Assessing the cumulative adverse effects of offshore wind energy development on seabird foraging guilds along the East Coast of the United States

M Wing Goodale, Anita Milman and Curtice R Griffin

Department of Environmental Conservation, University of Massachusetts at Amherst, 210 Holdsworth Hall, MA, 01003-9285 United States of America
Biodiversity Research Institute, 276 Canco Road, Portland, ME, 04103, United States of America

Author to whom any correspondence should be addressed.

E-mail: wing_goodale@briloon.org, amilman@eco.umass.edu and cgriffin@eco.umass.edu

Keywords: offshore wind farm, cumulative effects, mitigation, exposure, seabirds, guild

Abstract

Offshore wind farms are rapidly being permitted along the East Coast of the US, and with subsequent development could cumulatively affect seabird populations. Yet, the seabird guilds most likely at risk of cumulative effects have not been identified. Assessments of cumulative effects must first calculate the cumulative exposure of seabirds to areas suitable for offshore wind farms and then estimate how exposure will affect populations. This paper addresses this first need, and quantifies how three different wind farm siting scenarios could cumulatively expose seven seabird foraging guilds. The coastal bottom gleaner guild (sea ducks) would be exposed at similar rates regardless of siting decision, while other coastal guilds would be exposed at a higher rate when projects are built in shallow areas and close to shore rather than in high-wind areas. The pelagic seabird guild would be exposed at high rates when projects are built in high-wind areas. There was no single offshore wind farm siting scenario that reduced the cumulative exposure for all guilds. Based upon these findings, we identify the foraging guilds most likely to be cumulatively exposed and propose an approach for siting and mitigation that may reduce cumulative exposure for all guilds.

Introduction

Offshore wind energy development (OWED) is expanding along the East Coast of the US. The first US offshore wind farm began operating in 2016 and the US federal government is planning for 86 gigawatt (GW) of offshore wind to be installed by 2050 (DOE 2016). While offshore wind farms can provide many positive benefits (Ram 2011), they also have the potential to adversely affect seabirds (Langston 2013).

Research in Europe reported that offshore wind farms can adversely affect seabirds through mortality and displacement (Drewitt and Langston 2006, Fox et al 2006, Goodale and Milman 2016). Mortality can occur when birds collide with the superstructure or rotors during operation (Drewitt and Langston 2006, Fox et al 2006). Displacement occurs when birds consistently avoid wind farms and has been documented for sea ducks, gannets, auks, geese, and loons (Desholm and Kahler 2005, Larsen and Guillemette 2007, Percival 2010, Lindeboom et al 2011, Plonczkier and Simms 2012, Langston 2013, Garthe et al 2017, Mendel et al 2019). This displacement reduces potential mortalities, but birds that consistently avoid wind farms can experience effective habitat loss, which may negatively affect their fitness (Drewitt and Langston 2006, Masden et al 2009, Petersen et al 2011, Langston 2013, Petersen et al 2014).

Though the adverse effects of an individual wind farm are important, of greater concern is the cumulative adverse effects (CAE) of multiple offshore wind farms on seabirds. CAE occurs when the effects of multiple wind farms are incrementally combined with other anthropogenic stressors through space and time to affect populations (Goodale and Milman 2016). US laws and regulations require assessment of these cumulative effects during the permitting process (CEQ 1997). CAE assessments must first establish spatial boundaries relevant to the areas being developed.
and seabird populations of interest (Goodale and Milman 2016). Secondly, the effects on seabird populations from each new wind farm combined with effects from past, present, and reasonably foreseeable future actions needs to be determined (Goodale and Milman 2019). While assessing CAE is important to guide management actions, there has been little research on CAE due to the difficulty in relating the effects of one wind farm to population trends (Goodale and Milman 2016). Given the challenges in understanding population-level effects, a reasonable initial step for evaluating CAE is to assess cumulative exposure (Goodale and Milman 2019).

The cumulative exposure of seabirds to offshore wind farm development will depend on how the location of development overlaps with seabird use areas. Seabird guild distributions are heterogeneous and species will be differentially exposed depending on their foraging, reproductive, and migratory strategies. Coastal birds typically forage within sight of land, while inshore species feed out of sight of land but within the continental shelf of the East Coast. Pelagic species forage at the frontal zone along or beyond the continental shelf break (Furness and Monaghan 1987, Schreiber and Burger 2001, Gaston 2004). In addition, some pelagic species rely on wind for efficient flight (Schreiber and Burger 2001), leading to concentrations of these species in high-wind areas in the Gulf of Maine and beyond the continental shelf (Kinlan et al 2016).

Cumulative effects occur as a result of the exposure of vulnerable seabirds to the hazards of offshore wind farms across space and over time. Exposure affects an individual bird. The effects of exposure of many individual birds then accumulate and potentially have population-level effects. Understanding the relationship between seabird guild exposure and wind farm siting decisions is the first step in supporting CAE assessments and developing effective mitigation measures. The initial component of mitigation is to avoid effects, which entails siting wind farms away from areas of high biological productivity that provide critical foraging habitat for multiple guilds (Goodale and Milman 2016). Yet, tradeoffs may exist between siting decisions that may reduce exposure for some seabird groups while increasing exposure for other groups.

To date, there has been no research to assess if the cumulative effects of offshore wind farms on seabird guilds can be reduced through siting decisions. This paper addresses this gap by answering two questions: which seabird guilds are most likely to be at risk of CAE from different scenarios for wind farm development; and could any set of wind farm siting decisions serve to reduce exposure for multiple seabird guilds simultaneously. To answer these questions, we assess the cumulative exposure of seven seabird foraging guilds to three different wind farm siting scenarios along the East Coast of the US using the cumulative exposure model (‘CE model’; Goodale and Milman 2019). Below we describe the CE model process and present the results of the analysis, which illuminate the relationships between siting decisions and seabird guild exposure. By identifying guilds most likely to be cumulatively exposed and considering the vulnerability of seabirds to offshore wind farms, we then recommend a process to minimize cumulative exposure for multiple guilds, which may reduce CAE. This assessment provides stakeholders with guidance on how project-specific permitting and regional siting can reduce the CAE of OWED on seabirds.

Methods

Model process and inputs

As detailed below, the CE model estimates the locations of all potential wind farms in an area (‘offshore wind energy development (OWED) suitability layer’) and then assesses how different future siting decisions would expose each seabird guild.

OWED suitability layer

The OWED suitability layer was developed to set the boundaries of analysis to areas where seabirds would likely be exposed to future wind farm development. The suitability layer was spatially bounded to areas along the East Coast being considered for development (Farquhar 2011) and was temporally bounded by starting at the present and moving into the future when the East Coast has been saturated by wind farms. Nine layers were used in a Boolean map-layering process to develop the OWED suitability layer (table 1). Given the uncertainty about which factors are most important for siting offshore wind farms, Boolean logic simplifies continuous variables and reduces the number of input assumptions. Since an overly constrained OWED suitability layer could erroneously exclude areas from development and thus underestimate the seabird exposure, we selected Boolean cut-off values that included a greater area for development (Goodale and Milman 2019). The criteria used to set the Boolean values are described in table 1.

A wind farm grid, representing 300 megawatt (MW) wind farms, was placed in the OWED suitability layer. While offshore wind turbine capacity is rapidly increasing and larger turbines may be used in high-wind areas, smaller 6 MW turbines (Siemens 2016), spaced 8 rotor diameters apart (Jonkman et al 2009), were used in the model to increase the resolution of the analysis (i.e. a greater number of wind farms). The final OWED suitability layer had a 450 GW capacity (figure 1).

OWED siting scenarios

Wind farm siting is a tradeoff between distance from shore, bathymetry, and wind speed as well as other environmental and socioeconomic factors (Schwartz et al 2010, Dvorak et al 2013). Increased distance from shore and greater water depth strongly influence
Table 1. Offshore wind farm siting factors used as inputs to create OWED suitability layer. ‘Exclusions’ are specific areas of the ocean that have physical hazards or specific regulatory exclusions (e.g. shipping lanes), or have been identified as conflicting with military activities. ‘Constraints’ are OWED siting considerations that have thresholds beyond which OWED is no longer viable either technologically or economically.

| Category          | Factor                                      | Boolean values | Boolean value criteria                                                                 | LCOE sort order | Data source                     |
|-------------------|---------------------------------------------|----------------|---------------------------------------------------------------------------------------|----------------|---------------------------------|
| Exclusion         | Danger zones and restricted areas\(^b\)     | All = 0        | Development is unlikely in these areas                                                | NA             | http://marinecadastre.gov/      |
| Exclusion         | Dept. of Defense wind exclusions areas      | All = 0        | Development is unlikely in these areas                                                | NA             | http://marinecadastre.gov/      |
| Exclusion         | Ocean disposal sites\(^c\)                  | All = 0        | Development is unlikely in these areas                                                | NA             | http://marinecadastre.gov/      |
| Exclusion         | Shipping lanes\(^d\)                        | All = 0        | Development is unlikely in these areas                                                | NA             | http://marinecadastre.gov/      |
| Exclusion         | Unexploded ordnance                         | All = 0        | Development is unlikely in these areas                                                | NA             | http://marinecadastre.gov/      |
| Exclusion         | State waters as defined by Submerged Lands Act | All = 0        | Development is unlikely in these areas                                                | NA             | http://marinecadastre.gov/      |
| Constraint        | Wind speed \(^e\)                           | <7 m s\(^{-1}\) = 0 > 7 m s\(^{-1}\) = 1 | The minimum average wind speed was based upon economic factors (Schwartz et al. 2010) and the value commonly used as the minimum when assessing development potential (Musial and Ram 2010); no maximum was set because the greater the wind speed the greater the power production. | High to low    | http://marinecadastre.gov/      |
| Constraint        | Bathymetry \(^f\)                           | > 200 m = 0–199 m = 1 | Bathymetry was based upon greatest depth for floating turbines (Schwartz et al. 2010). | Shallow to deep| http://marinecadastre.gov/      |
| Constraint        | Distance from shore                         | 0–5.6 & > 92.6 km = 0 5.6–92.6 km = 1 | While offshore wind farms in Europe are 1.8–112 km from shore (4COffshore 2016), this analysis was constrained to federal waters where the government has established areas for development (BOEM 2018); the maximum distance was dictated by the extent of the wind speed layer. | Close to far   | Created using Euclidean distance function in ArcGIS |

\(^a\) Levelized cost of electricity.
\(^b\) Danger Area; Danger Zone; Missile Testing Area; Naval Operations Area; Prohibited Area; Restricted Airspace; Restricted Area; Separation Zone; Test Area; Torpedo Testing Area.
\(^c\) Chemical waste dumping grounds; dredge material disposal; dumping ground; explosive dumping ground; spoil ground.
\(^d\) Shipping Fairways Lanes and Zones; Traffic Separation Schemes/Traffic Lanes; Precautionary Areas; Recommended Routes.
\(^e\) Ammunition dumping areas; caution areas; chemical munitions dumping area; danger; danger unexploded bombs and shells; drill minefield; dumping area caution; dumping ground explosives; explosives; explosives dumping areas; obstruction; submerged explosives; submerged material; submerged mine; unexploded bombs, mine, ordnance, projectiles, rockets, and torpedo.
development and together can increase a project’s cost by as much as 50% (Green and Vasilakos 2011). While building in near-shore shallow locations reduces development costs, building in offshore locations with higher wind speeds increases energy production and may allow for the use of larger turbines, both of which can reduce the levelized cost of electricity (LCOE; i.e. lifetime costs divided by energy production; Manwell et al 2009, Schwartz et al 2010). Consequently, beyond the Wind Energy Areas (WEAs) currently identified for development (BOEM 2018), the location and order of future wind farm development remains unknown because there is no single offshore wind farm siting strategy that optimizes LCOE. In our analyses, we examine three siting scenarios: distance from shore, bathymetry, and wind speed. Each scenario assumes wind farm build-out occurs in a manner that optimizes the LCOE for the specified siting factor.

Seabird abundance
Seabird abundance models for 36 species (table 2) were spatially joined with the OWED suitability layer. These modeled seabird abundance estimates (Version 1.0) were developed by the National Oceanic and Atmospheric Administration (NOAA) using survey data collected from 1978–2014 along the East Coast of the US and spatial predictive modeling (Kinlan et al 2016). The models estimate the spatial distribution of seabird in US
Atlantic Outer Continental Shelf from Maine to Florida, indicating where species are more or less likely to be abundant, and are useful for supporting marine spatial planning (Kinlan et al. 2016). The models are influenced by uneven survey effort (potentially reducing accuracy in areas with low sampling), low sample size for some species, and limitations in environmental predictor variables (Kinlan et al. 2016), which could cause some error in abundance predictions. These models, however, represent a combination of all relevant surveys and are the best source for multispecies regional scale analysis.

To increase accuracy in our assessment, the analysis was conducted over a large geographic area, which reduced the influence on any individual cell in the model; species were combined into guilds; and annual maps were used to represent the average spatial distribution over the year (seasons with the greatest abundance contributed more to the annual pattern; Kinlan et al. 2016). While temporal exposure will vary between seasons, we used annual maps to reduce complexity of the analysis and assume high exposure during any season could contribute to CAE.

| Guild                        | Common name       | Scientific name |
|------------------------------|-------------------|-----------------|
| Coastal bottom gleaner       | Surf Scoter       | Melanitta perspicilla |
| Coastal bottom gleaner       | White-winged Scoter | Melanitta fusca |
| Coastal bottom gleaner       | Black Scoter      | Melanitta americana |
| Coastal bottom gleaner       | Long-tailed Duck  | Clangula hyemalis |
| Coastal diver                 | Red-throated Loon | Gavia stellata |
| Coastal diver                 | Common Loon       | Gavia immer |
| Coastal diver                 | Horned Grebe      | Podiceps auritus |
| Coastal diver                 | Double-crested Cormorant | Phalaenoptilus australis |
| Coastal plunger               | Northern Gannet   | Morus bassanus  |
| Coastal plunger               | Brown Pelican     | Pelecanus occidentalis |
| Coastal plunger               | Royal Tern        | Sterna maxima |
| Coastal plunger               | Roseate Tern      | Sterna dougallii |
| Coastal plunger               | Common Tern       | Sterna hirundo |
| Coastal plunger               | Arctic Tern       | Sterna paradisaea |
| Coastal plunger               | Least Tern        | Sterna antillarum |
| Coastal surface gleaner       | Laughing Gull     | Chroicocephalus philadelphia |
| Coastal surface gleaner       | Bonaparte’s Gull  | Larus delawarensis |
| Coastal surface gleaner       | Ring-billed Gull  | Larus argentatus |
| Coastal surface gleaner       | Herring Gull      | Larus canus |
| Coastal surface gleaner       | Great Black-backed Gull | Alle alle |
| Pelagic diver                 | Dovekie           | Uria aalge |
| Pelagic diver                 | Common Murre      | Fratercula arctica |
| Pelagic diver                 | Atlantic Puffin   | Alca torda |
| Pelagic diver                 | Razorbill         | Rissa tridactyla |
| Pelagic scavenger             | Black-legged Kittiwake | Fulmarus glacialis |
| Pelagic scavenger             | Northern Fulmar   | Calonectris diomedas |
| Pelagic scavenger             | Cory’s Shearwater | Puffinus gravis |
| Pelagic scavenger             | Great Shearwater  | Puffinus puffinus |
| Pelagic scavenger             | Sooty Shearwater  | Stercorarius pomarinus |
| Pelagic scavenger             | Manx Shearwater   | Oceanodroma leucorhoa |
| Pelagic scavenger             | Pomarine Jaeger   | Oceanodroma morrisonis |
| Pelagic scavenger             | Wilson’s Storm-Petrel | Oceanodroma castro |
| Pelagic scavenger             | Leach’s Storm-Petrel | Phalaropus lobatus |
| Pelagic scavenger             | Band-rumped Storm-Petrel | Phalaropus fulicaris |

Individual species were binned into guild groupings relevant to offshore wind siting (table 2) based upon foraging guilds described by De Graaf et al (1985) and foraging strategies identified in species accounts (Rodewald 2015). Species within the same guild have similar foraging strategies and thus generally similar vulnerabilities and exposure to offshore wind farm development (Furness et al. 2013, Willmott et al. 2013, Wade et al. 2016). The guilds were: coastal bottom gleaners (sea ducks), coastal divers (loons, grebes, and cormorants), coastal plunngers (gannets, pelicans, and terns), coastal surface gleaners (gulls), pelagic divers (auks), pelagic scavengers (kittiwakes, fulmars, and shearwaters), and pelagic surface gleaners (storm-petrels and phalaropes). In appendix (figure A1), maps of the average relative abundance predictions for each guild, developed from the NOAA models, are provided for reference. These guilds encompass all seabird guilds likely to be exposed to offshore wind farms along the East Coast.

Seabird cumulative exposure calculation
To assess how seabird guilds will be cumulatively exposed to the three siting scenarios, the CE model
first calculates the proportion of each seabird population exposed to each wind farm in the suitability layer, and then an average for each guild. For the purposes of this assessment, population was defined as the birds using the area delineated in the NOAA models (figure 1; appendix figure A1). However, since the models are intended to represent the relative difference in abundance across space, rather than the specific number of birds (Kinlan et al 2016), each NOAA abundance model was normalized to sum to 1 (by dividing each cell by the sum of the annual prediction).

Second, scenarios were created by ordering the OWED suitability layer from high to low favorability based upon reducing the LCOE for each factor. Then a scenario based on minimizing bird exposure (i.e. prioritizing development in areas with fewest birds) was developed by ordering the suitability layer from low to high number of birds estimated to be present based on the NOAA model. Finally, to calculate exposure of seabirds as development occurs, the model sums one wind farm at a time, and the proportion of each seabird population exposed for each scenario.

Model outputs
Our model produced cumulative exposure curves for each seabird guild and build-out scenario combination, and a cumulative exposure index that identified the siting decisions that had the greatest influence on seabird cumulative exposure. For each build-out scenario, the CE curve plots the relationship between guild exposure and GW of wind farm production from zero OWED to full build-out of the OWED suitability layer. The closer the curve is to the y-axis, the higher the initial rate of exposure; the closer the curve is to the x-axis, the lower the initial rate of exposure. For each guild, the y-axis is the average percentage of each species’ population that is exposed to development. The highest value on the y-axis scale varies for each graph because guild distribution varies (appendix figure A1), which causes differences in the proportion of the birds, within a guild, exposed to the suitability layer. The black vertical line represents 86 GW (DOE’s 2050 target for OWED, which is equivalent to ~20% development of the OWED suitability layer). With the exception of coastal bottom gleaners, most coastal species will be exposed at higher rates when projects are built close to shore and in shallow waters. Pelagic divers and scavengers will be exposed at higher rates when projects are built in high-wind resource areas.

Figure 2. Relationships between OWED siting scenarios and guilds. The red curve represents the incremental exposure of each guild within the OWED suitability layer when wind farms are always sited in areas with the fewest birds. The green line represents guild cumulative exposure when siting is prioritized to be in shallow areas, the teal line when siting close to shore, and the purple line when siting in areas with the highest wind speed. The maximum value of the y-axis scale varies for each graph because guild distribution varies (appendix figure A1), which causes differences in the proportion of the birds, within a guild, exposed to the suitability layer. The black vertical line represents 86 GW (DOE’s 2050 target for OWED, which is equivalent to ~20% development of the OWED suitability layer).
curve from the area below the bird abundance curve. The closer the CE index is to 1 for a siting scenario, the steeper the initial portion of the CE curve and the higher the initial rate of cumulative exposure.

**Model results interpretation**

The CE curves predict guild exposure patterns from zero development to complete saturation of the suitability layer. The curves can be interpreted at any GW of development and across the continuum of development. Since the entire OWED suitability layer is not likely to be built, viewing the curves at a specific point of development allows for a comparison between the percentages of each population exposed to a siting scenario, while also providing insight into which siting scenario will expose the birds the most.

While the curves can be interpreted at any point of development, for the purposes of this analysis, in addition to considering the entire curve, we also consider the point at which 86 GW of development has occurred, because that extent of development represents DOE’s 2050 scenario. This extent of development is equivalent to ~20% of the OWED suitability layer. The guild exposure patterns for full development of the OWED suitability layer were evaluated by viewing the relationship between siting scenario and bird abundance exposure curves, and with box-plots displaying the distribution of the CE index by siting scenario, with each box representing all species within a guild. All plots were developed using R version 3.3.1 (R Core Team 2015).

**Results**

The CE model predicted that coastal guilds will have greater exposure than pelagic guilds to offshore wind farm development and that siting decisions significantly influence cumulative exposure rates (figures 2 and 3). For the first 86 GW of development (DOE’s 2050 target), 8%–14% of the coastal bottom gleaner populations (i.e. proportion of the NOAA models) will be exposed regardless of siting decision, while 7%–10% of the coastal diver populations will be exposed to projects sited close to shore and in shallow areas, and only 3% of the coastal diver populations will be exposed to projects built in high-wind areas. Coastal plungers and coastal surface gleaners had similar but less pronounced exposure patterns: 3%–5% of the populations will be exposed to projects sited close to shore and in shallow water, and 1%–2% of the populations will be exposed to projects built in high-wind areas. For the pelagic guilds, siting in shallow areas will expose <1% of the populations; siting close to shore will expose 1%–3% of the populations; and siting in high-wind areas will expose 2%–5% of the populations. For full development of the OWED suitability layer, the proportion of the populations that will
be exposed was approximately 30% of coastal bottom gleaners and coastal divers, 11%–13% of coastal plungers and coastal surface gleaners, and 6%–10% of pelagic guilds (figure 2; appendix figure A1).

For complete build-out of the OWED suitability layer, distance from shore had the least influence on guild exposure; bathymetry had a moderate influence; and wind speed had the most influence (figure 3). As a group, coastal birds would be exposed at a higher rate when projects are built in shallow areas and close to shore rather than in high-wind areas. The exposure patterns of coastal bottom gleaners diverged from other coastal species since these birds will also be exposed at higher rates in high-wind areas. In contrast, coastal divers would be exposed the least when wind farms are sited in high-wind resource areas. Coastal plungers and surface gleaners had the greatest CE index range (figure 3), indicating that the spatial distribution of the groups varied substantially. Siting in shallow areas has the potential to expose these guilds at the highest rate.

The exposure pattern of pelagic birds was inverse to that of coastal species. Pelagic guilds will consistently be exposed at the highest rate when projects are built in high-wind areas, at a steady rate when projects are built close to shore, and at the lowest rate when projects are built in shallow areas.

Discussion

Our analyses suggest that coastal guilds have the greatest likelihood of being exposed to development regardless of siting decision; that OWED siting decisions cannot reduce cumulative exposure rates for all guilds simultaneously; and that the same siting scenarios yield opposite exposure patterns for coastal and pelagic guilds.

The relationships between guild exposure and build-out scenarios are partially driven by two factors affecting seabird distribution: distance from shore, and variation in annual abundance up and down the Atlantic coast (appendix figure A1). The exposure of coastal birds is expected to be higher than that of pelagic birds when wind farms are sited close to shore because distance from shore and bathymetry are generally correlated (Williams et al 2015), with the exception of the Gulf of Maine. Conversely, since wind speed increases with distance from shore (Schwartz et al 2010), exposure of coastal birds will be lower than that of pelagic birds when wind farms are sited in high-wind areas. These relationships are further enhanced by north–south trends, in which wind speed is highest in the Gulf of Maine where depth also rapidly increases. Since the pelagic guilds are concentrated offshore in the Gulf of Maine, they will be exposed the most.
when wind farms are sited in high-wind areas and exposed the least in shallow areas.

One exception to the broader trends is the high wind speed and relatively shallow depth southeast of Cape Cod, Massachusetts, an area heavily used by sea ducks (figure 2; appendix figure A1). Consequently, a high percentage of the coastal bottom gleaner populations in this area will be exposed OWED regardless of siting decision. This high exposure occurs because birds in this guild forage in shallow water (Anderson et al. 2015), concentrate close to shore, and have a northerly biased distribution, particularly near Nantucket Shoals (Silverman et al. 2013, Kinlan et al. 2016, Meattey et al. 2019).

A high percentage of the coastal diver population will be exposed to wind farms sited close to shore and in shallow areas, but projects sited in high-wind areas avoid exposing coastal divers because this guild’s distribution is biased to the mid-Atlantic region (Kinlan et al. 2016) where wind speeds are lower (Schwartz et al. 2010). Coastal plungers and coastal surface gleaners have exposure patterns similar to the other coastal guilds, but a lower proportion of the populations is predicted to be exposed because these guilds are widely distributed along the East Coast (Kinlan et al. 2016), and the birds utilize many coastal areas outside of the OWED suitability layer.

Pelagic guilds are more abundant offshore and, for some species, substantially more abundant on the outer banks of the Gulf of Maine (appendix figure A1; Kinlan et al. 2016), areas where wind farm development is unlikely. Thus, it is likely that a low percentage of pelagic birds would be exposed to both initial and complete build-out of the OWED suitability layer, and, due to the birds’ offshore and northerly bias distribution, few pelagic birds would be exposed to wind farms sited in shallow areas.

Based upon these varying patterns of cumulative exposure, we recommend that the guilds be grouped into four tiers (figure 4) to help guide management decisions that reduce the CAE of guilds most at risk. However, exposure alone will not cause adverse effects because some species may use the wind farm area and have a low likelihood of collision. To be at risk of CAE, species must both be cumulatively exposed to OWED and vulnerable to either collision or displacement (Goodale and Milman 2016). Similar to approaches taken in collision risk models (e.g. Band 2012), we use both guild cumulative exposure patterns and vulnerability to evaluate the likelihood of CAE. We use evidence of collision or displacement in the literature, and rankings in Furness et al. (2013), to determine vulnerability. The tiers are as follows: Tier 1, coastal bottom gleaner and coastal diver; Tier 2, coastal plunger and coastal surface gleaner; Tier 3, pelagic diver; and Tier 4, pelagic scavenger and pelagic surface gleaner.

Among the guilds, CAE is more likely for Tier 1 (coastal bottom gleaners and coastal divers). Our CE model indicates that Tier 1 guilds will be cumulatively exposed to wind farms built in shallow water and close to shore, which are the areas more likely to be developed in the near term due to current foundation technology (Jacobsen et al. 2016).

Offshore wind farms are documented to affect species within Tier 1 guilds. Coastal bottom gleaners are consistently identified as being vulnerable to displacement due to avoidance behaviors, which could lead to effective habitat loss (Desholm and Kahlert 2005, Petersen et al. 2011, Furness et al. 2013, Petersen et al. 2014, Dierschke et al. 2016, Mendel et al. 2019); although the effects of habitat loss on populations levels are difficult to determine (Mendel et al. 2019). Some coastal diver species are vulnerable to displacement and others are vulnerable to collision: red-throated loons are documented to be permanently displaced by wind farms (Percival 2010, Lindeboom et al. 2011, Mendel et al. 2019); Common Loons are predicted to have high displacement vulnerability (Furness et al. 2013); and Double-crested Cormorants may be vulnerable to collision because the birds are attracted to wind farms (Krijgsveld et al. 2011, Lindeboom et al. 2011).

Our CE model indicates Tier 2 guilds (coastal plungers and coastal surface gleaners) will have a lower proportion of the population exposed than Tier 1 guilds, but
will be exposed to wind farms built in shallow water where development is most likely. Species within Tier 2 are also vulnerable to collision, and potentially to displacement (Furness et al. 2013, Willmott et al. 2013, Harwood et al. 2017, Kelsey et al. 2018). The Northern Gannet, in contrast, is well documented to be vulnerable to displacement, but also may have the potential for collisions if they enter a wind farm (Krijkveld et al. 2011, Cook et al. 2012, Hartman et al. 2012, Furness et al. 2013, Garthe et al. 2014, Cleasby et al. 2015, Vanermen et al. 2015, Dierschke et al. 2016, Garthe et al. 2017).

While species within the Tier 3 guild (pelagic divers) are vulnerable to displacement (Dierschke et al. 2016), offshore wind development is less likely to cause CAE for this guild if projects are sited in shallow areas. CAE is unlikely for Tier 4 guilds (pelagic scavengers and surface gleaning), which have low cumulative exposure according to our CE model and low vulnerability ranking to gleaning unlikely for Tier 4 guilds. The Northern Gannet, in contrast, is well documented to be vulnerable to displacement, but also may have the potential for collisions if they enter a wind farm (Krijkveld et al. 2011, Cook et al. 2012, Hartman et al. 2012, Furness et al. 2013, Garthe et al. 2014, Cleasby et al. 2015, Vanermen et al. 2015, Dierschke et al. 2016, Garthe et al. 2017).

The development currently planned within the WEAs is generally following the recommendations above. The federal government and states recognize the importance of hotspots (NYSERDA 2015) and have specifically excluded from WEAs those locations with known concentrations of birds (BOEM 2018), such as Nantucket Shoals (BOEM 2014). Existing regional siting of WEAs and wind call areas (future lease areas) have effectively spread potential development from South Carolina to Massachusetts (BOEM 2017). In addition to being relatively dispersed along the East Coast, the WEAs are generally separated from each other; thus, assuming that only a few wind farms are built within each WEA, development will be effectively dispersed. However, if two or more wind farms are sited within a WEA, they should be separated as much as possible to provide movement corridors for species vulnerable to displacement. While the focus of existing development has to some degree avoided hotspots, dispersed siting, and spaced projects apart from one another, future siting should seek to spread out the exposure as much as possible, for example by identifying new WEAs in the Gulf of Maine.

Conclusions

Our analysis provides new insights into managing the cumulative exposure of seabirds to OWED. The CE model outputs indicate that the coastal bottom gleaning and coastal diver guilds are most likely to be cumulatively exposed to wind farm development along the East Coast of the US and should be the focus of CAE assessments. Since sea ducks and loons dominate these guilds and are identified to have high vulnerability to displacement, adverse effects from displacement may be a greater concern than collision for CAE. Therefore, on both the site-specific and regional planning scales, mitigation efforts focused on reducing habitat loss—i.e. avoiding hotspots, spreading out development, and providing movement corridors—are likely to be the most effective means of reducing the potential CAE of offshore wind farms on seabirds. As more offshore wind farms are built, ongoing monitoring and research will be critical to a better understanding of how exposure and vulnerability...
contribute to risk and how habitat loss affects populations, particular for species where little data are currently available.

Acknowledgments

We thank C Schweik, and J McGowan at University of Massachusetts, Amherst for helping guide manuscript preparation. We also thank staff at Biodiversity Research Institute for providing research support. This work was partially funded by the Robert and Patricia Switzer Foundation as well as the National Science Foundation-sponsored Integrative Graduate Education and Research Traineeship (IGERT): Offshore Wind Energy Engineering, Environmental Science, and Policy [grant number 1068864].

Appendix

Guild annual average relative abundance predictions developed from NOAA’s abundance models (figure A1; Version 1.0; Kinlan et al 2016). The species models were first normalized by dividing each cell by the sum of the layer, and the maps were created by averaging all species within a guild. The scale represents the relative proportion of individuals from the combined NOAA models in a given location. The NOAA models are periodically updated with new survey data and the most recent models can be found at: https://northeastoceandata.org/.

Figure A1. Guild annual average relative abundance predictions developed from NOAA’s abundance models (Version 1.0; Kinlan et al 2016).
Figure A1. (Continued.)
Figure A1. (Continued.)
Figure A1. (Continued.)
Figure A1. (Continued.)
Figure A1. (Continued.)
**References**

4COffshore 2016 (http://4coffshore.com/)
Anderson E M, Dickson R D, Lok E K, Palm E C, Savard J L, Bordage D and Reed A 2015 Surf Scoter (Melanitta perspicillata) *The Birds of North America* ed P G Rodewald (Ithaca, NY: Cornell Lab of Ornithology; Retrieved from the Birds of North America (https://doi.org/10.2173/bna.363)
Band W 2012 *Using a collision risk model to assess bird collision risk for offshore windfarms. Report commissioned by The Crown Estate, through the British Trust for Ornithology, via its Strategic Ornithological Support Services, Project SOSS-02 British Trust for Ornithology 1–62*
BOEM 2014 Commercial Wind Lease Issuance and Site Assessment Activities on the Atlantic Outer Continental Shelf Offshore Massachusetts (https://boem.gov/Revised-MA-EA-2014/)
BOEM 2017 *Atlantic OCS Renewable Energy: Massachusetts to South Carolina (https://boem.gov/uploadedImages/BOEM/Renewable_Energy_Program/Mapping_and_Data/ocs_wpa.jpg)*
BOEM 2018 *BOEM state activities (https://boem.gov/Renewable-Energy-State-Activities/)*
CEQ 1997 *Considering Cumulative Effects Under the National Environmental Policy Act, Washington, DC: Council on Environmental Quality (https://www.energy.gov/sites/prod/files/nepa/pub/nepa_documents/RedDont/G-CEQ-ConsidCumulEffects.pdf)*
Cleasby I R, Wakefield E D, Bearhop S, Bodey T W, Votier S C and Hamer K C 2015 *Three-dimensional tracking of a wide-*
Ram B 2011 Assessing integrated risks of offshore wind projects: Moving towards gigawatt-scale deployments Wind Eng. 35 247–66

Rodewald P E (ed) 2015 The Birds of North America (Ithaca, NY: Cornell Laboratory of Ornithology)

Schreiber E A and Burger J 2001 Biology of Marine Birds (Boca Raton, FL: CRC Press)

Schwartz M N, Heimiller D, Haymes S and Musial W 2010 Assessment of Offshore Wind Energy Resources for the United States NREL/TP-500-45889 The National Renewable Energy Laboratory (NREL) 1–96

Siemens 2016 Siemens 6.0 MW Offshore Wind Turbine (https://en.wind-turbine-models.com/turbines/657-siemens-swt-6.0-154)

Silverman E D, Saalfeld D T, Leirness J B and Koneff M D 2013 Wintering sea-duck distribution along the Atlantic coast of the United States J. Fish Wildlife Manage. 4 178–98

Vanermen N, Onkelinx T, Courtens W, Van de Walle M, Verstraete H and Stienen E W M 2015 Seabird avoidance and attraction at an offshore wind farm in the Belgian part of the North Sea Hydrobiologia 756 51–61

Veit R R, Goyert H F, White T P, Martin M-C, Manne L L and Gilbert A 2015 Pelagic seabirds off the East Coast of the United States 2008–2013 BOEM 2015–024 US Dept. of the Interior, Bureau of Ocean Energy Management, Office of Renewable Energy Programs, Sterling, VA, US Dept. of the Interior, Bureau of Ocean Energy Management, Office of Renewable Energy Programs, Sterling, VA. 186

Wade H M, Masden E A, Jackson A C and Furness R W 2016 Incorporating data uncertainty when estimating potential vulnerability of Scottish seabirds to marine renewable energy developments Mar. Policy 70 108–13

Williams K, Connelly E, Johnson S and Stenhouse I 2015 Wildlife densities and habitat use across temporal and spatial scales on the Mid-Atlantic outer continental shelf: final report to the department of energy EERE wind & water power technologies office Report BRI 2015–11 Award Number: DE-EE0005362 Biodiversity Research Institute, Portland, Maine p 715

Willmott J R, Forcey G and Kent A 2013 The relative vulnerability of migratory bird species to offshore wind energy projects on the Atlantic Outer Continental Shelf: an assessment method and database Final Report to the US Department of the Interior OCS Study BOEM 2013–207 Bureau of Ocean Energy Management, Office of Renewable Energy Programs p 275

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