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A conceptual model to determine vulnerability of wildlife populations to offshore wind energy development

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Abstract: As offshore wind energy development is planned in the United States, there is an increasing need for pre- and post-construction monitoring plans to be focused on species determined to be most vulnerable to hazards of a specific project. We propose a conceptual model that incorporates biological and sociological parameters. Specifically, we suggest that demographic, ethological/biological, and population sensitivity be considered with legal protection, economic importance, and/or stakeholder interest. We recommend that vulnerability determinations include qualitative and quantitative methods.

Key words: offshore wind energy development, vulnerability, wildlife

Offshore wind energy development (OWED) is rapidly expanding in Europe and is being planned in the United States as a response to concerns about climate change. Today, there is approximately 6 gigawatts (GW) of OWED capacity in Europe (European Wind Energy Association 2013), and the United States has set a goal of 54 GW by 2030 (DOE 2011); globally, 77.4 GW is predicted by 2021 (BTM Consult ApS 2012). Construction and operation of wind farms present risks to wildlife through exposure of vulnerable species to OWED hazards (Goodale and Milman 2014). Although OWED has a lower life-cycle adverse effect on the environment than fossil fuels (Ram 2011), potential adverse effects of OWED to fish, marine mammals, birds, and bats include direct effects of mortality and injury, indirect effects such as habitat change, and cumulative effects of OWEDs combined with other anthropogenic stressors (Drewitt and Langston 2006, Fox et al. 2006, MMS 2007, Boswell et al. 2010, Edrén et al. 2010, Kikuchi 2010, Burkhard and Gee 2012, McCann 2012, Teilmann et al. 2012, Langston 2013, Michel 2013, Goodale and Milman 2014). Limited time and resources dictate that pre- and post-construction monitoring and mitigation actions will be most effective if focused on species known to be vulnerable to the OWED (NYSERDA 2015). Therefore, a critical component in evaluating and mitigating adverse effects of OWED is developing a clear process to delineate which species will be most vulnerable to the hazards associated with a specific proposed OWED.

Identifying hazards, evaluating vulnerability, and delineating exposure are all critical components of assessing adverse effects of OWED on wildlife (Goodale and Milman 2014). Vulnerability, like many concepts, is open to interpretation and adaptation to different applications. Vulnerability as a general concept is the "potential for loss" (Wilson et al. 2005) or, more specifically, sensitivity of a species to a particular hazard (Furness et al. 2013). Approaches to evaluating vulnerability have been developed in many contexts. For conservation planning, vulnerability includes exposure, impact, and intensity (Wilson et al. 2005); for populations, vulnerability includes species distribution, relative abundance (local and regional), threats, and population trends (Carter et al. 2000); for climate change, vulnerability includes exposure, sensitivity, and resilience to stressors (Teck et al. 2010); for pollutants, vulnerability includes potential exposure, sensitivity to a pollutant, and recovery capacity (De Lange et al. 2009); and for disease, vulnerability is related to demography (Grear et al. 2006). Vulnerability of birds to offshore wind includes behavior, habitat specialization, vital rates, conservation status, and population exposure (i.e., relative abundance; Garthe and Hüppop 2004, Desholm 2009, Furness et al. 2013). Overall, these approaches include a factor of exposure to a hazard, magnitude of response to the exposure, and then scaling up of adverse effects to populations.

In this paper, we apply these concepts of vulnerability specifically to OWED and wildlife, and we build upon existing efforts to characterize vulnerability of birds to OWED. We also suggest explicitly including sociological factors in a vulnerability framework. Our intention is to provide wildlife managers, policy makers, and developers with a heuristic model to aid in determining which species are most likely to be adversely affected by an OWED and thus enable focused, site-specific pre- and post-construction monitoring and mitigation efforts.

Population vulnerability conceptual model

We focus on the vulnerability of wildlife populations to OWED, emphasizing population growth rates rather than total population numbers. Our focus on populations is rooted in the ethos that maintaining viable populations is a crucial component of protecting biodiversity, a central tenet of conservation biology (Van Dyke 2008). While populations are regulated by many factors (i.e., births and immigration minus mortality and emigration; Gotelli 2008), direct and indirect adverse effects of OWED can be viewed as an extrinsic density-independent factor. The conceptual model we have developed specifically outlines factors

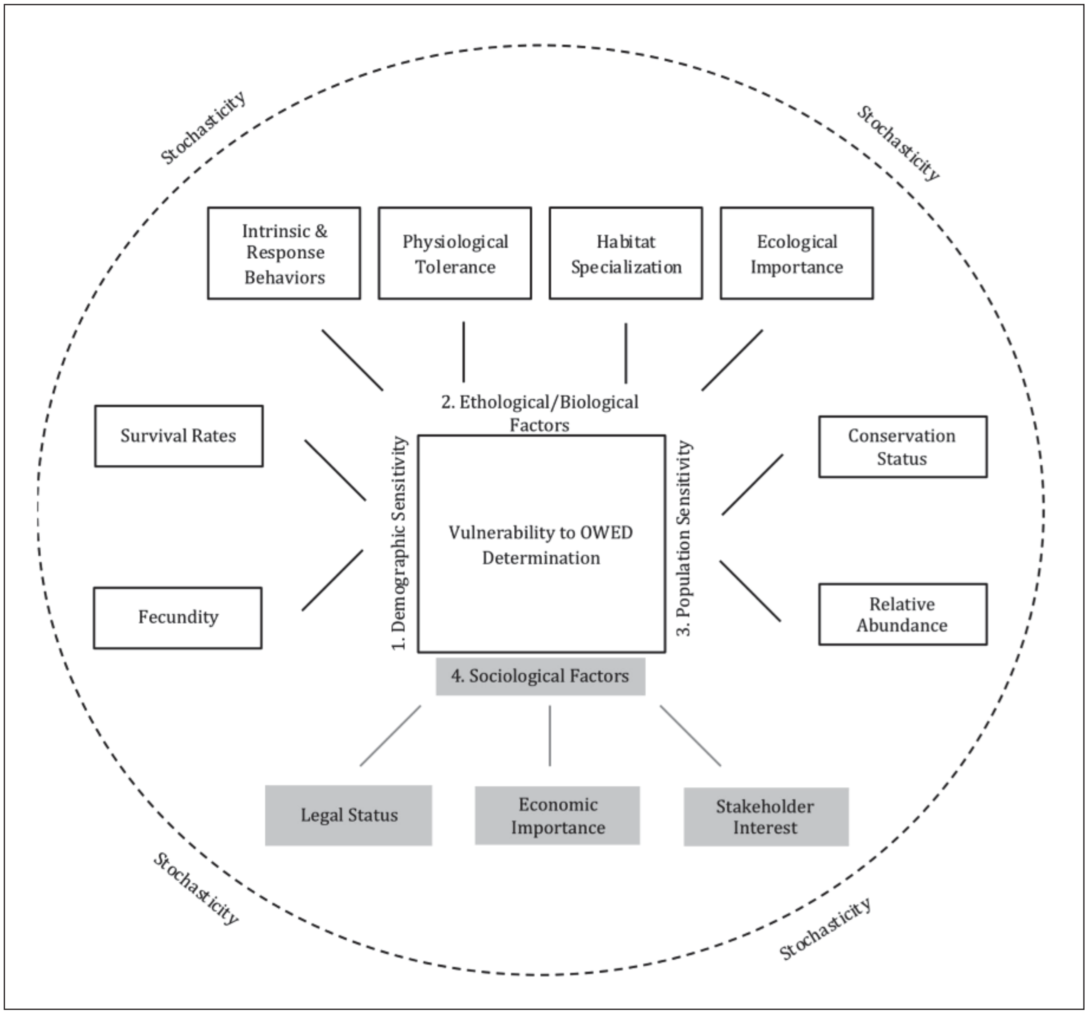

Figure 1. Factors influencing wildlife population vulnerability to offshore wind energy development (OWED). Demographic, ethological/biological, and population sensitivity and sociological factors (in gray) will contribute to vulnerability determinations.

Table 1. Factors leading to greater or lesser vulnerability of wildlife to OWED.

Sensitivity/Factor	Greater vulnerability	Lesser vulnerability
Demographic	Long-lived; high adult survival; low reproductive output	Short-lived; low adult survival; high reproductive output
Ethological	Intrinsic behaviors increase exposure; response behaviors lead to adverse effects	Intrinsic behaviors reduce exposure; response behaviors do not lead to adverse effects
Biological	Low physical tolerances; habitat specialists; high community importance	High physical tolerances; habitat generalists; low community importance
Population	Population declining; large proportion of population exposed	Population increasing; low proportion of population exposed
Sociological	Highly protected by law; high economic importance; important to stakeholders	Not protected by law; no economic importance; not important to stakeholders

that make adverse effects of OWED more likely to negatively affect population growth rates. We do not attempt to incorporate all factors that regulate a population.

We define vulnerability of wildlife to OWED to be biological factors that (1) increase exposure of individuals to OWED, (2) increase the probability that the exposure will lead to individual adverse effects, and (3) increase the probability that individual adverse effects will accumulate to population level effects. Specifically, this vulnerability includes demographic, ethological/biological, and population sensitivity. Demographic sensitivity relates to vital rates that will affect a population's ability to compensate for adverse effects of OWED. Ethological sensitivity relates to individual exposure (intrinsic behavior) and the adverse effect of exposure (response behavior); biological sensitivity relates to species' physical tolerances and habitat specialization; and ecological importance describes the role of the species in the community structure (e.g., whether it is a keystone species). Population sensitivity relates to exposure of the population to OWED hazards (relative abundance) and existing status of the population (conservation status). While any vulnerability assessment will be species- and site-specific, these biological factors encompass the likelihood that an individual is directly or indirectly affected by an OWED (ethological/behavioral sensitivity), and that this effect scales up to the population level (demographic and population sensitivity; Carter et al. 2000, Garthe and Hüppop 2004, Wilson et al. 2005, Grear et al. 2006, De Lange et al. 2009, Desholm 2009, Teck et al. 2010, Furness et al. 2013).

We also recognize that sociological factors (i.e., legal status, economic importance, and stakeholder interest) will influence which species wildlife managers and developers determine to be vulnerable, and that these factors should be explicitly included in vulnerability determinations. While biological vulnerability can be quantitatively assessed with empirical data, determination of vulnerable species by decision-makers will also be influenced by how important the species is considered legally, ecologically, and economically, and how it is perceived by stakeholders. For example, some fish species may be of higher priority than others because of their pivotal ecological role or economic importance. A marine mammal species may be considered more important because it is listed as an endangered species, and certain birds may be deemed a higher priority to stakeholders than others based on general public perceptions (e.g., species that are considered over-abundant, "nuisance species" may be ranked lower than others).

Overlain on biological and sociological factors is stochasticity, or random variation that cannot be predicted. Severity of adverse effects on wildlife from OWED will be influenced by environmental and demographic stochasticity that could increase a species' vulnerability. Certain OWED hazards may exponentially increase or decrease in the presence of anomalous weather events, accidents (e.g., pollution spills), or other natural (e.g., disease outbreaks) or anthropogenic phenomena that are either unknown, unexpected, or unpredictable (Figure 1, Table 1). In the following sections, we describe each parameter in detail.

Demographic sensitivity

Demographic sensitivity represents species elasticity, which Desholm (2009) describes as change in population growth rate based on change in adult mortality from turbine interactions. The degree to which individual losses affect population growth rate will be dictated by the decrease in survival (i.e., mortality from interacting with an OWED) and the decrease in fecundity (e.g., lesser breeding body weight due to lost foraging habitat or stress). All other things being equal, populations of species with a Type I survival curve, which have high survival of young and breeding adults (e.g., cetaceans, seabirds), are more likely to be adversely affected by loss of individuals than those with a Type III survival curve, which have high mortality of young and greater survival of adults (e.g., invertebrates; Gotelli 2008). Vital rates will control how loss of an individual is translated to population-level effects. In simple terms, loss of an individual in long-lived species with low reproductive rates is likely to have a greater effect on populations than the same loss in species that are short-lived and have a high reproductive rate. A population's ability to compensate for these individual losses will contribute to its vulnerability.

Ethological/biological factors

Species vulnerability will be influenced by behaviors that increase exposure to OWED and biological traits that increase likelihood of adverse effects. Species can be vulnerable to OWED based on basic feeding, breeding, migrating, or sheltering behaviors that the animal exhibits regardless of the presence of an OWED; we describe these as intrinsic or innate behaviors. For example, Furness et al. (2013) identified the following behaviors as contributing to collision vulnerability of birds: average flight altitude, flight maneuverability, percentage of time flying, and nocturnal flight activity. Other general behaviors, such as migratory strategy and dispersal ability (Gardali et al. 2012) may also increase exposure of individuals to hazards of OWED that can lead to direct mortality or injury and will vary by development phase. Some taxonomic groups, such as marine mammals, may be most vulnerable during construction and decommission activities, whereas others, such as birds and bats, will likely be more vulnerable during turbine operation. Explicit vulnerability evaluations for taxonomic groups other than birds have not yet been conducted.

Species vulnerability can also be caused by a species' response to the presence of an OWED; we describe these as response behaviors. These behaviors, while inherent to particular taxonomic groups, are not necessarily routine behaviors and are expressed in response to the stimulus of the OWED. For some species, this may be avoidance that can lead to partial or complete displacement from a project site, whereas for others, it may involve an attraction to wind farm structures. Furness et al. (2013) identified avian response behaviors as disturbance by wind farm structures, maintenance activities, and habitat specialization contributing to displacement.

Degrees of habitat specialization and physiological tolerance (Gardali et al. 2012) also have the potential to increase vulnerability. Biotic and abiotic factors that define a species' realized niche (Akçakaya et al. 1999) will dictate the habitat within which a species can survive. Some species, such as sessile cold-water corals, will have a high habitat specialization (Freiwald and Roberts 2006) and would be exceedingly vulnerable to a turbine foundation being placed within their habitat, whereas other species, such as Atlantic menhaden (*Brevoortia tyrannus*), a small fish that utilizes the entire continental shelf (Ahrenholz 1991), would have lower vulnerability. Physiological tolerances of a species will also dictate its vulnerability and will be specific to species and particular OWED hazards. For example, for species that avoid OWEDs during migration (Desholm and Kahlert 2005), increased energy expenditure may or may not affect overall fitness, and adverse effects of pile-driving noise (McCann 2012) or electromagnetic fields (Gill et al. 2012) may vary by species.

Finally, a vulnerability assessment must not only consider factors that make a species ethologically and biologically sensitive; it must also incorporate the relative importance of the species within its ecological community. If a species is a keystone predator, then the loss of individuals could have significant effects on the overall community structure and food web dynamics. Conversely, if a species is an important food resource for a guild, then its displacement, reduction, or elimination could cause a cascade of adverse effects to the entire ecological community. For example, pile driving during OWED construction reduced the prey base of the little tern (*Sternula albifrons*), which reduced colony-wide reproductive success (Perrow et al. 2011). Furthermore, if a species provides an important habitat to multiple other species, its disturbance during OWED construction has the potential to cause indirect effects that extend spatially and temporally beyond the construction window. An example would be disturbance of eelgrass (*Zostera*) beds in locations where transmission cables come to shore. In sum, direct effects of OWED on 1 species could cause indirect effects on others in the community.

Population sensitivity

Population sensitivity represents, firstly, how close the population is to extinction, independent of exposure to OWED (or, conversely to carrying capacity), and, secondly, proportion of the population that is then exposed to development (i.e., relative abundance). For some species that have populations that are already considered to be declining or are threatened by extinction, loss of 1 or several individuals may have an adverse effect on the population (e.g., North Atlantic right whale, *Eubalaena glacialis*). Existing vulnerability indices for birds include conservation status as a component of vulnerability (Garthe and Hüppop 2004, Furness et al. 2013). Regional, national, and international lists can be used to assess a species' current conservation status. Examples include state lists highlighting species of concern, species listed under the U.S. Endangered Species Act (ESA), or the International Union for Conservation of Nature (IUCN) Red List.

Another component of population sensitivity is relative abundance (Desholm 2009), also described as proportion of a biogeographic population exposed to an OWED (Garthe and Hüppop 2004, Furness et al. 2013). Relative abundance is a quotient of the number of individuals passing through the wind farm and a reference population (Desholm 2009). Relative abundance has spatial and temporal components. Spatially, if a population or sub-population is concentrated in a discrete geographic area near the OWED, then adverse effects from the OWED on individuals is more likely to contribute to a decline in regional population growth rates (e.g., sea ducks). As central-place foragers, colonial-nesting seabirds have the potential of high exposure to OWED during vulnerable life-stages (pair formation, incubation, and chick provisioning) where individuals and sub-populations could repeatedly interact with an OWED. This may be exaggerated in species with strong site fidelity, and especially where few safe or suitable breeding sites are available. In contrast, if a species population is widely distributed over a broader geographic area and has frequent immigration and emigration between sub-populations, adverse effects from a single OWED are less likely to cause declines in metapopulation growth rates. Temporally, a species will be more vulnerable if areas of high relative abundance persist over multiple years, causing sustained exposure to the hazards of OWED (i.e., the 20-year lifespan of a project).

Sociological factors

Which species are determined to be vulnerable will also be influenced by non-biological factors: legal status, economic importance, and stakeholder interest. The primary factor will most likely be a species' legal standing. Species that are protected by laws with strong "take" provisions—namely the ESA, Marine Mammal Protection Act, and Bald and Golden Eagle Protection Act (Eagle Act)—will be deemed high priorities by federal agencies. Thus, animals considered endangered under the ESA, such as deep-water corals, the Atlantic sturgeon (*Acipenser oxyrinchus*), the North Atlantic right whale, and the roseate tern (*Sterna dougallii*), will quickly be identified as priorities. Most species with a high level of legal protection are also going to have a high conservation status, although not always. Bald eagles have recovered from their endangered status, but, given their iconic status as a national symbol and their importance to Native American tribes, are still protected through the Eagle Act.

The second factor will be a species' economic importance (NYSERDA 2015). This would likely have a strong influence on which species individual states identify as a priority, particularly fishery stocks that are important for either commercial and/or recreational fishing. In Maine, for example, the American lobster (*Homarus americanus*) might be a priority species, while in New York, the summer flounder (*Paralichthys denatus*) might be a priority species.

Finally, there will also be species that will become a high priority to stakeholders because they are highly visible to the public or are valued by the public for aesthetic or other reasons; conversely, species that some stakeholders value less because they are considered a nuisance or are overly numerous may initially be deemed a lower priority. Common species will introduce the possibility that a particular project may adversely affect many individuals, but this does not compound into population-level effects. While wildlife managers and ecologists often focus attention and place value on populations, direct mortality of many individuals of common species would be considered a violation of certain laws (e.g., Migratory Bird Treaty Act) and may be important to the public, and, thus, warrant consideration within a vulnerability index.

Evaluation methods

To determine vulnerability of wildlife to OWED, we proposed that a mix of quantitative and qualitative methods be used to apply the conceptual framework. For a few species in discrete geographic areas, there may exist enough empirical data to quantitatively evaluate certain aspects of vulnerability. Caution should be taken in combining factors into an overall numerical rank, however, because 1 single factor, such as population sensitivity or a particular intrinsic behavior, could drive a high vulnerability determination. Furthermore, because quantitative assessments that use continuous data can create a false sense of precision, we suggest a simplistic assessment using rank-order categories (low, medium, and high) to estimate risk for each parameter based on basic biological knowledge. An accurate quantitative analysis will be difficult, if not impossible, for most species due to significant data gaps, complexity, and uncertainty. In fact, uncertainty about environmental effects is now causing delays in OWED permitting in the United Kingdom (Masden et al. 2015). Therefore, a process that allows for expert judgment and stakeholder involvement should be used. Collectively, these tools discussed briefly below, and others, would need to be used in a coordinated manner through a collaborative process, and tested for their efficacy.

Each element within the framework will require different tools for evaluation. While specific tools will need to be tailored to the scale and location of individual projects, we suggest the following methods be considered for each element of the model.

Demographic sensitivity

Conduct population model sensitivity analysis and population viability analysis (PVA). While there are likely to be significant gaps in data on vital rates for most species, conducting a sensitivity analysis of population models (e.g., an age- or stage-based Leslie matrix) could help inform decision-makers on significance to the population of the loss of juveniles or adults caused by OWEDs. Also, conducting PVAs would allow exploration of scenarios (e.g., mortality of 10, 100, 1,000, or 10,000 individuals) to inform decision-makers on level of risk (i.e., acceptable, tolerable, and intolerable; Renn et al. 2011).

Ethological/biological sensitivity

Conduct literature review, use expert judgment, and conduct year-round field studies under different weather conditions. The ethological/biological sensitivity could initially be approached through a literature review of what behaviors and physiological characteristics are known to increase vulnerability to offshore wind, and then what is known about those particular behaviors (Furness et al. 2013). Next, depending on funding constraints, field studies could be conducted to gather additional information on particular traits that are considered to increase vulnerability, such as migration routes of birds and cetaceans.

Population sensitivity

Determine listing status of a species, and conduct site-specific fieldwork (e.g., measure of relative abundance at project site). Conservation status could be assessed using local (e.g., state), regional (e.g., Partners in Flight), national (e.g., ESA listed species), or international (e.g., ICUN Red List) assessments. Surveys could be conducted at a potential development site to assess abundance relative to regional databases or local control sites, but should include a range of seasons and weather conditions.

Sociological importance

Develop project-specific, ad hoc working groups prior to any formal permitting involving state and non-state actors. While determining sociological importance will be contextual, stakeholders could be engaged through independent working groups as well as existing formal public comment processes associated with the National Environmental Policy Act (NEPA) and state permitting processes. In addition, sociological importance could also be gauged by standing independent, regional, or national groups that can put the species and site-specific vulnerability within context. While these types of groups have yet to be developed for OWED in the United States, European groups, such as the Collaborative Offshore Wind Research into the Environment (COWRIE) and Strategic Ornithological Support Service (SOSS), and terrestrial wind groups in the United States, such as the National Wind Coordinating Collaborative (NWCC), should be examined as examples.

Discussion

The conceptual model described in Figure 1 combines biological factors—demographic, ethological/biological, and population sensitivity—with sociological factors. Demographic sensitivity is the core suite of factors determining a population's growth rate. Ethological/biological sensitivity consists of behaviors, physiological sensitivity, and habitat specialization that increase risk of direct adverse effects. Sociological factors include legal status and economic importance, and overall stakeholder interest. We suggest that each of the primary 4 factors can independently, or combined, lead to a determination that a species is considered vulnerable. Because determining vulnerability will be defined by the interplay between the different parameters in the conceptual model, a high ranking on 1 factor, such as legal listing status, may place a species as a high priority despite having low vulnerability in biological traits. Some species, like the North Atlantic right whale, have the potential to score highly in nearly every category.

The conceptual model we have presented simplifies the highly complex, interactive nature of vulnerability. We recognize that other factors contribute to biological and sociological determinations of vulnerability, and that specific parameters used in vulnerability determinations will vary significantly from location to location. We recommend that this conceptual model be vetted and refined through a workshop or case study to test its efficacy in an applied context. A workshop could also help develop mathematical models and model parameters.

Financially and temporally feasible OWED pre- and post-construction monitoring and mitigation plans will require focused studies on species that are determined to be most vulnerable to the OWED hazards at a particular site. Determining which species are most vulnerable, however, is a significant challenge that will be hampered by many information gaps. We suggest that determining vulnerable species should include not only biological factors but also those that contribute to which species are deemed a priority by legal, economic, and other factors. We suggest that using qualitative and quantitative methods is more likely to provide a sound vulnerability determination.

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