition to the use of a particular type of deterrent, several studies assessed the integration of various deterrent techniques. Effective examples include using multiple acoustic deterrents to reduce Laughing Gulls (*Leucophaeus atricilla*) at an airport (Montoney and Boggs 1993) and Canada Geese on lawns (Mott and Timbrook 1988), and combining acoustic and chemical deterrents to reduce waterfowl landings at contaminated power plant pools (Stevens et al. 2000). However, a pilot study at an onshore wind facility in Canada determined that using predator owl deterrent models and bioacoustic alarms did not significantly deter birds from wind turbines (Dorey et al. 2019). As such, the effectiveness of integrated deterrent approaches for birds at onshore wind farms remains variable, and in our review of the literature, no similar approaches were tested at offshore wind farms.

Lastly, efforts to reduce bird attraction to certain structures or areas have used habitat enhancement in other locations. In the terrestrial wind context, it has been suggested that supplementary or diversionary feeding could be effective in reorienting raptors away from wind farms (Simmons et al. 2020). However, while a study of Hen Harriers (*Circus cyaneus*) showed an increase of 32-42% in flight activity in a created habitat enhancement area next to a terrestrial wind facility, there was no difference in activity within the wind facility (Gartman et al. 2016). In contrast, the felling of a plantation forest increased Golden Eagle use of the enhanced area, with a shift in their range away from the wind farm (Gartman et al. 2016). Reducing the attractiveness of the wind farm itself has also been tested in the onshore wind context with some effectiveness, including reducing attraction for Lesser Kestrels (*Falco naumanni)* by

724 tilling soil at the base of turbines (Garcia-Rosa and Tande 2023) or removing rock piles attractive to
725 rodent prey (Thelander et al. 2003). However, more research is needed in this area, particularly in terms
726 of relevant approaches for the offshore wind industry.

727 **Compensation**

728 Compensation for environmental effects that cannot be avoided or minimized may occur on or off site and
729 may include both in-kind or out-of-kind compensation (e.g., providing a resource of similar or different
730 structural or functional type to the affected resource). Federal regulations, such as the National
731 Environmental Policy Act (NEPA), in the United States and the Birds and Habitats Directives in the
732 European Union (Van Hoorick 2014), provide regulatory frameworks for compensatory mitigation of
733 effects to species and their habitats, but offsets can also be pursued outside of permitting processes.
734 Compensation has generally been proposed via three primary mechanisms: 1) direct implementation by
735 an individual project, 2) mitigation banking, or 3) in-lieu fee programs. Direct implementation (often via
736 permittee-responsible compensation) includes the implementation of shovel-ready projects such as habitat
737 restoration or creation. A mitigation bank is a site or suite of sites that provides ecological functions and
738 services expressed as credits that are conserved and managed in perpetuity for particular species and are
739 used expressly to offset effects occurring elsewhere to the same species. In-lieu fee programs, which are
740 similar to mitigation banks, provide ecological functions and services expressed as credits that are
741 conserved and managed for particular species or habitats and used to offset effects occurring elsewhere to
742 the same species or habitats (USFWS, 2023). One important distinction between mitigation banks and in-
743 lieu fee programs is that, generally, a mitigation bank maintains a large-scale mitigation site which is
744 already restored and protected, and where credits may be purchased. In contrast, an in-lieu fee program
745 receives funds to support activities that may not be complete at the time of the compensation payment.
746 We found 15 compensation approaches in the literature review as a means of mitigating effects. The
747 majority (75%) looked at compensation methods involving in-kind habitat conservation, restoration,
748 restriction of access (either from fishing or recreation), invasive species management, reduction of

749 bycatch, or other methods. The remaining studies (25%) reviewed financial means of compensation either
750 through development of funding pools, permittee-required compensation strategies, financial support of
751 rehabilitation programs, or in-lieu fee programs.
752
753 The majority of compensation approaches did not provide examples of implementation or assess the
754 effectiveness of compensation programs (n=13). There was little documented evidence within the
755 reviewed literature showing effectiveness of financial compensation at off-setting unavoidable effects
756 related to offshore wind development. Compensation has been used within the United States regulatory
757 context for other types of projects, primarily terrestrial, including Clean Water Act compliance (Arnett
758 and May 2016), and often includes habitat protection and restoration, which may be difficult to
759 measurably implement in the marine environment.
760
761 One strategy that has been extensively tested (though not in the OSW context) focused on the removal of
762 mammalian predators as a means of increasing colonia seabird productivity. Removal of invasive
763 predators from breeding colonies has generally been found to be an effective strategy (e.g., (Pascal et al.
764 2008, Nogales et al. 2013) though results from our reviewed studies were somewhat mixed. Luxmoore et
765 al. (2019) found that Guillemot/Murre (*Uria* spp.) populations did not respond to the removal of rats,
766 while Booker et al. (2019) attributed increases in closely-related Razorbill (*Alca torda*) and Atlantic
767 Puffin (*Fratercula arctica*) breeding numbers to the removal of rats (Booker et al. 2019). Thus, these
768 types of strategies are likely context-specific. We found no specific examples of compensatory mitigation
769 of bats in the literature review.
770

771 **SUMMARY OF EFFECTIVENESS**

772 There were few mitigation approaches available for birds and bats specific to the OSW industry that were
773 adequately tested in the reviewed literature. Commonly implemented approaches often had not been

demonstrated to be effective (e.g., raising the lower end of the rotor swept zone to reduce marine bird collision risk) or had been shown to be effective in other scenarios such as with terrestrial wind energy development, but not proven offshore (e.g., curtailment of turbine operations based on environmental conditions to reduce bat collision risk), likely due to feasibility, cost, or other limiting factors. Available data suggested that in order for mitigation to be effective, it likely needs to be species- and location-specific: a measure that works at one site for a given species and life history stage may not be as effective in other contexts. Thus, even the approaches that were successfully used in the terrestrial context (or with other marine industries such as offshore oil and gas) should be tested in relation to OSW development and particular species of interest, to ensure effectiveness at reducing risk. Since it may be difficult to identify mitigations that are broadly generalizable, an array of mitigation approaches should be further explored to provide options for specific scenarios.

Despite a lack of adequate testing offshore, there are a few key mitigation approaches that we suggest could be implemented across offshore wind facilities without the need for further study and testing, due to a strong base of evidence from other industries and/or because they are common sense measures that could be easily implemented. Other approaches may be promising, with limited evidence or in some cases conflicting evidence, and thus require additional research before consideration for offshore implementation. Still other methods either lack evidence (and thus also require research to assess their effectiveness) or are likely ineffective or inappropriate to implement in the offshore context. We have identified existing mitigation approaches that fall into each of these categories (Table 2) to help guide future mitigation implementation and research, recognizing that this is a very general assessment, and a one-size-fit-all approach does not exist.

Table 2. Categories of mitigation approaches for aerofauna at offshore wind farms and evaluation of available evidence and research needs. Mitigation approaches were placed into four categories: green = evidence of effectiveness OR a common sense approach to avoid conflict, but uncertain evidence due to logistical difficulty of study, yellow = some evidence of effectiveness for specific approaches or circumstances, but more research needed, orange = conflicting evidence, more research needed, red = no evidence it is effective, or there is evidence of ineffectiveness, gray = not relevant/appropriate.

Hierarchy Category	Mitigation Approach	Birds	Bats
Avoidance	Siting considerations	Green	Green
	Seasonal approaches	Green	Green
	Limiting activities	Green	Green
	Engagement and communication	Green	Green
Minimization	Turbine layout	Yellow	Yellow
	Turbine size	Orange	Red
	Curtailment	Orange	Yellow
	Feathering	Red	Yellow
	Temporary shutdown	Yellow	Red
	Limiting use of lighting	Green	Green
	Altering light color spectrum	Green	Orange
	Altering other lighting characteristics	Green	Red
	Visibility/detectability enhancement	Yellow	Yellow
	Use of acoustic deterrents	Orange	Yellow
	Use of visual deterrents	Orange	Red
	Use of physical deterrents	Yellow	Red
	Use of chemical and olfactory deterrents	Orange	Red
	Use of combined deterrents	Orange	Red
	Other attraction reduction	Red	Red
	Altering vessel speed and distance	Yellow	Gray
	Water quality	Green	Gray
Compensation and Offsets	Implementing compensation	Yellow	Yellow

LIMITATIONS OF THE LITERATURE REVIEW

Due to the search terms used in the MPD Tool and our subsequent literature review update, and how these terms are generally used in the literature, the results primarily included minimization measures, with much less representation of avoidance or compensation approaches. Despite the prevalence of the mitigation hierarchy in the scientific literature, the term "mitigation" is also sometimes used synonymously with "minimization," and that was evident in the types of studies that were identified during our review. Thus, the scope of this review largely excluded marine spatial planning exercises,

stakeholder engagement activities, and permitting documents developed by governmental agencies where siting-focused and compensation-focused mitigation tended to be discussed. It is possible that this review represents a gross underestimate of the true implementation frequency for these types of mitigation approaches, though it could also be an indication of the focus of mitigation efforts to date. Compensation for OSW development specifically is a relatively recent topic of discussion in the scientific community (Croll et al. 2022), and while the authors are aware of examples in other contexts (e.g., mitigation banks for bats: https://uniqueplacestosave.org/news/pushmataha-bat-conservation-bank), these were not well represented in the literature review. Finally, some of these activities (e.g., stakeholder engagement by government entities) also may not have been particularly well represented in the scientific literature more broadly, despite our best efforts to include gray literature.

In addition to the information provided in this paper, other data on the effectiveness of various mitigation measures can be found via the website Conservation Evidence (https://www.conservationevidence.com/). While not offshore wind-specific, this international project takes a science-based approach to assessing a wide range of biodiversity conservation measures and includes links to the scientific studies where mitigation effectiveness was examined. Several other efforts have focused specifically on assessing the effectiveness of mitigation measures for OSW development, though many of these have not focused on aerofauna (for example, see Verfuss et al., 2016). One recent assessment to inform OSW development in Scotland did include birds to some degree (Crown Estate Scotland 2024). However, this assessment was unable to find data on the effectiveness of mitigation measures in most cases and thus chose to define mitigation success as situations in which “no deleterious effects were recorded”; therefore, evidence of effectiveness as defined in this paper was lacking. This speaks to the difficulty in assessing effectiveness of mitigation approaches and general lack of data, though we did our best to assess the available information and scientific evidence for each approach in order to provide additional utility in identifying mitigation measures that should be implemented versus those that require additional study.

MANAGEMENT AND RESEARCH IMPLICATIONS

We recommend the adoption of avoidance measures and approaches to minimize attraction for reducing potential effects of OSW development on aerofauna. However, many potential mitigation strategies that have been identified in this review require additional research and testing before consideration for widespread implementation in the offshore context. This includes approaches that may have 1) some existing evidence of effectiveness for a specific approach or circumstance, 2) conflicting evidence, or 3) have yet to be tested. All approaches relating to the configuration of structures, deterrents, and altering vessel parameters fall into these categories.

Avoidance

Despite a lack of direct research in our literature review on the effectiveness of siting and other avoidance strategies, we strongly recommend implementation of these mitigation approaches. Avoidance-focused mitigation strategies are likely harder to test than some other types of mitigation such as on-site minimization measures, leading to relatively little evidence of effectiveness in the literature, despite the common-sense value in avoiding wildlife interactions as a way to mitigate effects. Nevertheless, there is a strong scientific consensus that siting and other avoidance measures remain the best available approach to reduce OSW development impacts, particularly for birds (Langston and Pullan 2003, Phalan et al. 2018, Fox and Petersen 2019, Danovaro et al. 2024).

It is generally difficult to test the effectiveness of avoidance measures, because there are typically no "control" scenarios to compare to "impacts" and the mitigation generally happens prior to the project even being built. As OSW farms continue to be built around the world, it will be important to gather data on avoidance-based mitigation approaches via natural experiments (e.g., as projects are sited in locations with varying value to wildlife, and resulting effects can be compared across projects). Continued development will also help to inform our understanding of what makes a "good" or "poor" location from the standpoint of avoiding aerofauna effects; for terrestrial wind energy, for example, our understanding

has shifted over time regarding what types of sites (based on landscape features such as topography and land cover, as well as measurements of wildlife activity) will lead to more or fewer aerofauna effects. The scientific community has discovered that pre-construction acoustic activity levels of bats, for example, or passage rates of migrants measured via marine radar, do not necessarily predict collision risk at terrestrial wind farms, and there is a need for the scientific and management communities to explore alternative ways of understanding what factors will most accurately predict post-construction effects, including mortality rates. This type of ongoing assessment to inform the adaptive management of future projects is an essential component of mitigation efforts.

Minimizing attraction

While uncertainty remains regarding the best colors of lighting to reduce attraction of aerofauna, there is strong evidence for the benefits of an overall reduction in lighting during all phases of OSW development, including minimizing the use of white lights where possible. Artificial lighting can have serious impacts on wildlife populations, species, and ecosystems (Jägerbrand and Bouroussis 2021, Walsh et al. 2024). All OSW facilities should enact mitigation to reduce artificial light at night (ALAN) pollution and avoid attracting and disorienting birds, particularly nocturnal migrants. This can be achieved by minimizing the use of steady-burning and white lights whenever possible, down-shielding of lights (but also not shining light directly on the water's surface), reduction of flood lighting during construction and maintenance, and other approaches that have been detailed in several guidance documents for OSW development (BOEM, 2021; E-TWG Bird and Bat Specialist Committee, 2020) as well as other industries (e.g., Environment and Climate Change Canada, 2016). While lights are required on turbines and other offshore infrastructure for aviation and marine navigation safety purposes, and regulations vary by country, it is recommended that the use of aircraft detection lighting systems (ADLS) and similar mechanisms to reduce ALAN be implemented wherever possible, including adjustments of current regulations where needed to allow for such measures. All OSW projects in the United States that have received final permitting approval to date for construction and operations plans have been required

to use ADLS to further reduce lighting of turbine structures (see, for example, BOEM, 2024, 2023, 2022, 2021), which has environmental as well as social benefits (e.g., by reducing the nighttime visibility of turbines from shore). New OSW developments in other regions would do well to take a similarly proactive approach to lighting offshore structures.

The use of alternative lighting options to reduce effects to birds is perhaps the best-understood and most thoroughly tested mitigation category reviewed. Use of non-white, flashing, less intense, shielded lights - with those lights operating as infrequently as possible - is the best available approach to reduce avian attraction, disorientation, and mortality around offshore wind structures. Nevertheless, additional research would be beneficial to better understand which wavelengths of (non-white) light can best reduce risk for different weather conditions and taxa, particularly in the offshore environment, since available findings are contradictory on this point. A better understanding of bat response to light would also be useful, as uncertainty remains regarding the mechanisms of attraction for this taxon. There is some evidence that bats actively approach turbines, and this may be dictated by multiple factors including potential foraging opportunities (Guest et al. 2022). Additional study of aerofauna responses to UV light would help inform its use as a possible mitigation measure. Our relatively poor understanding of animals' vision likely hinders our ability to make informed decisions about mitigation in this area.

Minimization through project design

The layout of offshore wind farms and the specifications of turbines (including size and air gap) may influence both how animals perceive the wind farm as a whole and how they move in and around the wind farm. This can have direct consequences for attraction, avoidance, and risk of collisions for aerofauna. While there is some evidence of the importance of turbine size and air gap in the terrestrial wind context, a great deal of additional research is needed to understand the degree to which these factors affect aerofauna in the offshore context. Understanding how structure configuration contributes to behavioral disturbance, displacement, and habitat fragmentation can be challenging, as this requires

913 regional-scale studies across multiple wind farms for comparison across a range of conditions. This type
914 of multi-facility study requires consistent data collection methods across projects along with public
915 availability of data from site-specific studies. Detecting changes in behavior may also require advanced
916 technology or human observers, both of which can be costly to deploy at the large scale required.
917 Understanding the effects of structure configuration on collisions offshore, which are both rare and
918 difficult to detect, likewise requires a high level of effort to achieve adequate statistical power. Mitigation
919 through project design offers promise to mitigate potential effects to aerofauna from OSW development,
920 but this promise remains largely unproven and will require large-scale, long-term research efforts. We
921 suggest that, if such approaches are implemented, they are accompanied by a rigorous regional-scale
922 monitoring plan to assess their effectiveness.

923 **Minimizing attraction and enhancing visibility**

924 Based on findings from other industries and contexts, there are many types of deterrents that offer some
925 level of promise. However, in many cases the studies of effectiveness focused on one or a few species
926 over a short period of time and often showed variable results. While deterrents have been used in the
927 OSW industry in Europe to reduce perching for taxa such as gulls and cormorants (Gartman et al. 2016),
928 these facilities were located closer to shore than those being built in North America. Consequently, there
929 is uncertainty in the level of attraction (for roosting, perching, and nesting) likely to be observed in the
930 North American context, and thus the need for these types of deterrents. As discussed above, the use of
931 offshore wind turbines by bats remains largely unknown in the region as well. Thus, for this type of
932 mitigation, we recommend not only additional research on effectiveness but also to only consider
933 implementation once there is evidence that attraction is occurring at large enough scales to warrant
934 investment in deterrents. While in general it is thought that reducing perching and roosting opportunities
935 can help reduce attractiveness of wind farms to birds, which in turn may help reduce collision risk
936 (Gartman et al. 2016), we lack direct evidence linking perching deterrents to collision risk reduction. Key

937 studies to fill knowledge gaps include those focused on species that occur offshore and long-term studies
938 to understand the potential for habituation.
939
940 There are other approaches to minimize attraction (and collision risk) that offer promise but also require
941 additional testing and validation. The use of paint for increasing visibility of turbines and other structures
942 shows promising evidence in other contexts but has to date been tested in a small number of contexts and
943 with few species, all in the onshore context. Differences in vision among bird (and bat) taxa suggest that
944 vision-related approaches to enhance turbine visibility must be carefully considered and tested.

945 **Minimizing collisions**

946 One of the largest data gaps identified in this review (as well as others; Hein et al. 2021) is the degree to
947 which bat mortality at offshore wind farms needs to be mitigated. Because of the high mortality rates of
948 migratory tree bats at onshore wind facilities (Arnett et al. 2008), there have been serious concerns about
949 the long-term impacts to these populations (Frick et al. 2017), and mitigation approaches for terrestrial
950 wind farms have received a high level of attention. In particular, curtailment of onshore turbines at low
951 wind speeds has been shown to significantly reduce mortality rates, both at the individual project scale
952 (Arnett et al. 2008) and when looking across projects (Adams et al. 2021, Whitby et al. 2021). While
953 there are many variations in how curtailment is implemented (e.g., blanket curtailment as well as
954 curtailment based on environmental conditions, temporal variation, smart systems that detect bats, etc.),
955 the aim is the same: to stop turbines from spinning when bats are in the area. Because bat activity is
956 typically higher at lower wind speeds, raising the cut-in speed for turbines to start generating electricity
957 ensures that there are fewer opportunities for negative interactions. Indeed, feathering and temporary
958 shutdown, while separate mitigation approaches, are also effective as they also result in the stoppage or
959 minimization of turbines spinning, resulting in reduced collisions for bats. Much of variation in this type
960 of mitigation approach, and the focus on conditional implementation, has more to do with the loss of
961 energy production that can be associated with this type of mitigation. Cost and other tradeoffs are

important considerations in the implementation of any mitigation (Best and Halpin 2019) and the implementation of curtailment can have direct tradeoffs with power production. As such, we recommend that curtailment and similar turbine operational parameter approaches be implemented only if bat mortality at offshore wind farms proves to be a key issue requiring mitigation. While there is evidence that migratory tree roosting bats occur offshore, uncertainty remains in both the abundance and distribution of bats in the offshore environment as well as the degree to which collision risk and associated mortality mirrors patterns onshore (Solick and Newman 2021). The further development and testing of collision detection technologies represents a key step towards better understanding mortality risk for bats at OSW farms.

While curtailment, feathering, and turbine shutdown have been proven effective for bats, at least in terrestrial settings, additional research is needed for birds before this type of approach is implemented in the offshore context. There is some evidence that targeted turbine shutdowns may be effective for particular species, primarily raptors, (e.g., when they have been detected entering a wind farm), but the greatest challenge to testing these types of strategies relates to the difficulty in collecting adequate data, including movement data in real time to inform turbine shutdowns, as well as measuring collisions offshore.

Minimizing disturbance

While many of the mitigation approaches discussed above relate to reducing attraction and/or collision, behavioral disturbance is a key effect from OSW development for marine birds (Allison et al. 2019, Fox and Petersen 2019). In particular, some species avoid OSW farms at various scales, which may result in effective habitat loss or increased energy expenditure (Williams et al. 2024). Birds may also be disturbed due to vessel and other OSW-related activity, which has the potential to have similar energetic consequences. Mitigation strategies such as altering vessel parameters to reduce disturbance have the potential to benefit marine birds, though this has only been tested in a few cases with with species and not

in the OSW industry specifically. While the impact of this type of disturbance is not well studied, it may be an important mitigation strategy to evaluate given its potential effectiveness in the maritime environment. Altering vessel parameters, in particular speed and distance to wildlife, represent key mitigation approaches used for marine mammals and sea turtles for the OSW and other maritime industries (Hazel et al. 2007, Conn and Silber 2013). Thus, additional research to understand variation in response among species, implementation of best practices, and the potential consequences of vessel disturbance would go a long way to understand the degree to which this type of effect could be mitigated effectively for marine birds. There may also be other types of disturbance, such as from aircraft, which were not explored in the literature included in our review but may also be mitigated to help reduce effects to aerofauna.

In the case of minimizing habitat disturbance, we also recommend implementing mitigation strategies related to water quality. While there were relatively few mitigation approaches related to water quality identified in the literature review, these are generally common-sense approaches that should be implemented to minimize potential negative effects. This includes practices like cleaning vessels/equipment to reduce the likelihood of invasive species introduction and following safety measures to avoid the introduction of toxic substances (Mockrin and Gravenmier 2012).

Compensatory mitigation

While there were few compensation-related approaches included in our literature review, in part, this may be due to the relatively nascent status of the industry in many parts of the world. Once the OSW industry progresses and such projects have been implemented, a thorough review of the results of these strategies would provide better understanding of the role compensation can play in mitigating effects on aerofauna. In the absence of proven on-site mitigation approaches (e.g., via avoidance and minimization) to fully offset effects to aerofauna from OSW development, implementing compensatory mitigation approaches should be explored in the immediate term (Croll et al. 2022). Potential strategies to consider in a

compensatory mitigation framework should include both on-site and off-site approaches and should be considered regardless of whether the regulatory framework for a given location with OSW development requires “no net loss” of animals or “net gain” of animals in relation to development activities (Edwards-Jones et al., 2024; USFWS, 2023). Without on-site mitigation approaches that have been proven to adequately ameliorate effects of development, off-site and potentially out-of-kind measures must also be considered in order to address remaining unmitigated effects.

There are a range of offset approaches that have been suggested primarily in the context of other industries. In the case of birds, most compensatory mitigation has focused on marine birds, and included approaches related to fisheries (e.g., fisheries closures for species that are key prey for seabirds, efforts to reduce fisheries bycatch), creation or restoration of nesting habitat and marine reserves, and the eradication and control of predators, including invasive mammals like rats (Jodice et al. 2019, McGregor et al. 2022). In general, these types of approaches have required off-site implementation (i.e., away from offshore facilities) in key foraging habitats and breeding sites; such efforts may require international coordination to work across different jurisdictions and life history stages. These efforts are often aimed at increasing survival directly (e.g., reducing mortality via fisheries bycatch) or indirectly (e.g., increasing resource and habitat availability) or are focused on increasing reproductive success (e.g., reduced predation on nests). Understanding the effectiveness of these types of approaches is challenging, as it generally requires long-term monitoring of populations to examine changes in key demographic parameters along with a quantitative understanding of the influences of other anthropogenic threats on these populations. Additionally, in some cases there may be no well-established offset approach that is known to be effective for a given species. However, there is clear evidence that colony-based and island-based mitigation approaches to control invasive predators in the case of seabirds, for example, do increase breeding success (e.g., Nogales et al., 2013; Pascal et al., 2008). A recent review focused on OSW development in the United States noted that compensatory mitigation may be the best approach to adequately prevent cumulative impacts that lead to population declines across both regional and

international scales, and that implementation will in turn require a strategically coordinated approach (Croll et al. 2022). As with on-site mitigation, compensatory mitigation must be carefully designed and monitored to assess effectiveness in mitigating OSW effects.

Monitoring programs to validate effectiveness of mitigation

Monitoring programs to assess mitigation effectiveness can be difficult to design and implement, particularly in the offshore context. Studies must be designed with sufficient statistical power, including acquisition of enough data to reliably detect a change in the selected effect metric if it occurs (Martins et al. 2023, Regional Synthesis Workgroup of the Environmental Technical Working Group 2023). This can be particularly challenging for rare effects, such as collisions (Skov et al. 2018, Tjørnløv et al. 2023), and may require studies of relatively long duration (e.g., May et al., 2020). These challenges are exacerbated in the offshore environment by logistical difficulties such as the inability to search for carcasses underneath turbines (Allison et al., 2019). Monitoring of more common types of effects for OSW, such as displacement, is also complicated due to high levels of variability in the marine environment, which make it difficult to tease apart effects of development or accompanying mitigation approaches from background variation in the distribution of aerofauna (Maclean et al. 2013, Lamb et al. 2024). Additionally, mitigation approaches implemented during the project design phase (such as changing turbine height, rotor diameter, air gap, distance between turbines, turbine layout, etc.) require the comparison of data across multiple wind facilities with differing characteristics to help assess the effectiveness of these approaches. This is only possible when data collection methods are harmonized across projects and data are publicly shared, so that multi-facility studies can be conducted.

A few recent high-profile studies have tested mitigation approaches in the field (e.g., May et al. 2020) or used meta-analytical frameworks to assess effectiveness of mitigation approaches across multiple studies (e.g., Adams et al., 2021; Whitby et al., 2021). A good example of progression in our understanding of mitigation effectiveness is the approach of painting one turbine blade black in order to reduce motion

smear and increase the visibility of the blades to birds in the terrestrial wind context. This approach was first tested in the laboratory in 2003 (Hodos 2003), and was implemented using a Before-After Control-Impact approach at a terrestrial wind facility in Norway in 2013. Because extensive mortality data was available from the Norwegian site prior to the treatment, and carcass searches were continued for >3 years after the treatment was implemented, an 11-year dataset was available to assess the effectiveness of the treatment. Given the relatively low rate of collisions per year, this long-term dataset was necessary to achieve sufficient statistical power to reliably detect a difference between control and impact scenarios. Indeed, the focal species of study, the White-tailed Eagle (*Haliaeetus albicilla*), collided with turbines only 7 times throughout this study period (7 prior to treatment and zero after). There was limited or no evidence of effectiveness for other avian taxa at the site (May et al. 2020). Several studies are currently underway to replicate the Norway study at other geographic locations and with other focal species (Vattenfall 2022). Such replication is essential to assess applicability across habitats and species with different visual acuity and behaviors. This exemplifies the large-scale effort often required to test and validate mitigation measures.

Given the importance of identifying the most effective mitigation strategies to achieve sustainability of the OSW industry, research to assess the effectiveness of various approaches is a high priority. There are several avenues of future research that are important to investigate in the near term. First, we recommend that research focus on mitigation approaches that have already been implemented at offshore wind farms and included in project permits in jurisdictions worldwide. This is important since approaches that have already been implemented at existing projects are more likely to also be proposed at new projects. This includes project design measures such as increasing the air gap to reduce collisions of marine birds. Second, we recommend focusing research on mitigation approaches with the greatest potential impact in reducing effects, if proven effective. Curtailment for bats could fall into this category, assuming bats are attracted to offshore turbines, given the proven effectiveness of this approach onshore (Adams et al. 2021, Whitby et al. 2021). Curtailment for birds is a commonly discussed measure with little or no evidence of

effectiveness (apart from curtailment triggered by species presence) that could also fall into this category. Thirdly, we recommend an immediate focus on mitigation approaches that can be tested at the individual project level, such as visibility enhancement measures. Studies that require comparisons across projects with different project designs will necessarily require the construction of multiple projects with differing characteristics and longer-term data collection to facilitate comparisons. In the immediate term, conducting well-designed studies of effects to aerofauna from OSW development, as well as ensuring the public availability of resulting effects data, is an essential step to allow for these longer-term studies of the influence of project design on wildlife mitigation.

CONCLUSIONS

We lack evidence of effectiveness for 86% of the mitigation approaches identified in this literature review. For birds, approaches related to lighting (reducing artificial light, avoiding white and steady-burning lights, etc.) were the most commonly tested and effective methods for reducing maladaptive attraction and collisions. For bats, alteration of turbine operations (e.g., curtailment and feathering of turbine blades) were most commonly shown to be effective. Most aerofauna minimization approaches have primarily been tested in the terrestrial context, however, leaving important questions regarding their applicability and effectiveness in the offshore environment. Avoidance of effects (via careful siting of industrial activity and related measures to avoid effects to wildlife and their habitats) remains the best available option for mitigation at OSW facilities. Minimization and restoration were the main focus of this review but there is limited evidence of effectiveness for most approaches, and we suggest implementation of dedicated testing for commonly suggested and implemented mitigation approaches such as curtailment for birds. Implementation of unproven mitigations creates the assumption that effects to aerofauna are being adequately addressed when that may not be the case. Very few mitigation approaches for birds and bats have sufficient data to support current implementation at OSW farms without more data being needed on their effectiveness, either in the short or long term.

Given the current status of available mitigation measures, a sensible approach to aerofauna mitigation at OSW facilities could include the universal implementation of approaches with sufficient evidence of effectiveness, such as reductions and adjustments to artificial lighting regimes at wind farm structures, as well as implementation of testing (at multiple locations, focused on a range of species) to further examine the effectiveness of commonly suggested and implemented mitigation approaches for which data are currently lacking. In the absence of sufficiently validated approaches for on-site mitigation of OSW effects to aerofauna, compensatory mitigation should also be pursued.

ACKNOWLEDGEMENTS

This study was funded by Environment and Climate Change Canada's Science and Technology Branch under a Grant and Contribution Agreement. The authors would like to thank the New York State Energy Research and Development Authority (NYSERDA), which funded the Mitigation Practices Database (available at https://www.nyetwg.com/mpd-tool) that was used in this effort, as well as members of the Offshore Wind Environmental Technical Working Group (E-TWG) who oversaw and provided input on that project. The authors would particularly like to thank NYSERDA project manager K. McClellan Press. The authors would also like to thank I. Stenhouse and L. LaMartina for their support during this project. We would also like to thank J. Wisbey and A. Millard for help with citation management and Sylvain Christin for help with French translation. Thanks to Rush Dhillon of Rush Studio for design of figures and the graphical abstract.

REFERENCES

Adams, E. M., J. Gulka, and K. A. Williams. 2021. A review of the effectiveness of operational curtailment for reducing bat fatalities at terrestrial wind farms in North America. I. Torre, editor. PLOS ONE 16:e0256382.

Aguilera, E., R. L. Knight, and J. L. Cummings. 1991. An Evaluation of Two Hazing Methods for Urban Canada Geese. Wildlife Society Bulletin 19:32–35.

Ahlén, I., L. Bach, H. J. Baagøe, and J. Pettersson. 2007. Bats and offshore wind turbines studies in southern Scandinavia. Swedish Environmental Protection Agency, Stockholm, Sweden.

Allison, T. D., J. E. Diffendorfer, E. F. Baerwald, J. A. Beston, D. Drake, A. M. Hale, C. D. Hein, M. M. Huso, S. R. Loss, J. E. Lovich, M. D. Strickland, K. A. Williams, and V. L. Winder. 2019. Impacts to wildlife of wind energy siting and operation in the United States. Issues in Ecology.

American Wind Wildlife Institute. 2019. AWWI Technical Report: A Summary of Bird Fatality Data in a Nationwide Database. Washington, DC. Available at www.awwi.org.

Arnett, E. B., W. K. Brown, W. P. Erickson, J. K. Fiedler, B. L. Hamilton, T. H. Henry, A. Jain, G. D. Johnson, J. Kerns, R. R. Koford, C. P. Nicholson, T. J. O'Connell, M. D. Piorkowski, and R. D. Tankersley. 2008. Patterns of bat fatalities at wind energy facilities in North America. Journal of Wildlife Management 72:61–78.

Arnett, E. B., and R. F. May. 2016. Mitigating wind energy impacts on wildlife: approaches for multiple taxa. Human-Wildlife Interactions 10:28–41.

Arnett, E., C. Hein, M. Schirmacher, M. Huso, and J. Szewczak. 2013. Correction: evaluating the effectiveness of an ultrasonic acoustic deterrent for reducing bat fatalities at wind turbines. PLOS ONE 8:10.1371/annotation/a81f59cb-0f82-4c84-a743-895acb4.

Baasch, D. M., A. M. Hegg, J. F. Dwyer, A. J. Caven, W. E. Taddicken, C. A. Worley, A. H. Medaries, C. G. Wagner, P. G. Dunbar, and N. D. Mittman. 2022. Mitigating avian collisions with power lines through illumination with ultraviolet light. Avian Conservation and Ecology 17.

Baerwald, E. F., J. Edworthy, M. Holder, and R. M. R. Barclay. 2009. A Large-Scale Mitigation Experiment to Reduce Bat Fatalities at Wind Energy Facilities. Journal of Wildlife Management 73:1077–1081.

Belant, J. L., and S. K. Ickes. 1997. Mylar Flags as Gull Deterrents. Pages 73–80 *in*. Proceedings of the Thirteenth Great Plains Wildlife Damage Control Workshop.

Bellefleur, D., P. Lee, and R. A. Ronconi. 2009. The impact of recreational boat traffic on Marbled Murrelets (Brachyramphus marmoratus). Journal of Environmental Management 90:531–538.

Bennett, V., and A. Hale. 2018. Resource Availability May Not Be a Useful Predictor of Migratory Bat Fatalities or Activity at Wind Turbines. Diversity 10:44.

Bennett, V. J., and A. M. Hale. 2014. Red aviation lights on wind turbines do not increase bat-turbine collisions. Animal Conservation 17:354–358.

Best, B. D., and P. N. Halpin. 2019. Minimizing wildlife impacts for offshore wind energy development: Winning tradeoffs for seabirds in space and cetaceans in time. B.-S. Yue, editor. PLOS ONE 14:e0215722.

Blackwell, B. F., G. E. Bernhardt, and R. A. Dolbeer. 2002. Lasers at Nonlethal Avian Repellents. The Journal of Wildlife Management 66:250–258.

BOEM. 2021. Conditions of Construction and Operations Plan Approval Lease Number OCS-A 0501 [Vineyard Wind 1]. U.S. Department of the Interior, Bureau of Ocean Energy Management, Washington D.C.

BOEM. 2022. Conditions of Construction and Operations Plan Approval Lease Number OCS-A 0517 [South Fork Wind]. U.S. Department of the Interior, Bureau of Ocean Energy Management, Washington D.C.

Bomford, M., and P. H. O'Brien. 1990. Sonic Deterrents in Animal Damage Control: A Review of Device Tests and Effectiveness. Wildlife Society Bulletin 18:411–422.

Bureau of Ocean Energy Management (BOEM). 2021. Guidelines for Lighting and Marking of Structures Supporting Renewable Energy Development. United States Department of the Interior Bureau of Ocean Energy Management Office of Renewable Energy Programs, Stirling, VA.

Bureau of Ocean Energy Management (BOEM). 2023. Conditions of Construction and Operations Plan Approval Lease Number OCS-A 0486 [Revolution Wind]. U.S. Department of the Interior, Bureau of Ocean Energy Management, Washington D.C.

Bureau of Ocean Energy Management (BOEM). 2024. Conditions of Construction and Operations Plan Approval Lease Number OCS-A 0483 [Coastal Virginia Offshore Wind]. U.S. Department of the Interior, Bureau of Ocean Energy Management, Washington D.C.

Burt, C. S., J. F. Kelly, G. E. Trankina, C. L. Silva, A. Khalighifar, H. C. Jenkins-Smith, A. S. Fox, K. M. Fristrup, and K. G. Horton. 2023. The effects of light pollution on migratory animal behavior. Trends in Ecology & Evolution 38:355–368.

Christensen-Dalsgaard, S., N. Dehnhard, B. Moe, G. H. R. Systad, and A. Follestad. 2019. Unmanned installations and birds. A desktop study on how to minimize area of conflict. Norwegian Institute for Nature Research, Trondheim, Norway.

Cohen, E. B., J. J. Buler, K. G. Horton, S. R. Loss, S. A. Cabrera-Cruz, J. A. Smolinsky, and P. P. Marra. 2022. Using weather radar to help minimize wind energy impacts on nocturnally migrating birds. Conservation Letters 15:e12887.

Conn, P. B., and G. K. Silber. 2013. Vessel speed restrictions reduce risk of collision-related mortality for North Atlantic right whales. Ecosphere 4:1–16.

Conover, M. R. 1984. Comparative Effectiveness of Avitrol, Exploders, and Hawk-Kites in Reducing Blackbird Damage to Corn. The Journal of Wildlife Management 48:109–116.

Cook, A. S. C. P., E. M. Humphreys, F. Bennet, E. A. Masden, and N. H. K. Burton. 2018. Quantifying avian avoidance of offshore wind turbines: Current evidence and key knowledge gaps. Marine Environmental Research 140:278–288.

Cook, A. S. C. P., V. H. Ross-Smith, S. Roos, N. H. K. Burton, N. Beale, C. Coleman, H. Daniel, S. Fitzpatrick, E. Rankin, K. Norman, and G. Martin. 2011. Identifying a range of options to prevent or reduce avian collision with offshore wind farms using a UK-based case study. British Trust for Ornithology, Thetford, UK.

Cook, A. S. C. P., E. Salkanovic, E. Masden, H. E. Lee, and A. H. Kiilerich. 2025. A critical appraisal of 40 years of avian collision risk modelling: How have we got here and where do we go next? Environmental Impact Assessment Review 110:107717.

Council on Environmental Quality. 2020. Protection of the environment (under the National Environment Policy Act). Council on Environmental Quality, Washington, D.C.

Crawford, R. L., and R. T. Engstrom. 2001. Characteristics of Avian Mortality at a North Florida Television tower: a 29-Year Study. Journal of Field Ornithology 72:380–388.

Croll, D. A., A. A. Ellis, J. Adams, A. S. C. P. Cook, S. Garthe, M. W. Goodale, C. S. Hall, E. Hazen, B. S. Keitt, E. C. Kelsey, J. B. Leirness, D. E. Lyons, M. W. McKown, A. Potiek, K. R. Searle, F. H. Soudijn, R. C. Rockwood, B. R. Tershy, M. Tinker, E. A. VanderWerf, K. A. Williams, L. Young, and K. Zilliacus. 2022. Framework for assessing and mitigating the impacts of offshore wind energy development on marine birds. Biological Conservation 276:109795.

Crown Estate Scotland. 2024. Collaboration for Environmental Mitigation & Nature Inclusive Design (CEMNID) Mitigation Measures Efficacy Review. Xodus Group.

Cryan, P. M., and A. C. Brown. 2007. Migration of bats past a remote island offers clues toward the problem of bat fatalities at wind turbines. Biological Conservation 139:1–11.

Cryan, P. M., P. M. Gorresen, B. R. Straw, S. (Simon) Thao, and E. DeGeorge. 2022. Influencing Activity of Bats by Dimly Lighting Wind Turbine Surfaces with Ultraviolet Light. Animals 12:9.

Curtis, P. D., C. R. Smith, and W. Evans. 1993. Techniques for reducing bird use at Nanticoke landfill near E.A. Link Airport, Broome County, New York. Page 11 *in*. Sixth Eastern Wildlife Damage Control Conference.

Danovaro, R., S. Bianchelli, P. Brambilla, G. Brussa, C. Corinaldesi, A. Del Borghi, A. Dell'Anno, S. Fraschetti, S. Greco, M. Grosso, E. Nepote, L. Rigamonti, and F. Boero. 2024. Making eco-sustainable floating offshore wind farms: Siting, mitigations, and compensations. Renewable and Sustainable Energy Reviews 197:114386.

Defingou, M., F. Bils, B. Horchler, T. Liesenjohann, and G. Nehls. 2019. PHAROS4MPAs: A Review of Solutions to Avoid and Mitigate Environmental Impacts of Offshore Windfarms. BioConsult SH for WWF France, Husum, Germany.

Degraer, S., D. A. Carey, J. W. P. Coolen, Z. L. Hutchison, F. Kerckhof, B. Rumes, and J. Vanaverbeke. 2020. Offshore wind farm artificial reefs affect ecosystem structure and functioning: A synthesis. Oceanography 33:48–57.

Dias, M. P., R. Martin, E. J. Pearmain, I. J. Burfield, C. Small, R. A. Phillips, O. Yates, B. Lascelles, P. G. Borboroglu, and J. P. Croxall. 2019. Threats to seabirds: A global assessment. Biological Conservation 237:525–537.

Dierschke, V., R. W. Furness, and S. Garthe. 2016. Seabirds and offshore wind farms in European waters: Avoidance and attraction. Biological Conservation 202:59–68.

Dooling, R. J. 2002. Avian Hearing and the Avoidance of Wind Turbines. National Renewable Energy Laboratory, Golden, CO.

Dorey, K., S. Dickey, and T. R. Walker. 2019. Testing efficacy of bird deterrents at wind turbine facilities: a pilot study in Nova Scotia, Canada. Proceedings of the Nova Scotian Institute of Science (NSIS) 50:91.

Drewitt, A. L., and R. H. W. Langston. 2006. Assessing the impacts of wind farms on birds. Ibis 148:29–42.

Drewitt, A. L., and R. H. W. Langston. 2008. Collision effects of wind-power generators and other obstacles on birds. Annals of the New York Academy of Sciences 1134:233–66.

Edwards-Jones, A., S. C. L. Watson, C. L. Szostek, and N. J. Beaumont. 2024. Stakeholder insights into embedding marine net gain for offshore wind farm planning and delivery. Environmental Challenges 14:100814.

English, P. A., T. I. Mason, J. T. Backstrom, B. J. Tibbles, A. A. Mackay, M. J. Smith, and T. Mitchell. 2017. Improving Efficiencies of National Environmental Policy Act Documentation for Offshore Wind Facilities Case Studies Report. US Dept. of the Interior, Bureau of Ocean Energy Management, Sterling, VA.

Enos, J. K., M. P. Ward, and M. E. Hauber. 2021. A review of the scientific evidence on the impact of biologically salient frightening devices to protect crops from avian pests. Crop Protection 148:105734.

Environment and Climate Change Canada. 2016. Procedures for handling and documenting stranded birds encountered on infrastructure offshore Atlantic Canada. Environment and Climate Change Canada, Gatineau, Quebec.

Eshleman, K. N., and A. Elmore. 2013. Recommended Best Management Practices for Marcellus Shale Gas Development in Maryland. Maryland Department of the Environment, Baltimore, Maryland.

E-TWG Bird and Bat Specialist Committee. 2020. Summary of Discussions from the Bird and Bat Specialist Committee of the Environmental Technical Working Group (E-TWG). New York Offshore Wind Environmental Technical Working Group, Albany, NY.

Evans, W. R., Y. Akashi, N. S. Altman, and A. M. Manville. 2007. Response of night-migrating songbirds in cloud to colored and flashing light. North American Birds 60:476–488.

Everaert, J., and E. W. M. Stienen. 2007. Impact of wind turbines on birds in Zeebrugge (Belgium): Significant effect on breeding tern colony due to collisions. Biodiversity and Conservation 16:3345–3359.

Fox, A. D., and I. K. Petersen. 2019. Offshore wind farms and their effects on birds. Dansk Orn. Foren. Tidsskr. 113:86–101.

Frick, W. F., E. F. Baerwald, J. F. Pollock, R. M. R. Barclay, J. A. Szymanski, T. J. Weller, A. L. Russell, S. C. Loeb, R. A. Medellin, and L. P. McGuire. 2017. Fatalities at wind turbines may threaten population viability of a migratory bat. Biological Conservation 209:172–177.

Frick, W. F., T. Kingston, and J. Flanders. 2020. A review of the major threats and challenges to global bat conservation. Annals of the New York Academy of Sciences 1469:5–25.

Garcia-Rosa, P. B., and J. O. G. Tande. 2023. Mitigation measures for preventing collision of birds with wind turbines. Journal of Physics: Conference Series 2626:012072.

Gartman, V., L. Bulling, M. Dahmen, G. Geißler, and J. Köppel. 2016. Mitigation measures for wildlife in wind energy development, consolidating the state of knowledge — Part 2: Operation, decommissioning. Journal of Environmental Assessment Policy and Management 18:1650014.

Garvin, J. C., J. L. Simonis, and J. L. Taylor. 2024. Does size matter? Investigation of the effect of wind turbine size on bird and bat mortality. Biological Conservation 291:110474.

Gaultier, S. P., T. M. Lilley, E. J. Vesterinen, and J. E. Brommer. 2023. The presence of wind turbines repels bats in boreal forests. Landscape and Urban Planning 231:104636.

Gauthreaux, S., and C. G. Belser. 2006. Effects of artificial night lighting on migrating birds. Pages 67–93 *in*. Ecological Consequences of Artificial Night Lighting. Island Press, Washington, D.C.

Gehring, J., P. Kerlinger, and A. M. Manville. 2009. Communication towers, lights, and birds: successful methods of reducing the frequency of avian collisions. Ecological Applications 19:505–514.

Gilmour, L. R. V., M. W. Holderied, S. P. C. Pickering, and G. Jones. 2020. Comparing acoustic and radar deterrence methods as mitigation measures to reduce human-bat impacts and conservation conflicts. M. Smotherman, editor. PLOS ONE 15:e0228668.

Gilmour, L. R. V., M. W. Holderied, S. P. C. Pickering, and G. Jones. 2021. Acoustic deterrents influence foraging activity, flight and echolocation behaviour of free-flying bats. The Journal of Experimental Biology 224:jeb242715.

Gilsdorf, J. M., S. E. Hygnstrom, and K. C. VerCauteren. 2002. Use of frightening devices in wildlife damage management. Integrated Pest Management 7:29–45.

Glahn, J. F., G. Ellis, P. Fioranelli, and B. S. Dorr. 2000. Evaluation of Moderate and Low-Powered Lasers for Dispersing Double-crested Cormorants from Their Night Roosts. Pages 34–45 *in*. Proceedings of the 9th Wildlife Damage Management Conference. Volume 11.

Goodale, M. W., and A. Milman. 2020. Assessing cumulative exposure of Northern Gannets to offshore wind farms. Wildlife Society Bulletin 44:252–259.

Goodale, M. W., A. Milman, and C. R. Griffin. 2019. Assessing the cumulative adverse effects of offshore wind energy development on seabird foraging guilds along the East Coast of the United States. Environmental Research Letters 14:074018.

Goodale, M. W., and I. J. Stenhouse. 2016. A conceptual model to determine vulnerability of wildlife populations to offshore wind energy development. Human-Wildlife Interactions 10:53–61.

Gorresen, M. M., P. M. Cryan, D. C. Dalton, S. Wolf, J. A. Johnson, C. M. Todd, and F. J. Bonaccorso. 2015. Dim Ultraviolet Light as a Means of Deterring Activity by the Hawaiian Hoary Bat *Lasiurus cinereus semotus*. Endangered Species Research 28:249–257.

Guest, E. E., B. F. Stamps, N. D. Durish, A. M. Hale, C. D. Hein, B. P. Morton, S. P. Weaver, and S. R. Fritts. 2022. An Updated Review of Hypotheses Regarding Bat Attraction to Wind Turbines. Animals 12.

Hayes, M. A., S. R. Lindsay, D. I. Solick, and C. M. Newman. 2023. Simulating the influences of bat curtailment on power production at wind energy facilities. Wildlife Society Bulletin 47:e1399.

Hazel, J., I. R. Lawler, H. Marsh, and S. Robson. 2007. Vessel speed increases collision risk for the green sea turtle *Chelonia mydas*. Endangered Species Research 3:105–113.

Hein, C., and B. Straw. 2021. Proceedings from the State of the Science and Technology for Minimizing Impacts to Bats from Wind Energy. National Renewable Energy Laboratory, Golden, CO.

Hein, C., K. A. Williams, and E. Jenkins. 2021. Bat Workgroup Report for the State of the Science Workshop on Wildlife and Offshore Wind Energy 2020: Cumulative Impacts. New York Energy Research and Development Authority, Albany, NY.

Hill, R., K. Hill, R. Aumuller, A. Schulz, T. Dittmann, C. Kulemeyer, and T. Coppack. 2014. Of birds, blades, and barriers: Detecting and analysing mass migration events at alpha ventus. Pages 111–132 *in* A. Beiersdorf and K. Wollny-Goerke, editors. Ecological Research at the Offshore Windfarm alpha ventus - Challenges, Results, and Perspectives. Springer Spektrum, Hamburg and Berlin, Germany.

Hodos, W. 2003. Minimization of Motion Smear: Reducing Avian Collisions with Wind Turbines. National Renewable Energy Laboratory, Golden, CO.

Jägerbrand, A. K., and C. A. Bouroussis. 2021. Ecological Impact of Artificial Light at Night: Effective Strategies and Measures to Deal with Protected Species and Habitats. Sustainability 13:5991.

Jodice, P. G. R., E. M. Adams, J. Lamb, Y. Satgé, and J. S. Gleason. 2019. GoMAMN Strategic Bird Monitoring Guidelines: Seabirds. Pages 129–170 *in*. Strategic Bird Monitoring Guidelines for the Northern Gulf of Mexico. Mississippi Agricultural and Forestry Experiment Station Research Bulletin, Mississippi State University.

Johnson, G. D., W. P. Erickson, M. D. Strickland, M. F. Shepherd, D. A. Shepherd, and S. A. Sarappo. 2003. Mortality of Bats at a Large-scale Wind Power Development at Buffalo Ridge, Minnesota. American Midland Naturalist 150:332–342.

Kerlinger, P., J. L. Gehring, W. P. Erickson, R. Curry, A. Jain, and J. Guarnaccia. 2010. Night migrant fatalities and obstruction lighting at wind turbines in North America. The Wilson Journal of Ornithology 122:744–754.

Kiesecker, J. M., H. Copeland, A. Pocewicz, and B. McKenney. 2010. Development by design: blending landscape-level planning with the mitigation hierarchy. Frontiers in Ecology and the Environment 8:261–266.

Lagerveld, S., T. Wilkes, M. E. B. van Puijenbroek, B. C. A. Noort, and S. C. V. Geelhoed. 2023. Acoustic monitoring reveals spatiotemporal occurrence of Nathusius' pipistrelle at the southern North Sea during autumn migration. Environmental Monitoring and Assessment 195:1016.

Lamb, J., J. Gulka, E. Adams, A. Cook, and K. A. Williams. 2024. A synthetic analysis of post-construction displacement and attraction of marine birds at offshore wind energy installations. Environmental Impact Assessment Review 108:107611.

Langston, R. H. W. 2013. Birds and wind projects across the pond: A UK perspective. Wildlife Society Bulletin 37:5–18.

Langston, R., and J. Pullan. 2003. Windfarms and Birds: An analysis of the effects of windfarms on birds, and guidance on environmental assessment criteria and site selection issues. BirdLife International to the Council of Europe, Bern Convention on the Conservation of European Wildlife and Natural Habitats, Strasbourg, Germany.

Long, C. V., J. A. Flint, and P. A. Lepper. 2011. Insect attraction to wind turbines: Does colour play a role? European Journal of Wildlife Research 57:323–331.

Lüdeke, J. 2019. Retrospective and Outlook for an Environmentally Sound Development of Offshore Wind Energy. International Journal of Environmental Science 4:1–19.

Maclean, I. M. D., M. M. Rehfisch, H. Skov, and C. B. Thaxter. 2013. Evaluating the statistical power of detecting changes in the abundance of seabirds at sea. M. Bolton, editor. Ibis 155:113–126.

Marques, A. T., H. Batalha, S. Rodrigues, H. Costa, M. João, R. Pereira, C. Fonseca, M. Mascarenhas, and J. Bernardino. 2014. Understanding bird collisions at wind farms: An updated review on the causes and possible mitigation strategies. Biological Conservation 179:40–52.

Martins, R. C., J. Bernardino, and F. Moreira. 2023. A review of post-construction monitoring practices used in the evaluation of transmission power line impacts on birds and mitigation effectiveness, with proposals for guideline improvement. Environmental Impact Assessment Review 100:107068.

May, R., T. Nygård, U. Falkdalen, J. Åström, Ø. Hamre, and B. G. Stokke. 2020. Paint it black: Efficacy of increased wind turbine rotor blade visibility to reduce avian fatalities. Ecology and Evolution 10:8927–8935.

May, R., O. Reitan, K. Bevanger, S.-H. Lorentsen, and T. Nygård. 2015. Mitigating wind-turbine induced avian mortality: Sensory, aerodynamic and cognitive constraints and options. Renewable and Sustainable Energy Reviews 42:170–181.

McGregor, R., M. Trinder, and N. Goodship. 2022. Assessment of compensatory measures for impacts of offshore windfarms on seabirds. Natural England, York, UK.

Miles, W., S. Money, R. Luxmoore, and R. W. Furness. 2010. Effects of artificial lights and moonlight on petrels at St Kilda. Bird Study 57:244–251.

Mockrin, M. H., and R. A. Gravenmier. 2012. Synthesis of wind energy development and potential impacts on wildlife in the Pacific Northwest, Oregon and Washington. United States Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.

Montevecchi, W. A. 2006. Influences of artificial light on marine birds. Pages 94–113 *in* C. Rich and T. Longcore, editors. Ecological Consequences of Artificial Night Lighting. Island Press, Washington, D.C.

Montoney, A. J., and H. C. Boggs. 1993. Effects of a Bird Hazard Reduction Force on Reducing Bird / Aircraft Strike Hazards At the Atlantic City International Airport , NJ. Pages 1–8 *in*. Proceedings of the 6th Eastern Wildlife Damage Control Conference.

Mott, D. F., and S. K. Timbrook. 1988. Alleviating Nuisance Canada Goose Problems with Acoustical Stimuli. Proceedings of the Thirteenth Vertebrate Pest Conference 301–304.

Murgatroyd, M., W. Bouten, and A. Amar. 2021. A predictive model for improving placement of wind turbines to minimise collision risk potential for a large soaring raptor. Journal of Applied Ecology 58:857–868.

Neate-Clegg, M. H. C., J. J. Horns, F. R. Adler, M. Ç. Kemahlı Aytekin, and Ç. H. Şekercioğlu. 2020. Monitoring the world's bird populations with community science data. Biological Conservation 248:108653.

Nicholls, B., and P. A. Racey. 2007. Bats Avoid Radar Installations: Could Electromagnetic Fields Deter Bats From Colliding With Wind Turbines? PLoS ONE 2:e297.

Nicholls, B., and P. A. Racey. 2009. The aversive effect of electromagnetic radiation on foraging bats - A possible means of discouraging bats from approaching wind turbines. PLoS ONE 4:e6246.

Nogales, M., E. Vidal, F. M. Medina, E. Bonnaud, B. R. Tershy, K. J. Campbell, and E. S. Zavaleta. 2013. Feral Cats and Biodiversity Conservation: The Urgent Prioritization of Island Management. BioScience 63:804–810.

ONeil, D. R. 2020. Reducing Bat Fatalities Using Ultrasonic Acoustic Deterrent Technology: A Potential Mechanism for Conservation at Offshore Wind Energy Sites. M.S. thesis, Harvard Extension School, Boston, MA.

Pascal, M., O. Lorvelec, V. Bretagnolle, and J. Culioli. 2008. Improving the breeding success of a colonial seabird: a cost-benefit comparison of the eradication and control of its rat predator. Endangered Species Research 4:267–276.

Peste, F., A. Paula, L. P. da Silva, J. Bernardino, P. Pereira, M. Mascarenhas, H. Costa, J. Vieira, C. Bastos, C. Fonseca, and M. J. R. Pereira. 2015. How to mitigate impacts of wind farms on bats? A review of potential conservation measures in the European context. Environmental Impact Assessment Review 51:10–22.

Phalan, B., G. Hayes, S. Brooks, D. Marsh, P. Howard, B. Costelloe, B. Vira, A. Kowalska, and S. Whitaker. 2018. Avoiding impacts on biodiversity through strengthening the first stage of the mitigation hierarchy. Oryx 52:316–324.

Poot, H., B. J. Ens, H. de Vries, M. A. H. Donners, M. R. Wernand, and J. M. Marquenie. 2008. Green light for nocturnally migrating birds. Ecology & Society 13:47.

Rebke, M., V. Dierschke, C. N. Weiner, R. Aumüller, K. Hill, and R. Hill. 2019. Attraction of nocturnally migrating birds to artificial light: The influence of colour, intensity and blinking mode under different cloud cover conditions. Biological Conservation 233:220–227.

Reed, J. R., J. L. Sincock, and J. P. Hailman. 1985. Light Attraction in Endangered Procellariiform Birds : Reduction by Shielding Upward Radiation. The Auk 102:377–383.

Regional Synthesis Workgroup of the Environmental Technical Working Group. 2023. Responsible Practices for Regional Wildlife Monitoring and Research in Relation to Offshore Wind Energy Development. New York Offshore Wind Environmental Technical Working Group, Albany, NY.

Reusch, C., M. Lozar, S. Kramer-Schadt, and C. C. Voigt. 2022. Coastal onshore wind turbines lead to habitat loss for bats in Northern Germany. Journal of Environmental Management 310:114715.

Ronconi, R. A., and C. C. St. Clair. 2002. Management Options to Reduce Boat Disturbance on Foraging Black Guillemots (*Cepphus grylle*) in the Bay of Fundy. Biological Conservation 108:265–271.

Russell, D. J. F., S. M. J. M. Brasseur, D. Thompson, G. D. Hastie, V. M. Janik, G. Aarts, B. T. McClintock, J. Matthiopoulos, S. E. W. Moss, and B. McConnell. 2014. Marine mammals trace anthropogenic structures at sea. Current Biology 24:638–639.

Rydell, J., H. Engström, A. Hedenström, J. K. Larsen, J. Pettersson, and M. Green. 2012. The effect of wind power on birds and bats-A synthesis. Swedish Environmental Protection Agency, Stockholm, Sweden.

Schirmacher, M. R. 2020. Evaluating the Effectiveness of an Ultrasonic Acoustic Deterrent in Reducing Bat Fatalities at Wind Energy Facilities. Bat Conservation International, Austin, TX.

Sherman, D. E., and A. E. Barras. 2004. Efficacy of a Laser Device for Hazing Canada Geese from Urban Areas of Northeast Ohio. The Ohio Journal of Science, 104:38–42.

Simmons, R. E., S. Ralston-Paton, R. Colyn, and M.-S. Garcia-Heras. 2020. Black Harriers and Wind Energy: Guidelines for impact assessment, monitoring and mitigation. BirdLife South Africa, Johannesburg, South Africa.

Sinclair, K., and E. DeGeorge. 2016. Framework for Testing the Effectiveness of Bat and Eagle Impact-Reduction Strategies at Wind Energy Projects. National Renewable Energy Laboratory, U.S. Department of Energy, Golden, CO.

Skov, H., S. Heinanen, T. Norman, R. M. Ward, S. Mendez-Roldan, and I. Ellis. 2018. ORJIP Bird Collision and Avoidance Study. Final Report - April 2018. The Carbon Trust, United Kingdom.

Smallwood, K. S., and D. A. Bell. 2020. Effects of Wind Turbine Curtailment on Bird and Bat Fatalities. Journal of Wildlife Management. https://doi.org/10.1002/jwmg.21844.

Solick, D. I., and C. M. Newman. 2021. Oceanic records of North American bats and implications for offshore wind energy development in the United States. Ecology and Evolution 11:14433–14447.

Spatz, D. R., N. D. Holmes, D. J. Will, S. Hein, Z. T. Carter, R. M. Fewster, B. Keitt, P. Genovesi, A. Samaniego, D. A. Croll, B. R. Tershy, and J. C. Russell. 2022. The global contribution of invasive vertebrate eradication as a key island restoration tool. Scientific Reports 12:13391.

Stantec Consulting Services Inc. 2016. Long-term bat monitoring on islands, offshore structures, and coastal sites in the Gulf of Maine, mid-Atlantic, and Great Lakes - Final Report. U.S. Department of Energy, Tompsham, ME.

Stevens, G. R., J. Rogue, R. Weber, and L. Clark. 2000. Evaluation of a Radar-activated, Demand-performance Bird Hazing System. International Biodeterioration and Biodegradation 45:129–137.

Stickley, A. R., and J. O. King. 1993. Long-Term Trial of An Inflatable Effigy Scare Device for Repelling Cormorants from Catfish Ponds. Pages 1–5 *in*. Proceedings of the 6th Eastern Wildlife Damage Control Conference.

Stone, E. L., S. Harris, and G. Jones. 2015. Impacts of artificial lighting on bats: A review of challenges and solutions. Mammalian Biology 80:213–219.

Syposz, M., O. Padget, J. Willis, B. M. V. Doren, N. Gillies, A. L. Fayet, M. J. Wood, A. Alejo, and T. Guilford. 2021. Avoidance of different durations, colours and intensities of artificial light by adult seabirds. Scientific Reports 1–13.

Szostek, C. L., A. Edwards-Jones, N. J. Beaumont, and S. C. L. Watson. 2024. Primary vs grey: A critical evaluation of literature sources used to assess the impacts of offshore wind farms. Environmental Science & Policy 154:103693.

Thaxter, C. B., V. H. Ross-Smith, W. Bouten, N. A. Clark, G. J. Conway, E. A. Masden, G. D. Clewley, L. J. Barber, and N. H. K. Burton. 2019. Avian vulnerability to wind farm collision through the year: Insights from lesser black-backed gulls (*Larus fuscus*) tracked from multiple breeding colonies. Journal of Applied Ecology 56:2410–2422.

Thelander, C. G., K. S. Smallwood, and L. Rugge. 2003. Bird Risk Behaviors and Fatalities at the Altamont Pass Wind Resource Area: Period of Performance, March 1998--December 2000. National Renewable Energy Laboratory, Golden, CO.

Thurber, B. G., R. J. Kilpatrick, G. H. Tang, C. Wakim, and J. R. Zimmerling. 2023. Economic Impacts of Curtailing Wind Turbine Operations for the Protection of Bat Populations in Ontario. Wind 3:291–301.

Tjørnløv, R. S., H. Skov, M. Armitage, M. Barker, J. B. Jørgensen, L. O. Mortensen, K. Thomas, T. Uhrenholdt, and 11820296. 2023. Resolving Key Uncertainties of Seabird Flight and Avoidance Behaviours at Offshore Wind Farms: Final report for the study period 2020-2021. Vattenfall, Horsholm, Denmark.

Tulp, I., H. Schekkerman, J. K. Larsen, J. Van Der Winden, R. J. W. Van De Haterd, P. Van Horssen, S. Dirksen, and A. L. Spaans. 1999. Nocturnal Flight Activity of Sea Ducks Near the Windfarm Tunø Knob in the Kattegat. Bureau Waardenburg, Culemborg, Netherlands.

U.S. Fish and Wildlife Service (USFWS). 2012. U.S. Fish and Wildlife Service Land-based Wind Energy Guidelines. U.S. Fish and Wildlife Service, Arlington, VA.

U.S. Fish and Wildlife Service (USFWS). 2021. Recommended Best Practices for Communication Tower Design, Siting, Construction, Operation, Maintenance, and Decommissioning. U.S. Fish and Wildlife Service, Migratory Bird Program, Falls Church, VA.

U.S. Fish and Wildlife Service (USFWS). 2023. U.S. Fish & Wildlife Service Mitigation Policy (Appendix 1, 501 FW 2). U.S. Fish and Wildlife Service, Arlington, VA.

Vaissière, A.-C., H. Levrel, S. Pioch, and A. Carlier. 2014. Biodiversity Offsets for Offshore Wind Farm Projects: The Current Situation in Europe. Marine Policy 48:172–183.

Van Hoorick, G. 2014. Compensatory Measures in European Nature Conservation Law. Utrecht Law Review 10:161.

Vattenfall. 2022. Research into the effect of black blade in wind turbine. <https://group.vattenfall.com/press-and-media/newsroom/2022/black-turbine-blades-reduce-bird-collisions>. Accessed 12 Aug 2024.

Verfuss, U. K., C. E. Sparling, C. Arnot, A. Judd, and M. Coyle. 2016. Review of Offshore Wind Farm Impact Monitoring and Mitigation with Regard to Marine Mammals. Pages 1175–1182 *in* A. N. Popper and A. Hawkins, editors. The Effects of Noise on Aquatic Life II. Volume 875. Advances in Experimental Medicine and Biology, Springer New York, New York, NY.

Voigt, C. C., K. Rehnig, O. Lindecke, and G. Pētersons. 2018. Migratory bats are attracted by red light but not by warm-white light: Implications for the protection of nocturnal migrants. Ecology and Evolution 1–9.

Walsh, C., O. Hüppop, T. Karwinkel, M. Liedvogel, O. Lindecke, J. D. McLaren, H. Schmaljohann, and B. Siebenhüner. 2024. Light Pollution at Sea: Implications and Potential Hazards of Human Activity for Offshore Bird and Bat Movements in the Greater North Sea.

Watson, R. T., P. S. Kolar, M. Ferrer, T. Nygård, N. Johnston, W. G. Hunt, H. A. Smit-Robinson, C. J. Farmer, M. Huso, and T. E. Katzner. 2018. Raptor Interactions With Wind Energy: Case Studies From Around the World. Journal of Raptor Research 52:1–18.

Werber, Y., G. Hareli, O. Yinon, N. Sapir, and Y. Yovel. 2023. Drone-mounted audio-visual deterrence of bats: implications for reducing aerial wildlife mortality by wind turbines. Remote Sensing in Ecology and Conservation 9:404–419.

Whisson, D. A., and J. Y. Takekawa. 2000. Testing the Effectiveness of an Aquatic Hazing Device on Waterbirds in the San Francisco Bay Estuary of California. Waterbirds: The International Journal of Waterbird Biology 23:56–63.

Whitby, M. D., M. R. Schirmacher, and W. F. Frick. 2021. The State of the Science on Operational Minimization to Reduce Bat Fatality at Wind Energy Facilities. A report submitted to the National Renewable Energy Laboratory. Bat Conservation International, Austin, Texas.

Wiese, F. K., W. A. Montevecchi, G. K. Davoren, F. Huettmann, A. W. Diamond, and J. Linke. 2001. Seabirds at risk around offshore oil platforms in the Northwest Atlantic. Marine Pollution Bulletin 42:1285–1290.

Williams, K. A., J. Gulka, A. S. C. P. Cook, R. H. Diehl, A. Farnsworth, H. Goyert, C. Hein, P. Loring, D. Mizrahi, I. K. Petersen, T. Peterson, K. M. Press, and I. J. Stenhouse. 2024. A framework for studying the effects of offshore wind energy development on birds and bats in the Eastern United States. Frontiers in Marine Science 11.

Williams, K., E. Connelly, S. Johnson, and I. Stenhouse. 2015. Wildlife Densities and Habitat Use Across Temporal and Spatial Scales on the Mid-Atlantic Outer Continental Shelf: Final Report to the Department of Energy EERE Wind & Water Power Technologies Office, Award Number: DE-EE0005362. Biodiversity Research Institute, Portland, ME.

Winiarski, K. J., D. L. Miller, P. W. C. Paton, and S. R. McWilliams. 2014. A spatial conservation prioritization approach for protecting marine birds given proposed offshore wind energy development. Biological Conservation 169:79–88.

Wolf, S., B. Keitt, A. Aguirre-Muñoz, B. Tershy, E. Palacios, and D. Croll. 2006. Transboundary seabird conservation in an important North American marine ecoregion. Environmental Conservation 33:294–305.

World Bank Group. 2015. Environmental, Health, and Safety Guidelines for Wind Energy. The World Bank Group.