Strategies for Mitigating Impacts to Aerofauna from Offshore Wind Energy Development: Available Evidence and Data Gaps

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Abstract

Offshore wind energy (OSW) development, while a key strategy for reducing global reliance on fossil fuels, nevertheless has environmental effects that should be mitigated. We reviewed the scientific literature and gray literature to identify approaches for mitigating (e.g., avoiding, minimizing, or compensating for) the effects of OSW development on birds and bats (aerofauna). The review included studies from other industries where relevant, including terrestrial wind energy and the offshore oil and gas industry. Of a total of 212 mitigation approaches from 233 source documents, 59% of proposed approaches were not tested in the reviewed literature to assess effectiveness at mitigating anthropogenic impacts to aerofauna. Of the mitigation approaches that were field tested or implemented, the reviewed literature indicated evidence of their effectiveness in only about 36% of cases. Thus, there was no evidence of effectiveness for 86% of the mitigation approaches identified in this literature review. For birds, minimization approaches related to lighting (e.g., reducing artificial light, avoiding white and steady-burning lights) were the most commonly tested and effective methods for reducing maladaptive attraction and collisions. For bats, minimization via alteration of turbine operations (e.g., curtailment and feathering of turbine blades) were most commonly shown to be effective. Minimization was the main focus of this review but there is limited evidence of effectiveness for most approaches, and we suggest implementation of dedicated testing to explore the effectiveness of commonly suggested and implemented mitigation measures such as curtailment for birds. As such, 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. To fully mitigate the effects of OSW development on aerofauna, compensation and offset strategies should also be further explored.

Keywords

Mitigation, birds, bats, offshore wind energy development, minimization, avoidance, effectiveness

1. Introduction

OSW development is rapidly growing worldwide. While this growth supports the reduction of greenhouse gas emissions, a critical step to minimizing the effects of climate change on wildlife, OSW development also represents potential risks to wildlife (Peste et al., 2015). Wildlife may be affected with risk of direct effects (e.g., injury/mortality via collisions) or indirect effects (e.g., altered movement patterns, behavior, habitat; (Goodale and Stenhouse, 2016). Many bird and bat species around the world are in decline and are protected at the state, provincial, federal, or international level (Dias et al., 2019; Frick et al., 2020; Neate-Clegg et al., 2020), and the added risks posted by OSW development are important to consider with this context. There are three main types of effects to aerofauna from OSW development: collisions, behavioral change, and habitat-mediated change (Williams et al., 2024). Our scientific understanding of the scale of these effects varies widely. Much of what we know about these pathways and effects come from the offshore wind industry in Europe as well as the onshore wind industry in North America and Europe; however, numerous gaps remain in our understanding (Williams et al., 2024).

Collisions that can lead to injury and mortality are well-documented for bats and avian migrants (e.g., songbirds, raptors) at onshore facilities (Allison et al., 2019). Indeed, concern over high mortality levels, particularly for migratory bats, has led to a large focus on collision mitigation in the onshore wind industry in North America (Adams et al., 2021). There are challenges to measuring collisions offshore, as the key detection method onshore (carcass searches) is largely impossible in the offshore environment. While there have been a few documented collisions of marine birds at offshore wind facilities in Europe via direct observation and camera systems (Skov et al., 2018; Tjørnløv et al., 2023), this phenomenon remains less understood for aerofauna in marine systems than in the terrestrial context. The stressor in the case of collisions is primarily the long-term presence of structures (e.g., novel turbines and substations in the marine environment), though increased risk of collision can also occur due to changes in behavior (e.g., attraction) and habitat-mediated change (e.g., increased prey around turbines). Given the potential for collisions to directly influence population size (as well as relative ease in detecting and measuring effects, at least onshore), many wind energy mitigation strategies for aerofauna focus on collision minimization.

Behavioral change in response to the presence and activities of offshore wind farms can take multiple forms, including avoidance, attraction, and displacement from ideal distributions (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 avoidance depending on many factors including species, facility location and design (Dierschke et al., 2016; Lamb et al., 2024). The mechanisms driving these behavioral responses are likely varied and may be difficult to tease apart in some cases. 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). Artificial light, and specifically steady-burning white light, has been shown to negatively affect a wide range of wildlife (Burt et al., 2023). Birds tend to be attracted to and disoriented by artificial light at night, particularly during migration; this can lead to death via collisions or via exhaustion (as they circle the light source for long periods; (Montevecchi, 2006). Though less commonly reported, artificial light may also cause avoidance in seabirds (Syposz et al., 2021). Artificial lighting is widely known to attract bats, 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),

lighting on offshore wind turbines, vessels, and substations has been identified as a potential risk to aerofauna (Williams et al., 2024).

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. The effects of sound have been documented in marine mammals (Madsen et al., 2006; Thomsen et al., 2006), but this is not well studied in aerofauna.

Finally, habitat-mediated effects to aerofauna include changes in the physical environment and/or resource availability. 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. These habitat-mediated effects are difficult to measure and generally remain poorly understood for aerofauna.

While we can gain understanding of these effects from areas where OSW development is a more established industry (e.g., Europe), there remains a lot of uncertainty in potential effects and the mechanisms driving these effects. In the face of this uncertainty, it is important to consider how best to mitigate these effects. Mitigation of effects such as those posed to aerofauna by the OSW industry is guided by a well-established hierarchy. This mitigation hierarchy has three main components: 1) avoidance, 2) minimization, and 3) compensation. Given this framework, ‘mitigation’ hereafter is used to refer to all steps in the mitigation hierarchy.

Avoidance is a first priority at the top of the hierarchy; the best strategy for dealing with anthropogenic impacts is to avoid those impacts altogether. Subsequent steps occur in descending order of priority such that effects that cannot be avoided should be minimized, then compensated for (Council on Environmental Quality, 2020). From the perspective of mitigating the effects of OSW development on aerofauna, avoidance primarily occurs during planning processes via the siting of projects away from high risk areas (Arnett and May, 2016). Minimization primarily occurs during pre-construction and operations, and can include design decisions (e.g., micro-siting, turbine height, lighting, addition of perching deterrents) as well as operational parameters (e.g., cut-in speeds at which turbines begin generating electricity). The final step in the mitigation hierarchy is compensation or offsets, whereby activities are employed to improve and enhance impacted populations for which effects cannot be fully avoided or minimized. Compensation can occur either on- or off-site and may include options such as habitat creation (e.g., new breeding, roosting, wintering sites) and improvement of existing habitat via invasive species removal or predator control (Arnett and May, 2016). Compensation aims to ensure that negative environmental impacts that cannot be avoided or minimized can be moderated by environmental gains to

produce net neutral or net positive outcomes for affected populations and ecosystems (Kiesecker et al., 2010).

While various mitigation approaches have been proposed for the offshore wind industry, often drawing upon efforts from other industries such as terrestrial wind and offshore oil and gas, many methods remain untested in the offshore wind context. Given the harsh and inaccessible nature of the offshore environment, it can be both challenging and expensive to test mitigation strategies, Moreover, high levels of environmental variability in the marine environment, often coupled with low sample sizes for studies that are trying to measure change in these systems, create challenges in achieving adequate statistical power to provide evidence of effectiveness (Maclean et al., 2013; Regional Synthesis Workgroup of the Environmental Technical Working Group, 2023). Additionally, wildlife species and their habitats may be affected by a range of effects and stressors, as noted above, and the sensitivity and vulnerability of species varies in relation to a variety of factors, both internal (e.g., demographics, life history), and external (e.g., facility layout, location). As a result, many mitigation measures may or may not be effective, and in some cases have already been implemented without the necessary evidence that they are appropriate and effective approaches in the offshore context. This can lead to wasted resources and potential false assurance that effects of OSW development are being appropriately mitigated.

The goal of this review is to assess the state of knowledge for mitigation for aerofauna in relation to OSW development. This includes an inventory of the different mitigations that have been proposed for use for OSW development across jurisdictions. Our focus is on mitigation for aspects of projects in the marine environment (e.g., project footprint, cable and transit routes) as opposed to onshore aspects (e.g., transmission interconnection), recognizing that some mitigation measures discussed in this review may also apply to onshore components of projects. We aim to summarize the weight of evidence supporting various mitigation approaches and identify key knowledge gaps in our understanding, along with potential criteria for prioritizing future studies to examine the effectiveness of mitigation options.

2. Materials and Methods

To assess the state of knowledge of OSW development mitigation for aerofauna, we utilized an existing database of mitigation approaches and conducted an additional literature review to update the information within.

2.1 Mitigation Practices Database

In 2018-2019, the New York State Energy Research and Development Authority funded a desktop review to aggregate and assess practices for minimization and avoidance of impacts to fisheries and offshore species (i.e., birds, bats, marine mammals, sea turtles, fish, and benthos) associated with all phases of OSW development. The database developed from this literature review of existing mitigation approaches, initially called the Mitigation and Monitoring Tool, was made publicly available online and in 2023 was moved to a new location and renamed the Mitigation Practices Database (MPD) Tool (https://www.nyetwg.com/mpd-tool). The sources included in the database for aerofauna (n=109) included peer-reviewed and gray literature (e.g, agency reports, environmental assessments, technical guidance 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). Sources identified during this literature review process cited other papers that were also included in the database 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 (Appendix A; Table S1). This same structure was used for the subsequent update to the literature review conducted in 2024. 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.

2.2 Update to Literature Review

An additional literature review was conducted to update information on mitigation approaches for aerofauna from 2019-2023. A series of literature searches were conducted (focusing primarily 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”). The abstract or summary of each source was 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 extracted following the structure of the MPD Tool database, above. This initial filtering resulted in the identification of 129 additional sources, of which 78 were included in the literature review (the remaining 51 were deemed not relevant following a more in-depth review of the entire document).

2.3 Data Synthesis

Additional sources from 2019-2023 were synthesized with the original mitigation strategies included in the MPD Tool database based on 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. For the various mitigation approaches for aerofauna, we summarized by mitigation category including 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).

3. Results

3.1 Overall Summary

A broad range of mitigation approaches were identified from the existing literature, including 212 approaches from 183 sources (Appendix B-C), focusing on a variety of stressors, potential effects, and industries. There were 76 sources from the literature review update, of which 28 were incorporated into existing approaches in the MPD Tool, while 48 identified new approaches. Mitigation approaches fell into 8 general categories (Figure 1): 1) avoidance measures (e.g., wind farm siting and seasonal restrictions/limitations on activities, other activity limitations), 2) configuration of structures (e.g., wind farm layout, turbine size), 3) turbine operation parameters (e.g., curtailment, shutdown, feathering), 4) lighting to reduce attraction, 5) visibility and detection enhancement, 6) vessel operations and water quality, 7) deterrents and other attraction reduction measures, and 8) compensation/offsets.

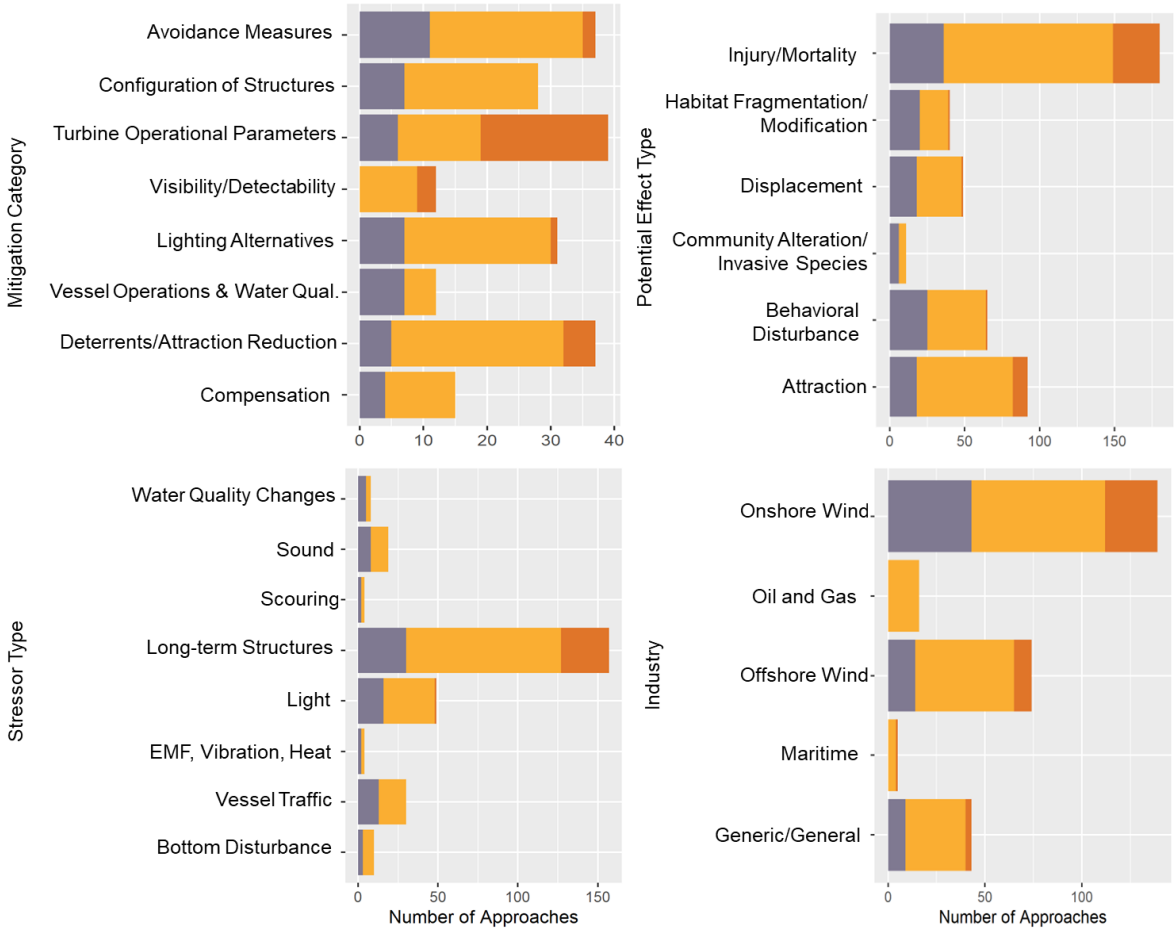

Figure 1. Number of mitigation approaches by general category (top left), potential effect type (top right), stressor (bottom left), and industry (bottom right). Mitigation approaches were directed towards birds (yellow), bats (orange), or both taxa (gray). Mitigation categories are mutually exclusive; however, each mitigation approach could be listed under multiple stressors, effects, and industries.

Across all categories, there were a wider variety of mitigation approaches focused on birds (n=180) than bats (n=78), of which some were applicable to both (n=47). A few approaches (about 15% of the total) were specific to marine birds or nocturnal avian migrants, but most were relatively general. Most mitigation approaches fell into the minimization category of the mitigation hierarchy (n=178), followed by avoidance (n=26), and lastly compensate/offset (n=14). Most mitigation approaches came at least in part from the onshore wind industry (66%), with about 45% of mitigation approaches focused on offshore/marine environments, including offshore oil and gas, offshore wind, and other maritime industries (Figure 1); the remainder were "general" mitigation approaches that were not suggested in relation to a specific type of industrial development, including studies focused on the agricultural sector.

Most mitigation approaches (74%) focused on the presence of long-term structures as the primary stressor type, followed by lighting (23%) and changes in vessel traffic (14%). This is unsurprising given the identification of long-term structures as the main source of OSW's potential effects to aerofauna (Williams et al., 2024). Most mitigation approaches focused on mitigating injury/mortality (85%) or behavioral disturbance (31%; Figure 1). Within approaches focused on injury/mortality, 51% also focused on attraction. 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 turbine operation mitigations included the greatest number of bat-related approaches (Figure 1), 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 40% of mitigation approaches have been implemented or field tested (Figure 2), regardless of category or taxonomic focus. An additional 19% had clearly not been implemented or tested. For the remaining 41%, it was unclear if the approaches had been implemented or tested. It is likely that implementing and testing of certain approaches were not explored due to feasibility, cost, or other limiting factors. This means that 66% of approaches had likely not been tested to assess whether they were effective. Of those mitigation approaches that were field tested or implemented, evidence of their effectiveness was found in about 36% of cases (or 14% of all mitigation approaches in the database). Thus, there was no evidence of effectiveness for 86% of the mitigation approaches identified in this literature review.

The mitigation approaches for which there was evidence of effectiveness were primarily focused on birds, or on both birds and bats (74%). However, a higher *ratio* of mitigation approaches that had been tested for bats were shown to be effective (primarily approaches relating to curtailment). 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 towards onshore, onshore/offshore, or generic situations. 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.

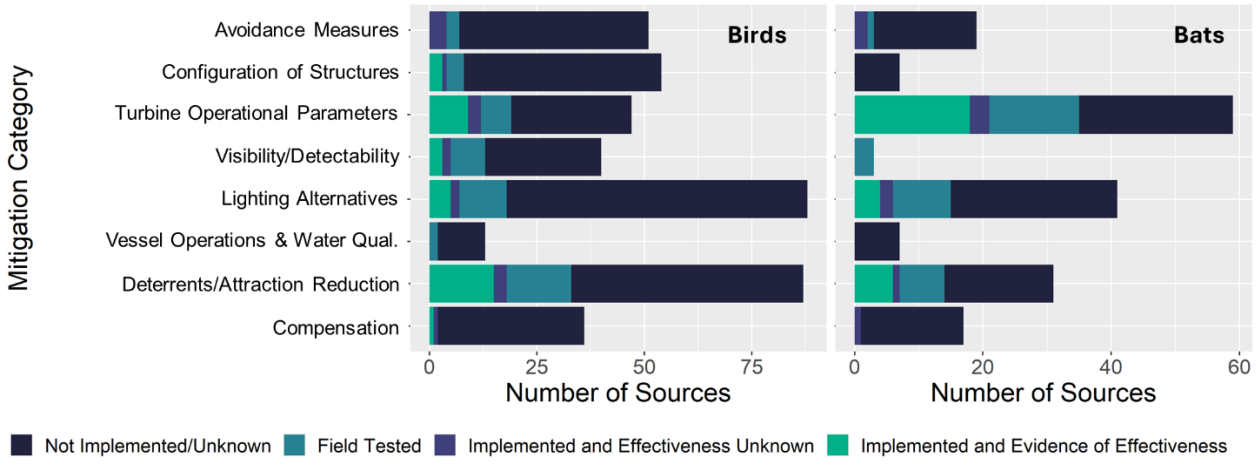

Figure 2. Number of sources by category for birds (left) and bats (right) for various mitigation approaches along with the level of testing and evidence for effectiveness (dark blue = mitigation approach was not implemented/tested in the source document or it was unclear whether it had been implemented; 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).

The most tested or implemented bird mitigation approaches were focused on minimization (i.e., deterrents) and attraction reduction measures. Other minimization measures had high rates of testing, including lighting and visibility enhancement and turbine operation parameters. Much of the testing of these types of mitigation approaches occurred in relation to the onshore wind industry. For bat mitigation, turbine operation parameters (e.g., curtailment) had the highest testing rate and evidence of effectiveness, though lighting and visibility enhancement, and deterrence/attraction reduction, also exhibited high rates of testing and effectiveness. In contrast, mitigation methods focused on the configuration of wind farm structures, siting, seasonality, and compensation, were not well tested in the reviewed literature.

3.2 Avoidance Measures

Per the mitigation hierarchy, avoidance of impacts is the most effective and highest-priority strategy for mitigating anthropogenic impacts to wildlife and ecosystems (Council on Environmental Quality, 2020; Croll et al., 2022). Thirty-seven different mitigation approaches were suggested in 43 reviewed literature sources to avoid impacts to aerofauna by 1) siting development activities away from important populations or habitats (n=13 approaches), 2) conducting development activities outside of important habitat use periods (e.g., seasonal restrictions; n=5 approaches), 3) limiting activities (for example, phasing construction activities to avoid higher-risk time periods; n=15), and 4) communication and engagement with stakeholders (n=4). Approaches varied in their specifics, but many were very similar in concept. Surprisingly, given that siting is generally considered to be the best available mitigation

approach for avoiding risk to birds (Williams et al., 2024), the literature included some kind of preliminary or desktop-based assessment of their effectiveness for only three of these proposed approaches, and only included one document where an approach was actually implemented and showed evidence of effectiveness.

3.2.1 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 (Defingou et al., 2019; May et al., 2015; Simmons et al., 2020), designated Important Bird Areas and other areas of high bird usage, e.g., with known natural concentrations of birds (Drewitt and Langston, 2006; Langston and Pullan, 2003; Lüdeke, 2019), known feeding, staging, or loafing locations (Defingou et al., 2019; Lüdeke, 2019; Thaxter et al., 2019), migratory and commuting pathways (Defingou et al., 2019; Langston and Pullan, 2003; Lüdeke, 2019; Mockrin and Gravenmier, 2012), areas of high prey density (Watson et al., 2018), shallow waters and waters in proximity to shore (Goodale and Milman, 2020; Lagerveld et al., 2023; Williams et al., 2015), sensitive habitats (Mockrin and Gravenmier, 2012; Rydell et al., 2012), and undisturbed areas (Eshleman and Elmore, 2013; Mockrin and Gravenmier, 2012). 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 (Cohen et al., 2022; Gaultier et al., 2023; Murgatroyd et al., 2021). 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 (Eshleman and Elmore, 2013; Mockrin and Gravenmier, 2012; Rydell et al., 2012).

While siting-related mitigation strategies are almost entirely applicable prior to construction of wind farms, at least one review paper also suggested that micro-siting can be an important avoidance strategy for repowering existing wind farms, e.g., via revision to wind farm layouts or decommissioning of turbines that proved to be particularly problematic from the standpoint of wildlife effects (Marques et al., 2014). However, this type of micrositing must be informed by data such as collision rates at individual turbines, which are generally more accessible for terrestrial wind energy projects than offshore wind facilities.

Most jurisdictions have implemented some type of spatial planning to inform siting projects, with at least some consideration of wildlife-related impacts as part of that process (including other taxa as well as aerofauna; for example, see (Farmer et al., 2023; Randall et al., 2022). Similar spatial planning efforts to avoid important wildlife areas have also occurred for other industries such as terrestrial wind energy development (Liang et al., 2023). Despite the common acceptance of avoidance as the most effective way to mitigate impacts, relatively few studies in our database actually tested this assumption. Several studies used different types of avian movement data to inform model-based assessments of risk, however; 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 would 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. (Murgatroyd et al., 2021) modeled movement data for Verraux's Eagle (*Aquila verreauxii*) and found that a combination of nesting areas and topographic features could be used to predict collision risk across the landscape, and thus inform siting decisions.

3.2.2 Temporal Avoidance

Several approaches focus on temporal, rather than spatial, separation (n=7). This involves scheduling disruptive activities to avoid sensitive life history periods and/or times of high habitat use. This includes scheduling construction activities to avoid the avian breeding season and other times of high bird or bat abundance, such as migratory or wintering periods, depending on the taxa and location (Cook et al., 2011; English et al., 2017; Eshleman and Elmore, 2013; Langston, 2013; May et al., 2015; Mockrin and Gravenmier, 2012; Vaissière et al., 2014; World Bank Group, 2015). Additionally, avoiding scheduling vessel and helicopter activity, as well as other maintenance activities, outside of sensitive life history periods and times of peak habitat use at the development site was recommended (Gartman et al., 2016; U.S. Fish and Wildlife Service (USFWS), 2021).

Seasonal limitations on construction activities to mitigate impacts on marine birds have been implemented in multiple locations in the UK, with construction 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).

3.2.3 Limiting Activities

In addition to season-specific limitations, 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. 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 colocating equipment across projects (Drewitt and Langston, 2008) . Of the 14 strategies identified, two were implemented, four were not implemented, and for seven strategies implementation status was unknown. The two implemented strategies were for offshore wind in the UK. In one case, turbine installation progressed from north to south over the course of a season to minimize the effect on a nearby Little Tern (*Sternula albifrons*) colony (English et al., 2017); in the other example, a phased development approach was applied, with the second phase only permitted once the developer demonstrated no construction-related change to Red-throated Loon (*Gavia stellata*) habitat that would compromise identified conservation objectives (English et al., 2017). Despite these examples, it is typically quite difficult to collect data on effectiveness for these types of mitigation strategies (as with siting and seasonality approaches above).

3.2.4 Engagement and Communication

While not exclusive to siting, engagement and communication with stakeholders was identified as a mitigation strategy in five reviewed papers, though none were tested for effectiveness. These recommendations typically related to early and standardized stakeholder and community engagement. Early interaction with state and federal agencies was also described, particularly in regard to siting, as a

method of minimizing the potential for impacts (U.S. Fish and Wildlife Service (USFWS), 2021). None of these strategies were tested for effectiveness within the reviewed literature, likely as the majority of these strategies were documented in guidance papers intended to provide planning assistance.

3.3 Minimization Approaches

3.3.1 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=26 topics) included 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), as well as minimizing the use of wires that volant animals may be unable to see. Turbine layout considerations included placing turbines within an array or clustered, and how much space should be between them. Considerations related to clustering included migration corridors (Cook et al., 2011), leaving larger gaps between rows in the direction of prevailing winds (Tulp et al., 1999), and identifying daily flight paths to foraging and breeding sites to ensure safe passage through or around the wind farm (Vaissière et al., 2014).

The relationship between turbine size and mortality risk was variable, in part because "size" represented a catchall term used to describe multiple turbine characteristics, including overall height, distance between the surface of the water and the turbine blade (i.e., air gap), and rotor diameter (Garvin et al., 2024). Increasing the air gap has been suggested to reduce mortality for marine birds that largely fly close to the water's surface. There have also been suggestions that increasing turbine height, and therefore reducing the total number of turbines needed to produce the same amount of electricity, can 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 (Garvin et al., 2024). The effectiveness of this type of measure relates directly to flight height of species, and thus may be difficult to optimize for multiple species and groups. There was little testing or evidence in other contexts, including for offshore wind development. Because collision risk models are commonly used for the offshore wind industry, model exercises could be performed to optimize height to reduce collision risk for particular species; however, these models remained unvalidated in most cases.

3.3.2 Turbine Operation Parameters

Aerofauna collisions at onshore wind facilities (Schuster et al., 2015) have led this industry to focus on mechanisms to reduce this risk. A primary focus to date has been on altering turbine operational parameters and implementing shutdowns. 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). Because bat activity is typically higher at lower wind speeds, raising the cut-in speed for turbines to start generating electricity ensures that there are fewer opportunities for negative interactions. Other related turbine shutdown approaches have also been suggested or implemented.

While one strategy was to implement turbine curtailment consistently at night (termed blanket curtailment; (Allison et al., 2019), this approach could lead to loss of energy production (Thurber et al., 2023). As such there were various possible approaches for implementing more targeted curtailment during periods of higher activity for aerofauna 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 to detect bats or birds within the vicinity of the turbine (e.g., radar, human observers, acoustic detectors) to trigger curtailment, often termed 'smart curtailment'. Various curtailment strategies were primarily field tested and implemented in the onshore wind industry, both due to the longer history of this industry and relative ease of detecting mortalities (via carcass searches) relative to offshore wind development.

There was strong evidence in the literature that curtailment was an effective mitigation strategy for bats in the onshore wind context. Multiple review papers included in the database 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 had not yet been shown to be effective for many bat species (Hayes et al., 2023), and this was thus an area of active research in recent studies.

Given the effectiveness of curtailment for protecting bats, it was an oft-suggested mitigation approach for birds at wind farms as well. However, there is currently little or no evidence that 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). At least one automated detection technology to inform smart curtailment for eagles has also been tested (McClure et al. 2018); while it was effective at detecting and classifying eagles, no data were available in our review to determine its effectiveness at actually reducing collisions. 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 mitigation strategies generally included temporary shutdown of turbines during periods of high activity. Rather than partially basing these shutdowns on wind speeds, periods of high activity were 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, and 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 (American Wind Wildlife Institute, 2019; Arnett and May, 2016; Baerwald et al., 2009). 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 evidence of effectiveness in the offshore context.

3.3.3 Lighting to Reduce Attraction

There were 42 lighting-related mitigation approaches in the reviewed literature related to reducing attraction. This included information from 82 source documents, with most sources discussing more than one lighting alternative (E-TWG Bird and Bat Specialist Committee, 2020). 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. Several visibility enhancement approaches (n=12) including those that are lighting-related (e.g., using strobe light or ultraviolet light to make structures more visible such that animals could avoid collisions) and non-lighting related (e.g., painting or texturizing turbine blades and towers to increase visibility of wind farm structures) were also explored.

Studies of attraction of birds to various colors/schemes of light on offshore wind turbines have found that it is best to restrict the light sources offshore as much as possible (Rebke et al., 2019). This included approaches such as 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 so it is recommended that flood lighting is avoided, particularly at night, in poor weather, and during migration (E-TWG Bird and Bat Specialist Committee, 2020; Gauthreaux and Belser, 2006).

Limiting permanent lighting on offshore structures (as allowed by local safety regulations) was also a commonly suggested mitigation approach. Aircraft Detection Lighting Systems (ADLS), for example, were suggested numerous times in source documents to ensure that aviation obstruction lights on turbine towers and nacelles were only lit when an aircraft was in the vicinity. All commercial-scale offshore wind farms being planned in the United States have been required to implement ADLS (Bureau of Ocean Energy Management (BOEM), 2024, 2023, 2022, 2021a). 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 has not been implemented in the source documents examined..

In addition to lighting reduction, the color spectrum is also a focus of lighting-related 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 in the literature. 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). Poot et al. (Poot et al., 2008) hypothesized that shorter wavelengths (blue and green light) were less disruptive to birds' magnetic compass used for migration than red or white light, and several other studies in marine ecosystems in Europe seemed to support this assertion (e.g., (Hill et al., 2014; van de Laar, 2007). However, a study 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). Several studies suggested the use of red light including near Procellarid breeding colonies (Syposz et al., 2021) and at offshore wind farms in the North Sea (Rebke et al., 2019) Other studies at communications towers and terrestrial wind farms in the United States found that steady-burning red lights attracted migrant birds, but flashing red lights did not (Kerlinger et al. 2010, Gehring et al. 2009). While the available evidence clearly indicated that avoidance of the use of white lights helped to mitigate impacts to 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. 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 as compared to unlit turbines.

Other lighting characteristics have also been suggested as minimization approaches, including the use of flashing lights and altering intensity. Flashing (but not strobing) light was found to reduce avian attraction relative to continuously burning light (Cook et al., 2011; Evans et al., 2007; Gartman et al., 2016; Gehring et al., 2009; Kerlinger et al., 2010) 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 this topic.

3.3.4 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 which have been field tested for birds or bats (n=6) or

implemented with evidence of effectiveness for birds (n=4). The use of flashing or flickering lights were tested in onshore environments for aerofauna. Day et al. (2005) determined that lights flashing 40 times/min at an island in Alaska 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.). 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; American Wind Wildlife Institute, 2019; Arnett and May, 2016; Hein and Straw, 2021). For bats, (Long et al., 2011) determined that the common turbine colors 'Pure White' and 'Light Grey' were among those found to attract significantly more insects than other colors tested, which was suggested to provide foraging opportunities for bats and increase collision risk. Another study (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 wind turbines were inconclusive (Hein and Straw, 2021). Further testing on these visual and sensory 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 evidence of effectiveness. 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 rotation speed detection (Blary et al. 2023). Painting turbine foundations has also shown effectiveness for mitigating bird collisions (Gartman et al., 2016). A field study investigating the impact of tower base painting on Willow Ptarmigan (*Lagopus lagopus*) mortality rates found a 48.2% reduction in the annual number of recorded carcasses per search at painted relative to unpainted turbines (Stokke et al. 2020). As some birds have the ability to see in the UV spectrum, using UV-reflective paint to increase turbine blade and tower visibility was also suggested. One paper recommended, but did not test, the use of highly reflective achromatic patterns (black and white) that extended across the full spectrum of incident light (Martin and Banks 2023). Although UV paint is an established method for reducing bird strikes against windows (Marques et al. 2014, Defingou et al. 2019), its effectiveness in onshore and offshore wind development has not been proven (Young et al. 2003).

3.3.5 Vessel Operations and Water Quality

In addition to approaches related to turbine operations (e.g., curtailment, feathering), and lighting and visibility of turbines and other structures, there are additional operational considerations (n=12 approaches) focused on vessels and safety measures to ensure water quality. These measures were primarily relevant to birds; for a majority (n=10), the implementation status was unknown or not implemented, while two approaches in our literature review were field tested. Vessels in the marine environment have the potential to disturb wildlife, including marine birds (Schwemmer et al., 2011). Six mitigation approaches related to vessel operation parameters were reviewed, which include those aimed at reducing bird disturbance by minimizing vessel speed and density, implementing setbacks from high-use areas (i.e., breeding or foraging grounds), and using caution in low visibility conditions. Limiting vessel speed and volume and adopting set-back distances were field tested as mitigation strategies in maritime industries. For example, (Bellefleur et al., 2009) determined that Marbled Murrelets required a minimum buffer distance of 29 m between a boat and birds on the water to reduce disturbance such that 75% of the studied population would be minimally affected. Additionally, (Ronconi and St. Clair, 2002)) found that using a vessel setback distance of 600 m from shore with a speed limit of 25 km/h reduced Black Guillemot (*Cepphus grylle*) flushing behavior to 10% most of the time. At onshore wind farms, there has also been some suggestion to manage vehicle volumes and remain particularly alert when visibility is poor to reduce aerofauna collisions and disturbance (Mockrin and Gravenmier, 2012; U.S. Fish and Wildlife Service (USFWS), 2012), but this has not yet been tested or implemented. Additionally, no studies examined the effectiveness of implementing vessel operation parameters for offshore wind development specifically.

Water quality is tied to the overall health of the ecosystem. There were five mitigation strategies tied to water quality from three sources, but none of these mitigation strategies were tested for effectiveness. Potential strategies include implementing methods to reduce impacts to water quality (i.e., best management practices), following applicable regulations, proper handling of toxic substances following appropriate federal and state measures, and reducing the likelihood of invasive species introduction (U.S. Fish and Wildlife Service (USFWS), 2012).

3.3.6 Deterrents and Attraction Reduction

Thirty-seven different mitigation strategies were proposed from 69 literature sources related to deterring aerofauna from approaching activities and/or structures or reducing the attractiveness of such activities and/or structures. Of these, 17 were untested (or their testing status could not be determined), another 10 were field tested, and 9 were implemented with evidence of effectiveness. While some industries distinguish between deterrents and hazing devices, for the purposes of this review, we use ‘deterrents’ as an encompassing term to include both. There are various types of deterrents aimed at scaring or otherwise repulsing individuals to counteract attraction and in turn reduce collision risk. These act on various senses of individuals and include acoustic (n=9), visual (n=6), physical (n=4), olfactory and chemical (n=2) deterrents, or some combination of these (n=5). In addition, approaches to reduce attraction have been suggested that relate to altering prey resources (n=7) and habitat (n=4).

Various types of acoustic deterrents have been suggested and tested. Ultrasonic deterrents (which jam the ability of bats to receive and interpret echolocation calls) have shown some evidence of effectiveness for

reducing bat mortality at onshore wind facilities (Hein et al., 2021; ONeil, 2020). More specifically, one study found that broadband ultrasound in the 20-100 kHz range decreased bat mortality by up to 64% per treatment turbine relative to control turbines, but that effectiveness is limited by the distance and area that ultrasound can be broadcast (Arnett et al., 2013)). Similarly, research conducted by (Gilmour et al., 2020) determined that ultrasonic auditory deterrents lowered bat activity by 80% when deployed alone and in combination with radar at riparian sites in Wales. In a related study, also in Wales (Gilmour et al., 2021), auditory deterrents significantly reduced passes of Soprano Pipistrelle (*Pipistrellus pygmaeus*; 27%), Mouse-eared bats (*Myotis* spp.; 29%), and Noctule (*Nyctalus* spp.) and House bats (*Eptesicus* spp.; 68%). However, research performed in an agricultural setting in the United States did not detect a clear reduction in bat mortalities from the use of ultrasonic acoustic deterrents for any individual species, including Hoary Bats (*Lasiurus cinereus*), Silver-haired Bats (*Lasionycteris noctivagans*), and Big Brown Bats (*Eptesicus fuscus;* (Schirmacher, 2020)). The mortality rate of Eastern Red Bat (*Lasiurus borealis*) was also estimated to be 1.3-4.2 times greater when turbines were operating normally and deterrents were on, as compared to when deterrents were off. Eastern red bats are the most common species detected offshore in the northwest Atlantic, and ultrasonic deterrents have not yet been tested in the offshore context for them or any other species.

Several studies from Europe in the literature review tested the use of other auditory devices, such as electromagnetic signals, to deter bats from approaching wind turbines, with some evidence that the approach reduces bat activity levels (Nicholls and Racey, 2009, 2007). For example, Nicholls and Racey (2009) found that bat activity levels and foraging effort in Scotland were both reduced during experimental trials with exposure to a unidirectional radar antenna. Monitoring efforts around traffic control, military, and weather radar showed reduced bat activity in areas with electromagnetic exposure of strength of >2 volts/meter for multiple *Pipistrellus* and *Myotis* bat species (Nicholls and Racey, 2007), suggesting that this may be a potential approach for further study in the offshore context.

In the case of birds, bioacoustic deterrents, which primarily involve the playback of recorded alarm or distress calls, have been effectively used in agricultural and riparian settings (Enos et al., 2021), though effectiveness appears to vary by species, and habituation is common. However, according to a literature review on bioacoustics (Bomford and O'Brien, 1990), more than 80% of visiting Black-crowned Night Herons (*Nycticorax nycticorax*) were frightened off trout ponds when recorded distress calls of juvenile and adult Night Herons were broadcast, and habituation did not occur after 6 months. In another study, cornfields receiving taped Carrion Crow (*Corvus corone*) distress calls had significantly less damage than the control or fields with suspended dead crow bodies (Bomford and O'Brien, 1990). Several lab experiments testing bioacoustic effects on starlings determined that bioacoustic devices cause an aversive response when compared to other noises (Bomford and O'Brien, 1990), though habituation was reported. 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. Propane exploders reduced Red-winged Blackbird (*Agelaius phoeniceus*) damage to cornfields by 77%, with no evidence of habituation after 4 weeks (Conover, 1984). 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, aquatic hazing devices were ineffective at deterring waterbirds species, such as Greater and Lesser Scaup (*Aythya affinis* and *A. marila*) and Surf Scoter (*Melanitta perspicillata*), from oil spills in the San Francisco Bay (Whisson and Takekawa, 2000). Other research suggested that using acoustic whistle cues (2-4 kHz) may help birds hear turbine blades and avoid collision, but this strategy was not tested (Dooling, 2002). Lastly, ultrasonic acoustic deterrents were implemented as a strategy to deter birds from perching at offshore platforms (Christensen-Dalsgaard et al., 2019), but there was minimal empirical proof of their effectiveness (Defingou et al., 2019).

Visual deterrents are a common strategy used in agriculture and other terrestrial industries (e.g., airports, landfills), and therefore many have been field tested and implemented. Visual deterrents have included lasers, effigies, flagging, flickering light, unmanned aerial vehicles (UAVs), automated detection systems, and paint. Lasers have deterred certain bird species under low light conditions but were not consistently effective across studies and did not disperse birds long distances. For example, in field trials, (Glahn et al., 2000) directed lasers at roost trees at or near sunset, which dispersed Double-crested Cormorants (*Phalacrocorax auritus*) and reduced roost populations by at least 90% after 1 to 3 evenings of harassment. However, there have been variable results for other species, including Canada Geese , with some instances of effectiveness at dispersing birds (Blackwell et al., 2002) and other efforts being ineffective (Sherman and Barras, 2004). In the maritime environment, automated laser systems were successfully used on installations to deter gulls from large open areas such as helicopter landing platforms, and seemed to work best in low light conditions (Christensen-Dalsgaard et al., 2019). For offshore wind development, lasers were identified as a potential mitigation method to minimize avian collision risk with turbines in the UK (Cook et al., 2011), but this approach was not tested.

Effigies, including scarecrows, hawk-kites, and eye-spot balloons, have also been used as a visual stimulus to deter birds (Arnett and May, 2016; Enos et al., 2021; Gilsdorf et al., 2002). (Conover, 1984) reported that hawk-kites, plastic kites imprinted with a picture of a flying hawk and suspended in the air, reduced Red-winged Blackbird damage to cornfields by 83%, with no habituation observed during the 4-week study period. (Stickley and King, 1993) found that the use of a "Scary Man" pop-up inflatable effigy device proved effective in reducing Double-crested Cormorant numbers on catfish ponds for 10-19 days. Eye-spot balloons (floating balloons mimicking a generic aerial predator) have also reduced passerine abundance and/or resulting crop damage in several studies conducted at vineyards and agricultural fields, but more research is required to determine effectiveness (Enos et al., 2021).

Reflective materials have been tested as a deterrence method for birds in terrestrial contexts, with variable results. Mylar reflective tape was ineffective at deterring Herring Gulls from nesting colonies, but did reduce the use of loafing sites in some cases (Belant and Ickes, 1997) was ineffective in reducing bird damage to agricultural fields, possibly due to habituation (Gilsdorf et al., 2002). However, white plastic

flags successfully repelled Snow Geese (*Chen caerulescens*) from rye and winter wheat fields during a two-month study period (Gilsdorf et al., 2002).

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 and there may also be considerations to avoid disturbance from these methods.

Structural deterrents, such as wires, spikes, and netting, were 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 (Curry and Kerlinger 1998). However, their effectiveness was not determined. While these alternative perches may have helped keep birds off of active turbines, it may have also increased bird attraction to the general area of the turbines and heightened collision risk (Smallwood and Karas 2009, Cook et al. 2011).

Several studies tested chemical deterrents (taste, olfactory, and tactile repellents) to deter birds from landfills, crop fields, and other onshore areas (Gilsdorf et al. 2003, Cook et al. 2011). Curtis et al. (1993) evaluated the impacts of methyl anthranilate and found that the treatment did not effectively reduce avian numbers at a landfill site. Comparatively, Conover (1984) determined that using 4-amino-pyridine (Avitrol FC-99) on corn fields increased the number of Red-winged Black Birds, but decreased the number of sparrows following treatment, suggesting chemical responses may be species-specific. In the offshore 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 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. For example, Montoney and Boggs (1995) used a combination of pyrotechnics, amplified distress tapes, and live ammunition to harass Laughing Gulls (*Leucophaeus atricilla*) away from an airport, resulting in an 86% reduction in aircraft strikes and a 100% decrease in runway closures due to bird activity. For Canada Geese, Mott and Timbrook (1988) determined that a combination of alarm calls and racket bombs produced a 96% reduction in geese observations on lawns, though continual harassment would likely be necessary as reinvasion of geese was observed one week after treatment

stopped. An integrated approach using alarm calls, pyrotechnics, and methyl anthranilate was shown to be effective at reducing waterfowl landings at ponds with no apparent habituation (Stevens et al. 2000). Combining different deterrent strategies has been tested for mitigating bird collisions with terrestrial wind turbines as well. A review paper (Garcia-Rosa and Tande 2023) highlighted results of a 9-month study that tested a deterrence module operation for raptors at an operational wind farm, which involved species-level identification, unmanned aerial vehicles, and seven detection and deterrent systems. It was estimated that the installed systems potentially reduced Golden Eagle collision risk by 33–53%. Yet, a pilot study at a wind turbine facility in Nova Scotia 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 unclear, 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. For instance, it has been suggested that supplementary or diversionary feeding could be effective in reorienting foraging harriers away from profitable prey areas (Simmons et al. 2020). However, while a study of Hen Harriers (*Circus cyaneus*) at an onshore wind facility 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 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 with some effectiveness. For example, superficially tilling the soil (3-8 cm deep) at the base of wind turbines in Spain made the area less attractive for Lesser Kestrels (*Falco naumanni*; Garcia-Rosa and Tande 2023). Similarly, rock piles and other areas attractive to rodent prey were correlated with raptor mortality at turbines at Altamont Pass Wind Resource Area in California, and it was suggested that making the areas around turbines less attractive to raptor prey could help to reduce mortalities (Thelander et al., 2003). However, more research is needed in this area, particularly in terms of relevant approaches for the offshore wind industry.

3.4 Compensation

Compensation for environmental effects that cannot be avoided or minimized may occur onsite or offsite and may include both in-kind or out-of-kind compensation (e.g., providing a resource of similar or different structural or functional type to the impacted resource). Federal regulations, such as the National Environmental Policy Act (NEPA) in the United States and the Birds and Habitats Directives in the European Union (Van Hoorick, 2014), provide regulatory frameworks for compensatory mitigation of impacts to species and their habitats, but offsets can also be pursued outside of federal permitting processes. Compensation has generally been implemented via three primary mechanisms: 1) direct implementation by an individual project, 2) mitigation banking, or 3) in-lieu fee programs. Direct implementation (often via permittee-responsible compensation) includes the implementation of shovel-ready projects such as habitat restoration or creation. A mitigation bank is a site or suite of sites that provides ecological functions and services expressed as credits that are conserved and managed in perpetuity for particular species and are used expressly to offset impacts occurring elsewhere to the same species. In-lieu fee programs, which are similar to mitigation banks, provide ecological functions and services expressed as credits that are conserved and managed for particular species or habitats and used to offset impacts occurring elsewhere to the same species or habitats (USFWS 2023).

We reviewed sixteen papers related to compensation as a means of mitigating unavoidable impacts. The majority (75%) of these studies looked at compensation methods involving in-kind habitat conservation, restoration, restriction of access (either from fishing or recreation), invasive species management, reduction of bycatch, or other methods. The remaining studies (25%) reviewed financial means of compensation either through development of funding pools, permittee-required compensation strategies, financial support of rehabilitation programs, or in-lieu fee programs.

The majority of compensation strategies did not provide examples of implementation or assess the effectiveness of compensation programs (n=13). There was little documented evidence within the reviewed literature showing effectiveness of financial compensation at off-setting unavoidable impacts related to offshore wind development. In part, this may be due to the relatively nascent status of the industry in many parts of the world. Compensation has been used within the United States regulatory context for other types of projects, primarily terrestrial, including Clean Water Act compliance (Arnett and May 2016), and often includes habitat protection and restoration, which may be difficult to measurably implement in the marine environment. Once the offshore wind 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 impacts on aerofauna.

One strategy that has been extensively tested (though not specifically in relation to OSW development) focused on the removal of mammalian predators as a means of increasing productivity of seabird breeding colonies. Removal of invasive predators from breeding colonies has generally been found to be an effective strategy (e.g., (Nogales et al., 2013; Pascal et al., 2008). Results from our reviewed studies were somewhat mixed; Luxmoore et al. (2019) found that Guillemot/Murre (*Uria* spp.) populations did not respond to the removal of rats, while Booker et al. (2019) attributed increases in Razorbill (*Alca torda*) and Atlantic Puffin (*Fratercula arctica*) breeding numbers to the removal of rats (Booker et al. 2019).

4. Discussion

There were few mitigation measures available for birds and bats at offshore wind farms that were adequately tested in the reviewed literature. Commonly implemented measures 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). 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 measures 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 that the measures can effectively reduce risk. Since it may be difficult to identify mitigations that are broadly generalizable, an array of mitigation measures should be further explored to provide options for specific scenarios.

Despite a lack of adequate testing offshore, there are a few key mitigation measures 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 1) 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 for mitigation.

4.1 Limitations of the Literature Review

Due to the search terms used in our review, and how these terms are generally used in the literature, our literature review was primarily focused on minimization measures, rather than on avoidance or compensation. We suspect that this review represents a gross underestimate of the true implementation frequency for these types of mitigation measures. Despite the prevalence of the mitigation hierarchy in the

Table 1. 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

scientific literature, the term "mitigation" is also sometimes used synonymously with "minimization," and that was evident in the types of studies that were located 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, which was where most siting-focused and compensation-focused mitigation tended to be discussed. Compensation for OSW development specifically is also a relatively recent topic of discussion in the scientific community (Croll et al., 2022). Finally, some of these activities (e.g., stakeholder engagement by government entities) also may not have been particularly well represented in the scientific literature, 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 did include birds to some degree (Crown Estate Scotland, 2024). This report aimed to inform OSW development in Scotland by 1) identifying the "most appropriate mitigation measures" for OSW developments in this region, and 2) examining approaches for Nature Inclusive Design at Scottish projects. However, it should be noted that 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" and therefore evidence of effectiveness as defined in this paper is lacking. This speaks to the difficulty in assessing effectiveness of mitigation approaches and general lack of data, however 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.

4.2 Approaches with Evidence of Effectiveness

4.2.1 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 type 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, as far back as 2003, that siting and other avoidance measures remain the best available approach to reduce OSW development impacts, particularly for birds (Langston and Pullan, 2003).

In addition to siting and limiting the timing of certain activities, we also recommend implementing mitigation strategies related to water quality. While there were relatively few mitigation approaches related to water quality identified in the database, these are generally common-sense approaches that

should be implemented to avoid potential negative impacts. This includes practices like cleaning vehicles/equipment to reduce the likelihood of invasive species introduction and following safety measures to avoid the introduction of toxic substances (Mockrin and Gravenmier, 2012).

It is generally difficult to test the effectiveness of avoidance measures, because there are typically no "impact" scenarios to compare to "controls" 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 measures via natural experiments (e.g., as projects are sited in locations with varying value to wildlife, and resulting impacts 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 impacts; 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 impacts. As 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 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.

4.2.2 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 measures to reduce artificial light at night (ALAN) pollution and avoid attracting and disorienting birds, particularly nocturnal migrants. This includes 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), and other measures that have been detailed in several guidance documents for OSW development (Bureau of Ocean Energy Management (BOEM), 2021b; 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. Additionally, temporary lighting may be a particular risk; reduction in use of flood-lighting during construction and maintenance activities, especially during spring and fall migration, is essential to minimize risks to migrating birds (E-TWG Bird and Bat Specialist Committee, 2020).

Recent guidance for lighting of OSW developments in the United States recommends the use of many of the above mitigation approaches to reduce the effects of artificial light on birds, bats, and other wildlife (Bureau of Ocean Energy Management (BOEM), 2021b; E-TWG Bird and Bat Specialist Committee, 2020). This includes the use of red aviation safety lighting at the lowest practicable flash rate, avoidance

of flood lighting where possible, and the use of timers and other sensors to enforce lighting shutoffs. All 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, (Bureau of Ocean Energy Management (BOEM), 2024, 2023, 2022, 2021a), 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 impacts 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, since available studies 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). It is possible that bat attraction may be dictated less by their own reaction to light than by the attraction of their insect prey or other factors (Guest et al., 2022). Future aerofauna studies should be focused specifically on the offshore environment to best inform mitigation for OSW development. 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.

4.3 Approaches that Require Additional Research

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.

4.3.1 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 the effects of structure configuration on indirect effects such as behavioral disturbance, displacement, and habitat fragmentation can be challenging, as this requires regional-scale studies across multiple wind farms to allow for comparison. This type of multi-facility study requires consistent data collection methods across projects along with public availability of

992 data from site-specific studies. Detecting changes in behavior may also require advanced technology or
993 human observers, both of which can be costly to deploy at the large scale required. Understanding the
994 effects of structure configuration on collisions offshore, which are both rare and difficult to detect,
995 likewise requires a high level of effort to achieve adequate statistical power. Mitigation through project
996 design offers promise to mitigate potential effects to aerofauna from OSW development, but this promise
997 remains largely unproven and will require large-scale, long-term research efforts. We suggest that, if such
998 approaches are implemented, they are accompanied by a rigorous regional-scale monitoring plan to assess
999 their effectiveness.

1000 *4.3.2 Minimizing Attraction and Enhancing Visibility*

1001 Based on findings from other industries and contexts, there are many types of deterrents that offer some
1002 level of promise. However, in many cases the studies of effectiveness focused on one or a few species
1003 over a short period of time, and often showed variable results. While deterrents have been used in the
1004 OSW industry in Europe to reduce perching for taxa such as gulls and cormorants (Gartman et al., 2016),
1005 these facilities were located closer to shore than those being built in North America. Consequently, there
1006 is uncertainty in the level of attraction (for roosting, perching, and nesting) likely to be observed in the
1007 North American context, and thus the need for these types of deterrents. As discussed above, the use of
1008 offshore wind turbines by bats remains largely unknown in the region as well. Thus, for this type of
1009 mitigation, we recommend not only additional research on effectiveness but also to only consider
1010 implementation once there is evidence that attraction is occurring at large enough scales to warrant
1011 investment in deterrents. While in general it is thought that reducing perching and roosting opportunities
1012 can help reduce attractiveness of wind farms to birds, which in turn may help reduce collision risk
1013 (Gartman et al., 2016), we lack direct evidence linking perching deterrents to collision risk reduction. Key
1014 studies to fill knowledge gaps include those specific to species that occur offshore and long-term studies
1015 to understand the potential for habituation.
1016
1017 There are other approaches to minimize attraction (and collision risk) that offer promise but also require
1018 additional testing and validation. The use of paint for increasing visibility of turbines and other structures
1019 shows promising evidence in other contexts but has to date been tested in a small number of contexts and
1020 with few species, all in the onshore context. Differences in vision among bird (and bat) taxa suggest that
1021 vision-related measures to enhance turbine visibility must be carefully considered and tested.

1022 *4.3.3 Minimizing Collisions*

1023 One of the largest data gaps identified in this review (as well as others; (Hein et al., 2021) is the degree to
1024 which bat mortality at offshore wind farms needs to be mitigated. Because of the high mortality rates of
1025 migratory tree bats at onshore wind facilities (Arnett et al., 2008), there have been serious concerns about
1026 the long-term impacts to these populations (Frick et al., 2017), and mitigation measures for terrestrial
1027 wind farms have received a high level of attention. In particular, curtailment of onshore turbines at low
1028 wind speeds has been shown to significantly reduce mortality rates, both when examining this approach at
1029 an individual project scale (Arnett et al., 2008) and when looking across projects (Adams et al., 2021;
1030 Whitby et al., 2021). While there are many variations in how curtailment is implemented (e.g., blanket
1031 curtailment as well as curtailment based on environmental conditions, temporal variation, smart systems
1032 that detect bats, etc.), the aim is the same: to stop turbines from spinning when bats are in the area.

Indeed, feathering and temporary shutdown, while separate mitigation approaches, are also effective as they also result in the stoppage or minimization of turbines spinning, resulting in reduced collisions for bats. Much of the reason for variations in this type of mitigation approach, and the focus on conditional implementation, has more to do with the loss of 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. 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 testing of these types of strategies for the OSW industry.

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 specific species (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.

4.3.4 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 offshore wind 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 specific 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 (Conn and Silber, 2013; Hazel et al., 2007). 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 aircrafts, which were not included in our review but may also help reduce disturbance.

4.4. Importance of Exploring Compensatory Mitigation Measures

In the absence of proven on-site mitigation approaches (e.g., via avoidance and minimization) to fully offset effects to aerofauna from OSW development, compensatory mitigation measures should be explored in the immediate term (Croll et al., 2022). Potential strategies to consider in a compensatory

mitigation framework should include both onsite and offsite approaches and should be considered regardless of whether the regulatory framework for a given location with OSW development require "no net loss" of animals or "net gain" of animals in relation to development activities (Edwards-Jones et al., 2024; U.S. Fish and Wildlife Service (USFWS), 2023). Without on-site mitigation measures 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 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 measures 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 measures must be carefully designed and monitored to assess effectiveness in mitigating OSW impacts.

4.5 Monitoring Programs to Validate Effectiveness of Mitigation Measures

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, 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 measures) from background variation in the distribution of aerofauna (Lamb et al., 2024; Maclean et al., 2013). 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 measures 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. This approach was first tested in the laboratory in 2003 (Hodos, 2003), and was implemented using a Before-After Control-Impact (BACI) approach at a terrestrial wind facility in Norway in 2013. Because extensive mortality data was available from the Norwegian site prior to the treatment (2006-2013), 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 in order to have sufficient statistical power to ensure that the study could 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 in order to assess whether this approach will work in other habitats and for other species with different visual acuity and behaviors. This example exemplifies the large-scale effort often required to test and validate mitigation measures.

Given the importance of identifying the most effective mitigation measures to achieve sustainability of the OSW industry, research to assess the effectiveness of measures 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 measures 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 that could also fall into this category. Thirdly, we recommend an immediate focus on mitigation measures 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 and comparisons. In the immediate term, conducting well-designed studies of effects of 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.

5. Conclusions

There was no evidence of effectiveness for 86% of the mitigation approaches identified in this literature review. Of a total of 212 mitigation approaches from 233 source documents, 59% of proposed approaches were not tested in the reviewed literature to assess whether they were effective at mitigating anthropogenic impacts to aerofauna. Of the mitigation approaches that were field tested or implemented, the reviewed literature indicated evidence of their effectiveness in only about 36% of cases. 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. 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 measures 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 measures such as curtailment for birds. Implementation of unproven mitigations creates the assumption that impacts 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 measures 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 measures for which data are currently lacking. In the absence of sufficiently validated measures for on-site mitigation of OSW effects to aerofauna, compensatory mitigation approaches should also be pursued.

6. Glossary

Aerofauna - birds and bats

Air gap - distance between the surface of the water and the lowest edge of the rotor-swept zone (e.g., bottom edge of the turbine blades). Increasing the size of the air gap is a commonly proposed mitigation measure for some marine bird species, since collision risk models often predict that a larger air gap will reduce collisions.

Avoidance - the first step in the mitigation hierarchy, in which impacts to wildlife or ecosystems are avoided altogether. Within the context of offshore wind energy development, avoidance of impacts primarily occurs during planning processes when projects are sited away from high-risk or high-use areas for wildlife. Note that the term “avoidance” is also used in the offshore wind context to describe the behavior of aerofauna around turbines or other infrastructure (see also “displacement,” below). Behavioral avoidance may occur at the macro-, meso- or micro-scale. Animals’ avoidance of individual

turbine blades when they are present within the rotor-swept zone is termed micro-avoidance; meso-avoidance involves animals present within the broader wind farm footprint staying away from individual turbines; and avoidance of the entire offshore wind facility is termed macro-avoidance, which can have resultant changes in wildlife distributions (e.g., displacement).

Compensation - the final step in the mitigation hierarchy, in which impacts that cannot be adequately avoided or minimized are "offset" by activities intended to improve and enhance impacted populations. Compensation can occur on-site (e.g., where the impact was created) or away from the site of impact, and may include options such as habitat creation (e.g., new breeding, roosting, wintering sites) and improvement of existing habitat via invasive species removal or predator control (Arnett and May, 2016). Compensation aims to ensure that negative environmental impacts that cannot be avoided or minimized can be moderated by environmental gains to produce net neutral or net positive outcomes for affected populations and ecosystems.

Curtailment - mitigation approach that involves halting operations of wind turbines under specified circumstances. So-called "blanket" curtailment for bats at terrestrial wind farms typically involves raising the threshold for ambient wind speed at which turbines begin generating electricity (the turbine "cut-in speed"), so that turbines are not spinning as quickly at low wind speeds. Curtailment approaches may also use other environmental conditions and/or detections of animals in the vicinity of the wind farm to inform curtailment of turbine operations.

Deterrent - human invention aimed at scaring or otherwise repulsing wildlife to reduce their presence in an area. Can be used to reduce potential harm to human interests caused by aerofauna (e.g., to reduce crop damage caused by birds) or to reduce possible harm to wildlife (for example, by attempting to counteract attraction to a location or structure that may increase collision risk). While some industries distinguish between deterrents and hazing devices, for the purposes of this review, we use 'deterrents' as an encompassing term to include both. May include acoustic, visual, physical, olfactory and chemical, or other approaches.

Displacement - see "avoidance," above.

Effectiveness - 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.

Feathering - when turbine blades are pitched to catch as little wind as possible, thus slowing the blade rotation. Below the cut-in wind speed at which turbines begin generating electricity, turbine blades still spin in the wind but do so much more slowly. In addition to curtailment (above), blades can be feathered when the turbine is not generating electricity in order to reduce bat mortality at terrestrial wind farms.

Minimization - the second step in the mitigation hierarchy, in which expected effects to aerofauna are reduced/minimized to the degree possible. For offshore wind energy development, this primarily occurs during pre-construction and operations, and can include design decisions (e.g., micro-siting, turbine height, lighting, addition of perching deterrents) as well as operational parameters (e.g., cut-in speeds at which turbines begin generating electricity).

Mitigation - activities intended to avoid, minimize, or compensate for deleterious anthropogenic impacts to wildlife or ecosystems. The "mitigation hierarchy" is a commonly accepted framework for conducting mitigation activities in which avoidance is preferred to minimization, and minimization preferred to compensation (see definitions above).

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