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Title

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

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Keywords

Seabirds, offshore wind farm, guild, cumulative effects, exposure, mitigation

Abstract

Offshore wind farms are rapidly being permitted along the East Coast of the U.S., 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 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 is expanding along the East Coast of the U.S. The first U.S. offshore wind farm began operating in 2016 and the U.S. 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

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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 Kahlert 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). U.S. laws and regulations require assessment of these cumulative effects during the permitting process (CEQ 1997; Hyder 1999; Hegmann et al. 1999; Cooper 2004). 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,

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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 U.S. 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 offshore wind energy development 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).

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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[1]	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[2]	All = 0	Development is unlikely in these areas	NA	http://marinecadastre.gov/
Exclusion	Shipping lanes[3]	All = 0	Development is unlikely in these areas	NA	http://marinecadastre.gov/
Exclusion	Unexploded ordnance[4]	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	< 7 m/s = 0 > 7 m/s = 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	> 200 m = 0 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 to 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

*Levelized cost of electricity

[1] Danger Area; Danger Zone; Missile Testing Area; Naval Operations Area; Prohibited Area; Restricted Airspace; Restricted Area; Separation Zone; Test Area; Torpedo Testing Area

[2] Chemical waste dumping grounds; dredge material disposal; dumping ground; explosive dumping ground; spoil ground

[3] Shipping Fairways Lanes and Zones; Traffic Separation Schemes/Traffic Lanes; Precautionary Areas; Recommended Routes

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[4] 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

Figure 1. OWED suitability layer that represents all areas where wind farms can be built along the East Coast of the U.S. and the full coverage area of the NOAA models used to define the population in the analysis.

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

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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 U.S. and spatial predictive modeling (Kinlan et al. 2016). The models estimate the spatial distribution of seabird in U.S. 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.

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 plungers (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 A, 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.

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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 A). 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.

Table 2. Seabird guild groupings

Guild	Common name	Scientific name
Coastal bottom gleaner	Surf Scoter	*Melanitta perspicillata*
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	*Phalacrocorax auritus*
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	*Leucophaeus atricilla*
Coastal surface gleaner	Bonaparte's Gull	*Chroicocephalus philadelphia*
Coastal surface gleaner	Ring-billed Gull	*Larus delawarensis*
Coastal surface gleaner	Herring Gull	*Larus argentatus*
Coastal surface gleaner	Great Black-backed Gull	*Larus marinus*
Pelagic diver	Dovekie	*Alle alle*
Pelagic diver	Common Murre	*Uria aalge*
Pelagic diver	Atlantic Puffin	*Fratercula arctica*
Pelagic diver	Razorbill	*Alca torda*
Pelagic scavenger	Black-legged Kittiwake	*Rissa tridactyla*
Pelagic scavenger	Northern Fulmar	*Fulmarus glacialis*
Pelagic scavenger	Cory's Shearwater	*Calonectris diomedea*
Pelagic scavenger	Great Shearwater	*Puffinus gravis*
Pelagic scavenger	Sooty Shearwater	*Puffinus griseus*
Pelagic scavenger	Manx Shearwater	*Puffinus puffinus*
Pelagic scavenger	Pomarine Jaeger	*Stercorarius pomarinus*
Pelagic surface gleaner	Wilson's Storm-Petrel	*Oceanites oceanicus*
Pelagic surface gleaner	Leach's Storm-Petrel	*Oceanodroma leucorhoa*
Pelagic surface gleaner	Band-rumped Storm-Petrel	*Oceanodroma castro*
Pelagic surface gleaner	Red-necked Phalarope	*Phalaropus lobatus*
Pelagic surface gleaner	Red Phalarope	*Phalaropus fulicarius*

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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 represents the maximum exposure of a guild if all wind farms within the OWED suitability layer were built. For comparison, the model also plots the "Abundance of birds" exposure curve, which indicates the build-out scenario where wind farms are sited in the area with the fewest birds. The CE index for each species/siting scenario combination was developed by subtracting the area below the siting scenario 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).

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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 & 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 A).

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.

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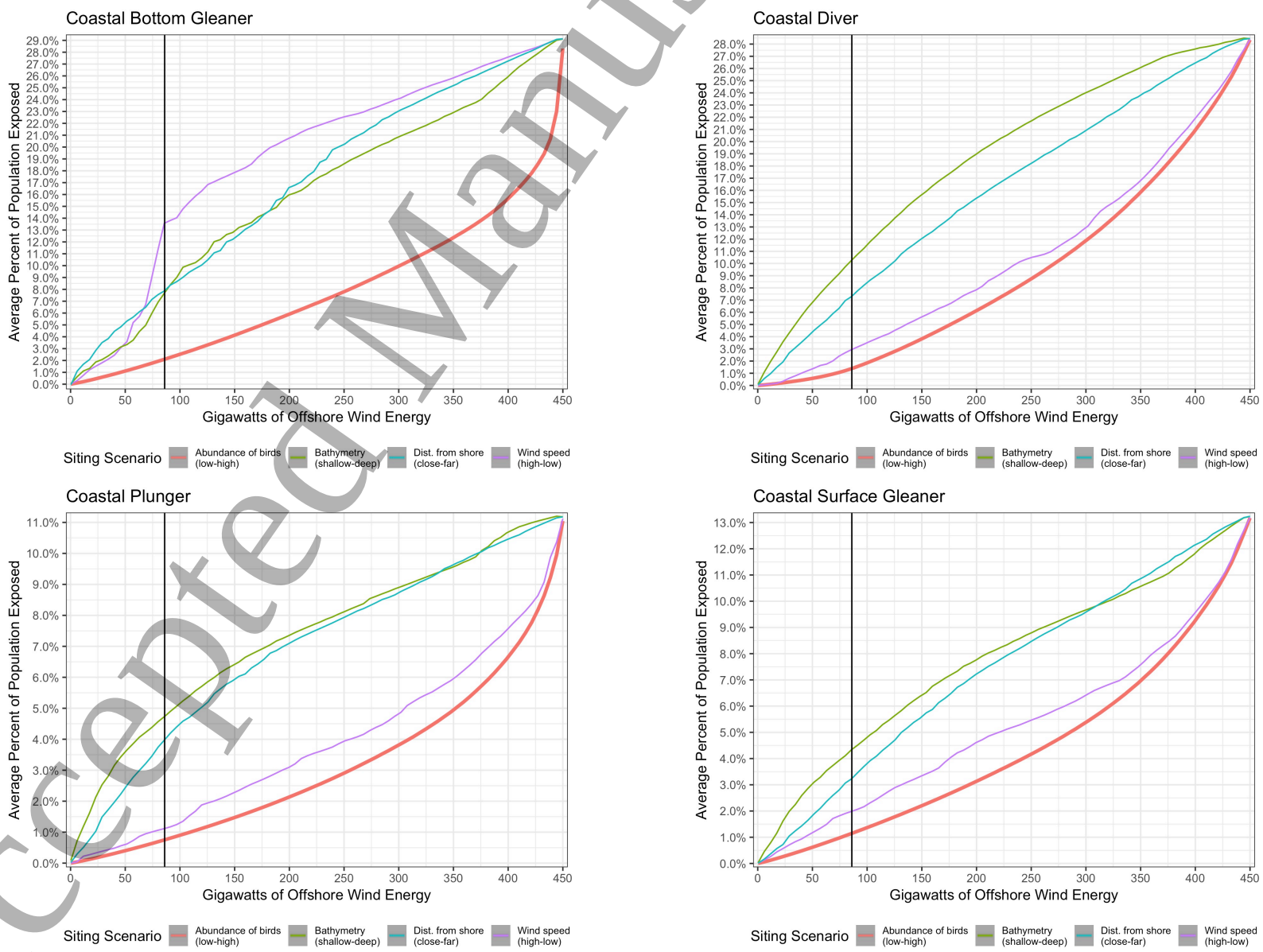

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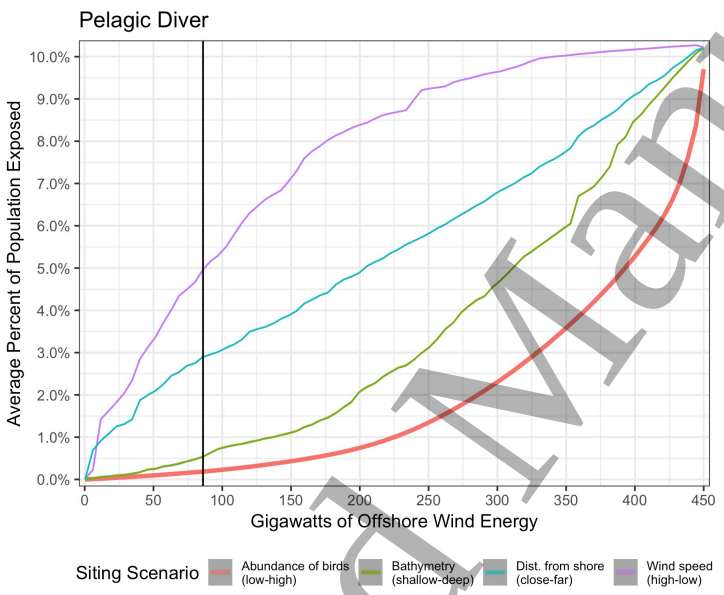

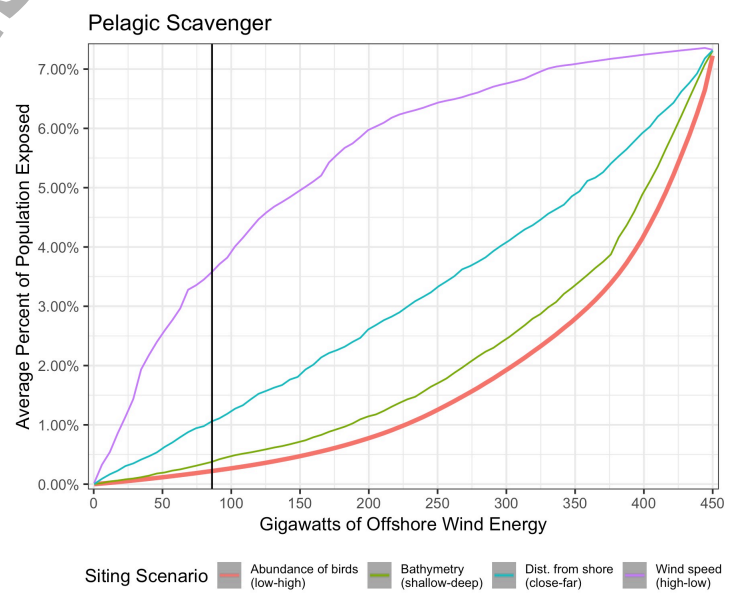

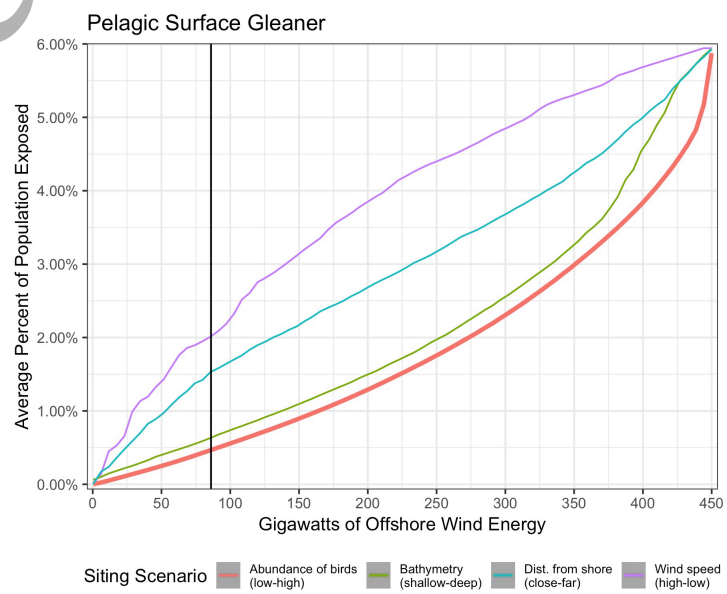

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Figure 2. Relationships between OWED siting scenarios and guilds. The red curve represents the incremental exposure of each guild within the OWED suitability layer when wind farms are always sited in areas with the fewest birds. The green line represents 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 A), 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.

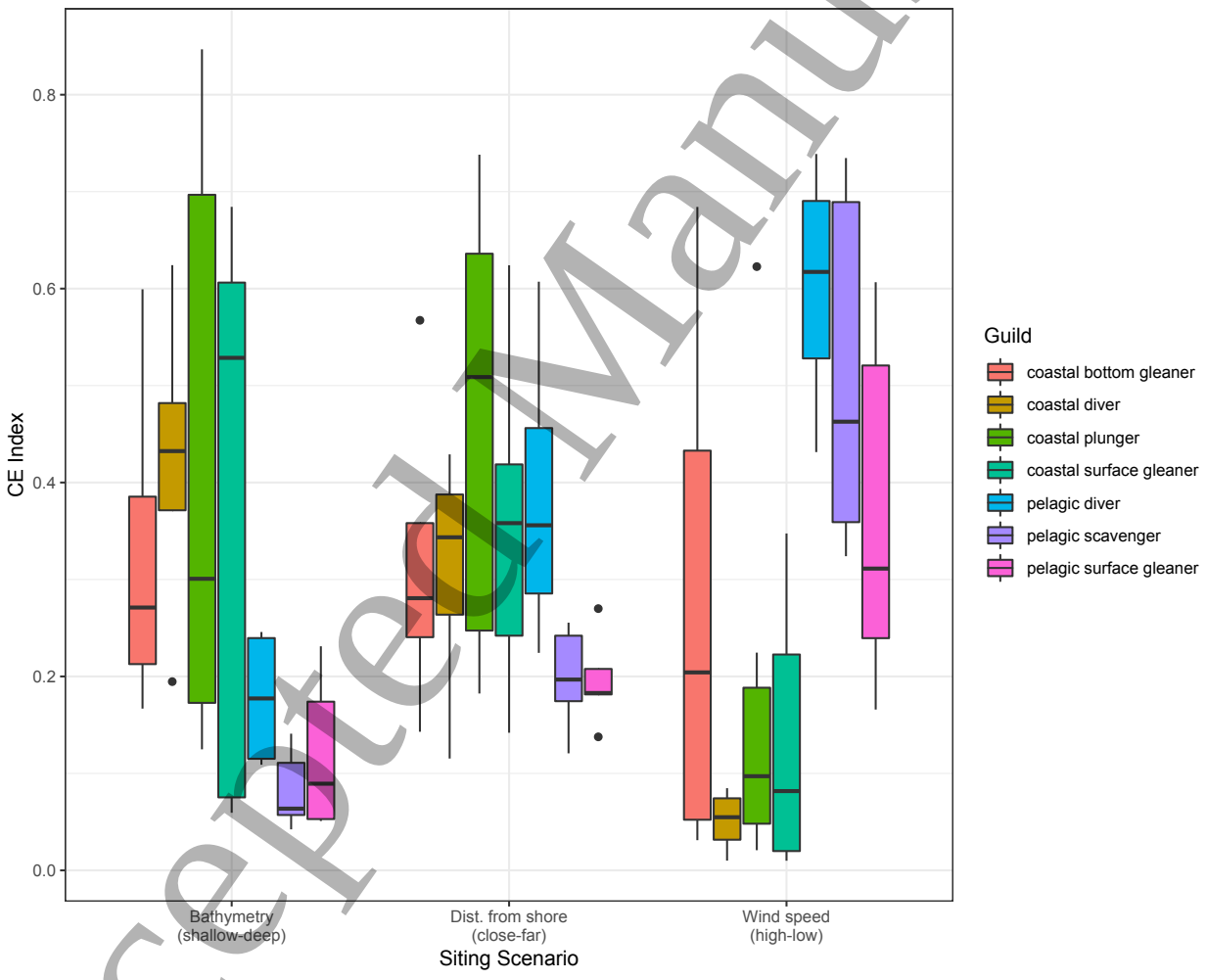

Figure 3. Distribution of the CE index by guild for each OWED siting scenario. Results indicate that pelagic seabird guilds will be exposed at higher rates when projects are built in high-wind areas while coastal seabird guilds will be exposed at higher rates when projects are built in shallow areas. Distance from shore had the least influence on exposure.

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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 A). 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 winds 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 A). 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 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 A; (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

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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 (Krijgsveld 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 gleaners), which have low cumulative exposure according to our CE model and low vulnerability ranking to OWED (Furness et al. 2013, Johnston et al. 2014): shearwaters and storm-petrels fly close to the water surface, effectively avoiding the rotor swept zone (Johnston et al. 2014), and are not documented to be displaced. However, substantial uncertainty remains on the vulnerability of many Tier 4 species (Wade et al. 2016) because

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many of them are not common in the North Sea, where most relevant studies have been conducted.

From our CE model outputs and the distribution patterns displayed by the NOAA models (Appendix A), we predict that exposure can be reduced for Tier 1 guilds by siting projects farther offshore (e.g., > 10 km) and in the Gulf of Maine. Exposure can be reduced for Tier 2 guilds by siting projects farther offshore, and for Tier 3 and 4 guilds by siting in shallower areas (e.g., < 20 m) and south of Long Island.

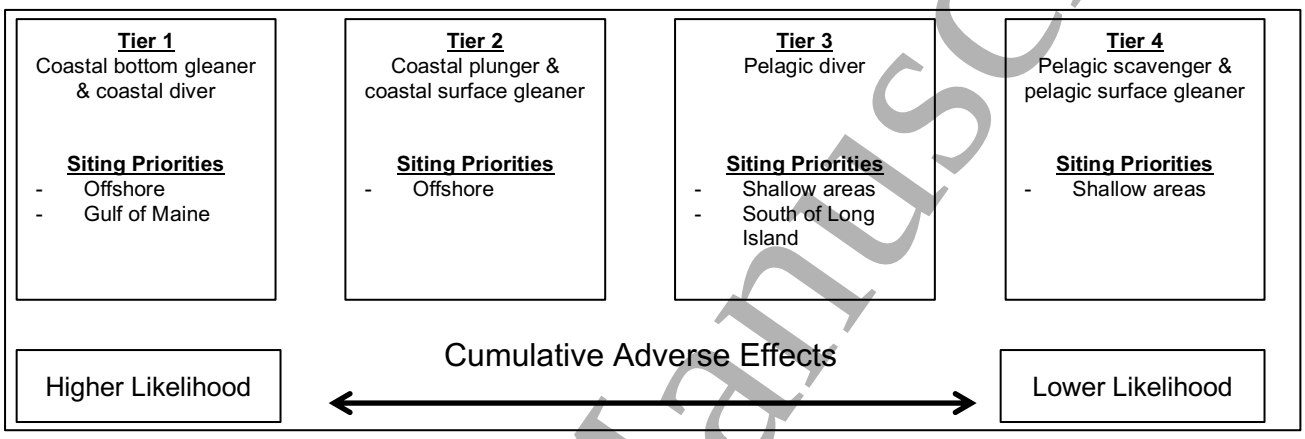

Figure 4. Seabird guild tiers to be considered during CAE assessments, and siting priorities to reduce exposure. Tier 1 & 2 guilds have the highest likelihood of CAE because of relatively high cumulative exposure to offshore wind farms along the East Coast of the U.S. and documented vulnerability to collision or displacement. Species in the Tier 3 guild are vulnerable to displacement but have lower cumulative exposure. Tier 4 guilds have the lowest likelihood of CAE due to the CE model predictions of low cumulative exposure rates combined with the low vulnerability ranking of those guilds to offshore wind farms (Furness et al. 2013). Nonetheless, additional research is needed to reduce uncertainty regarding the vulnerability of these species (Wade et al. 2016) and to confirm this expectation.

Due to the diversity of the species in Tier 1, 2, and 3 guilds, no one siting decision can avoid exposing all the guilds. Thus, to reduce CAE across multiple guilds, we recommend the following siting process: first, avoid known seabird abundance hotspots; next, disperse wind farms throughout the entire OWED suitability layer; and finally, site wind farms as far apart as possible.

Hotspots are areas where oceanographic features lead to persistent aggregations of seabirds because of high food availability (Nur et al. 2011). For example, seabirds concentrate in and around upwelling areas (Furness and Monaghan 1987), shoals (Veit 2015), and river mouths and embayments (Williams et al. 2015). Identifying hotspots and excluding them from the OWED suitability layer could reduce potential adverse effects to birds by directing development into areas of lower conservation value (Winiarski et al. 2014). Hotspots should be identified first for species in Tier 1 and 2 (e.g., areas with high relative abundance in Appendix A), which are primarily wintering in the region and have

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reduced flying behavior during this time. CAE may be avoided in particular for these species by directing development to areas with lower bird concentrations.

Dispersing wind farms throughout the entire OWED suitability layer will spread development between north and south and near-shore and offshore, effectively diffusing exposure over all guilds. Diffused exposure may reduce cumulative mortality or cumulative habitat loss for all species, potentially minimizing the adverse effects on populations. If a species is identified as a conservation concern due to other stressors, the siting decisions could be modified to place fewer wind farms within that species' core use areas. Finally, siting wind farms with the greatest possible distance between them would avoid concentrated exposure for Tier 1 and 2 coastal guilds. Widely spaced developments could provide movement corridors for Tier 1 species that are vulnerable to displacement, such as sea ducks and loons (Krijgsveld 2014), and spread any collision mortality within Tier 2 guilds out over multiple sub-populations.

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 offshore wind energy development. The CE model outputs indicate that the coastal bottom gleaner and coastal diver guilds are most likely to be cumulatively exposed to wind farm development along the East Coast of the U.S. 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.

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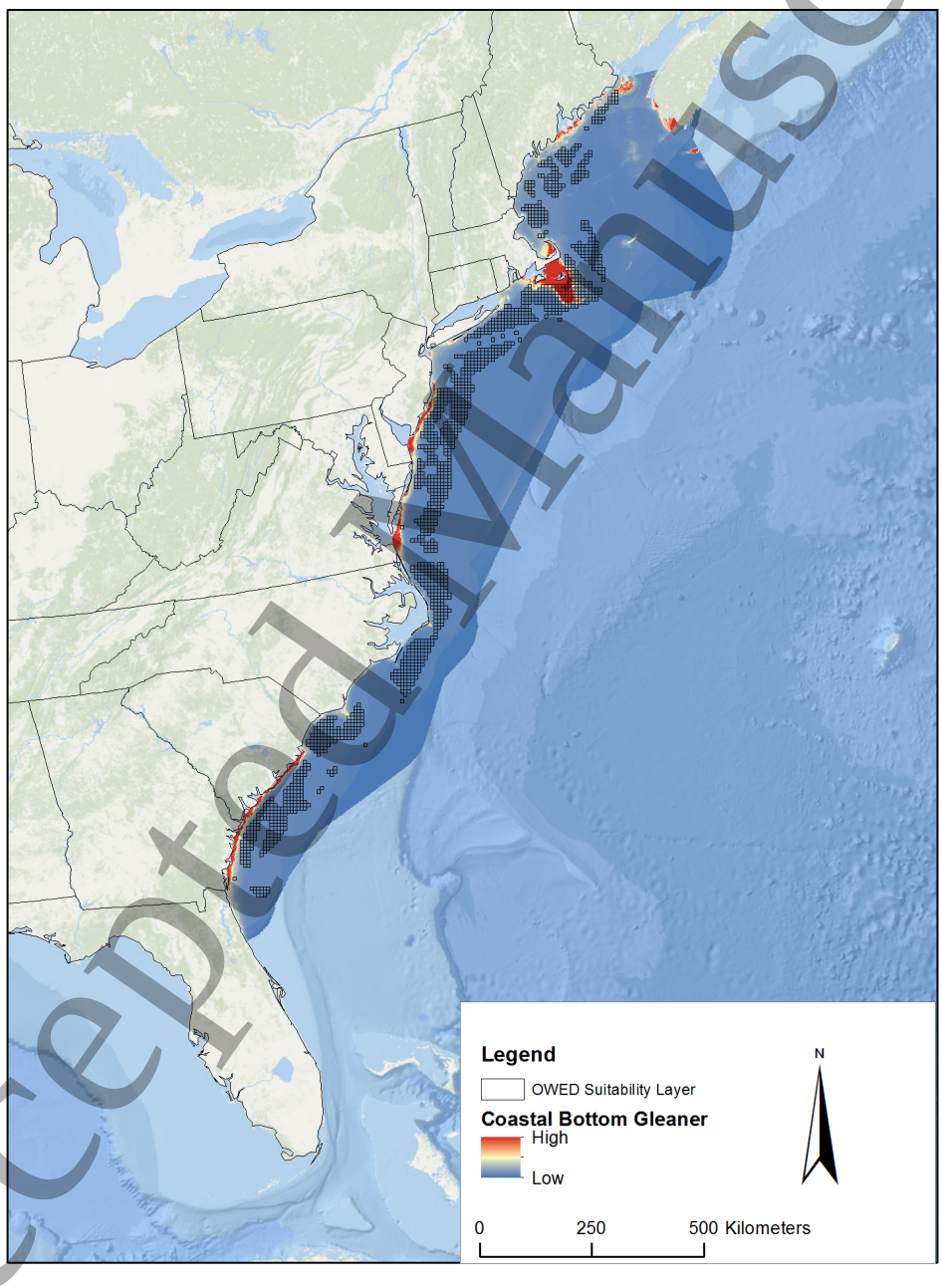
Appendix A: Guild annual average relative abundance predictions developed from NOAA's abundance models (Version 1.0; Kinlan et al. 2016)). The species models were first normalized by dividing each cell by the sum of the layer, and the maps were created by averaging all species within a guild. The scale 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://www.northeastoceandata.org/.



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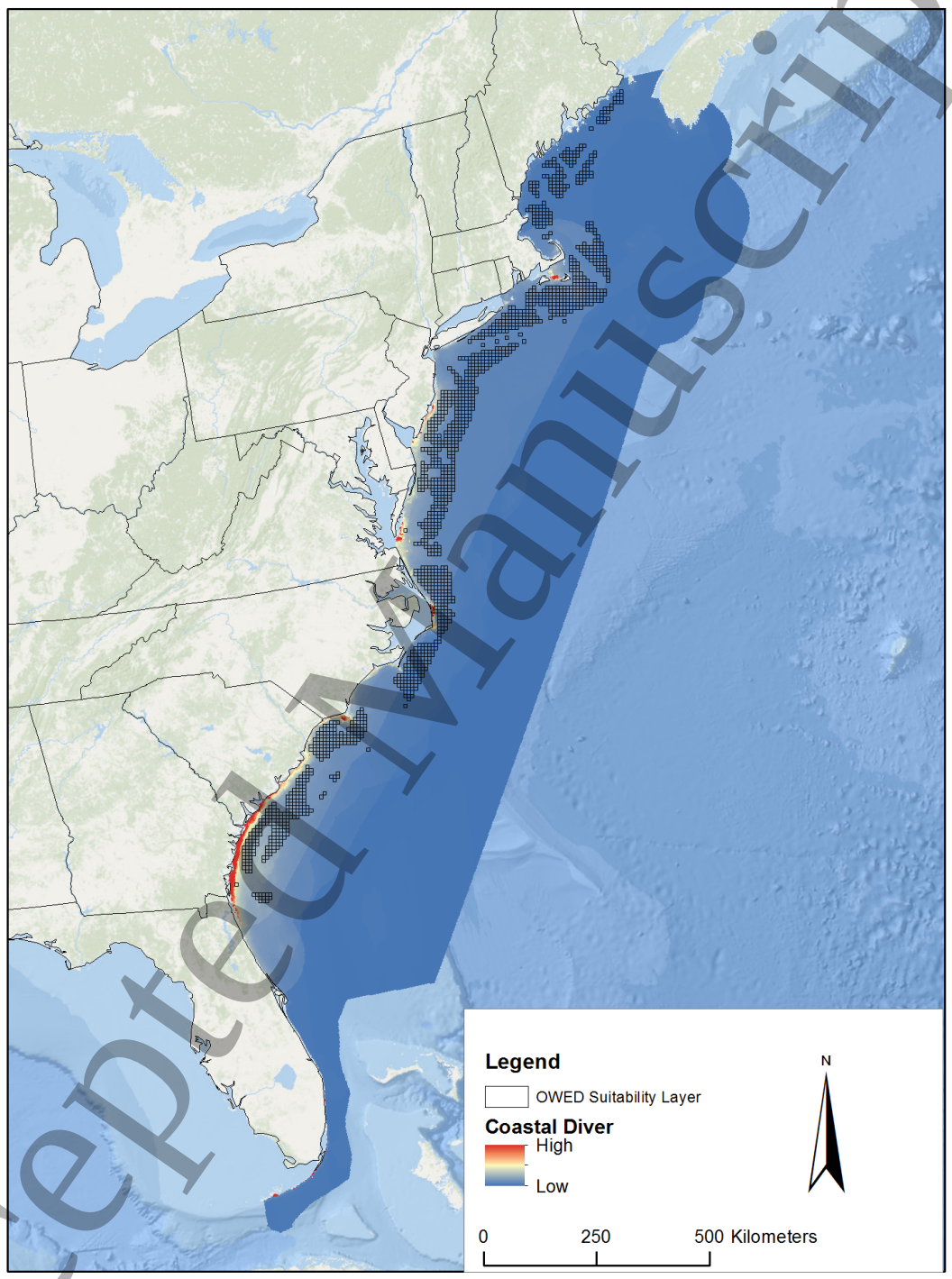

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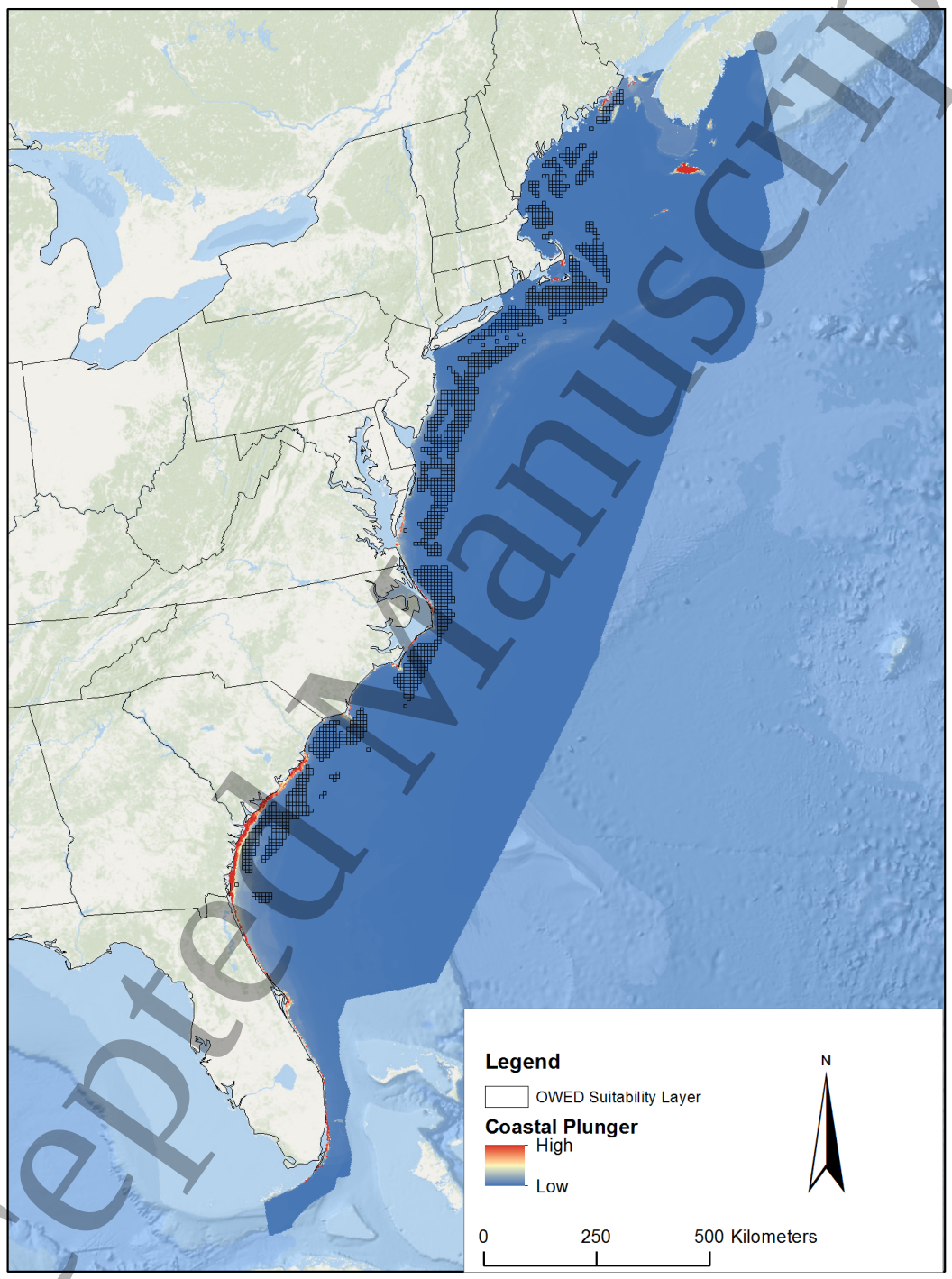

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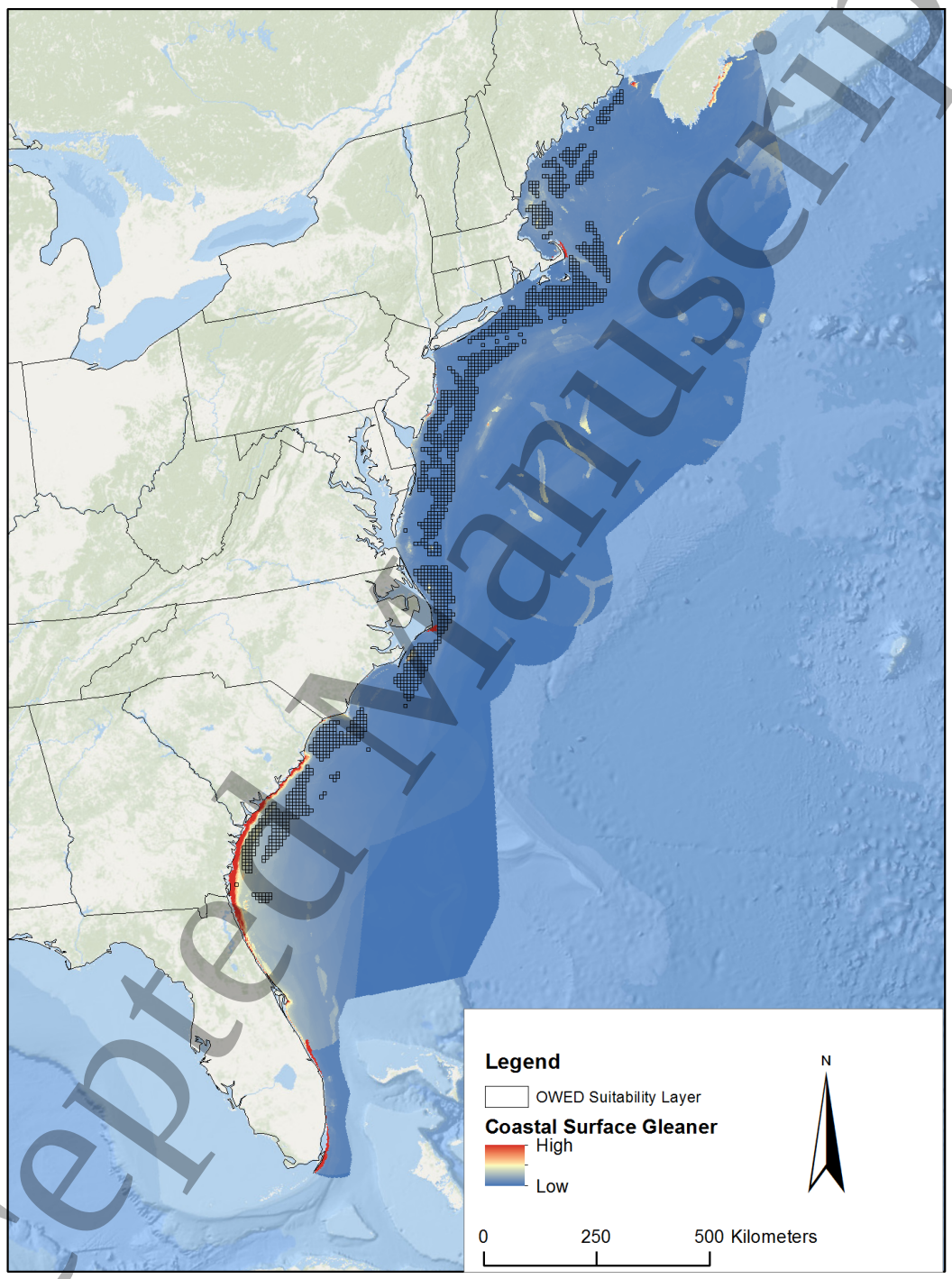

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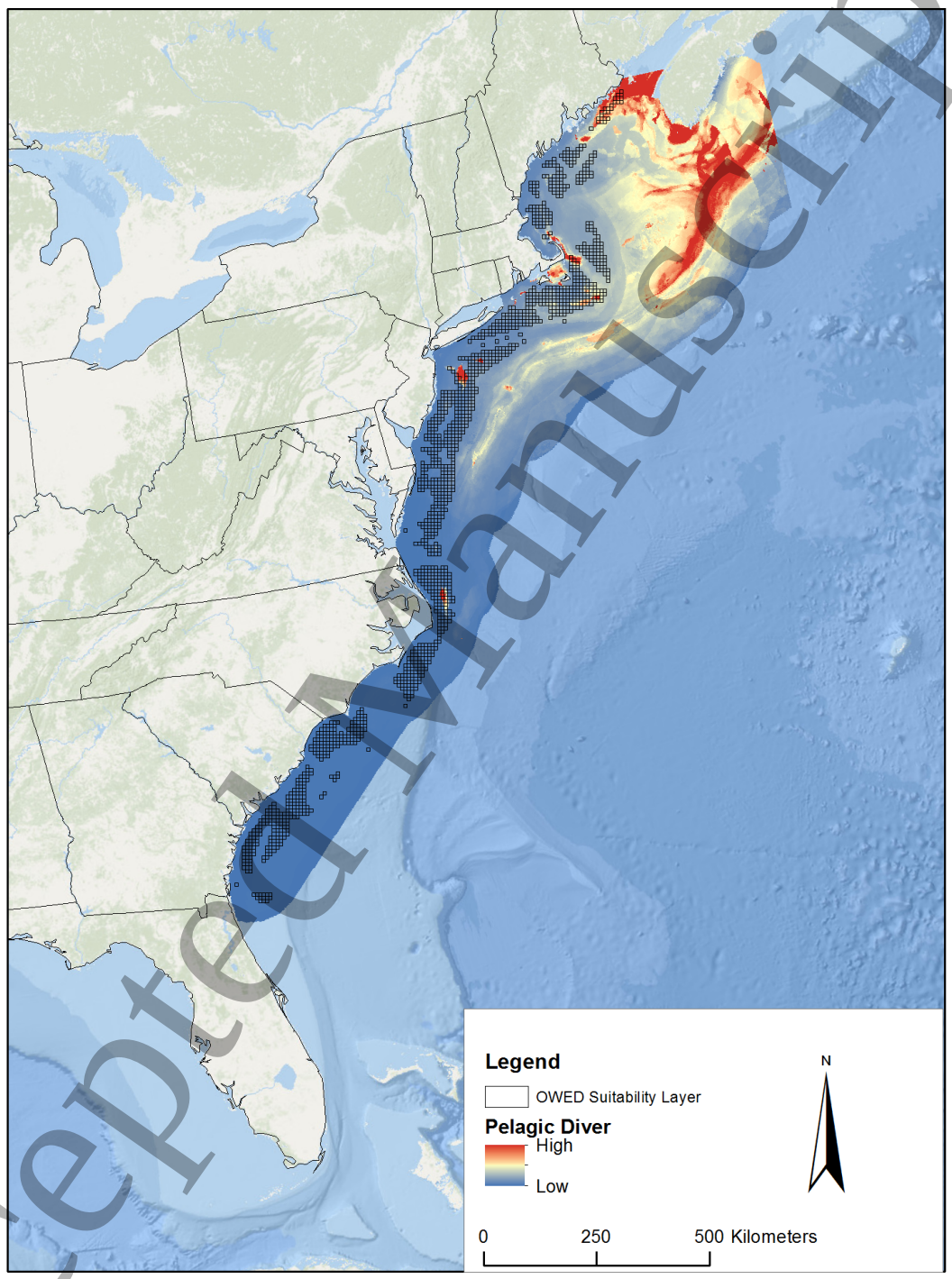

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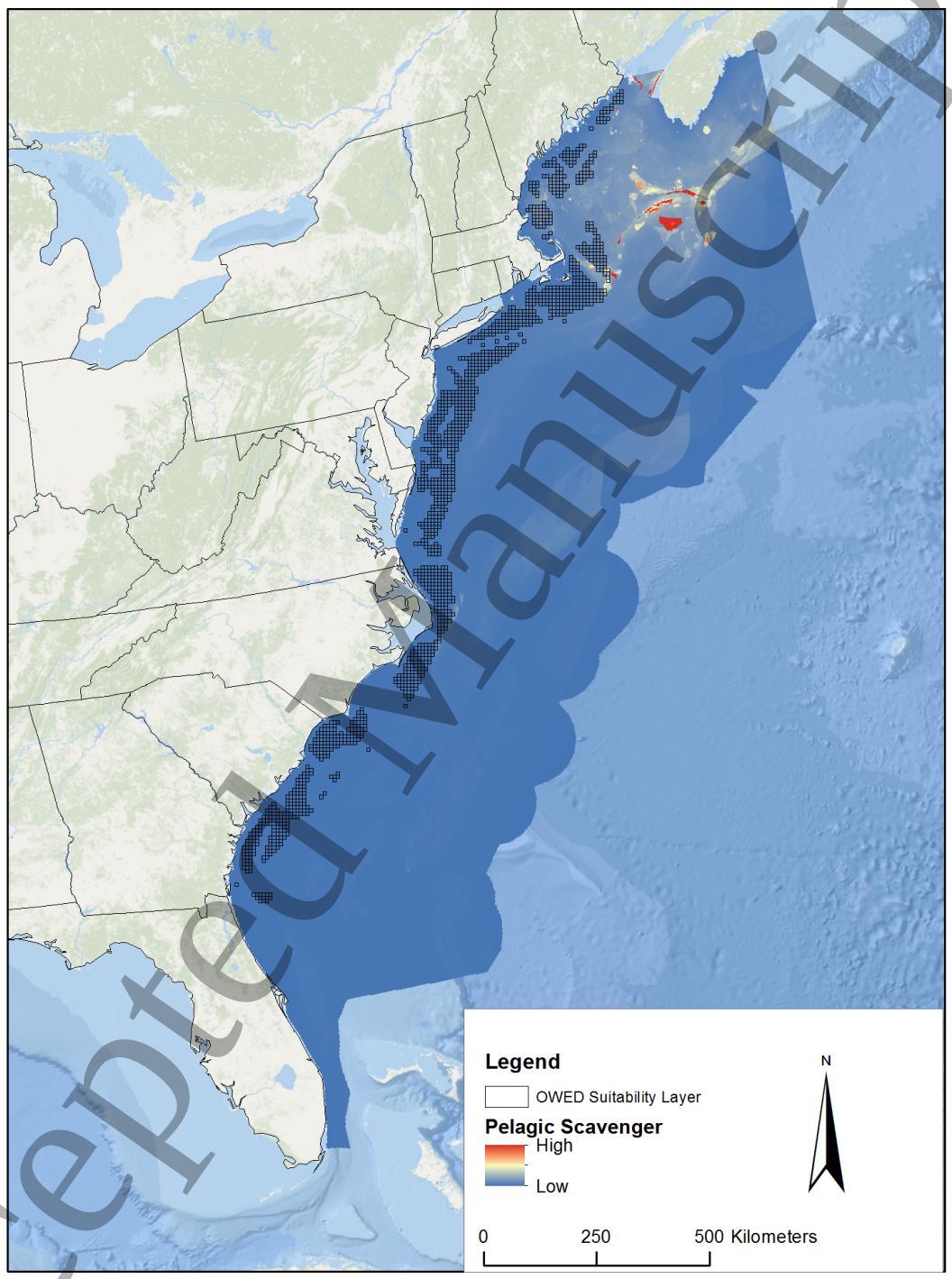

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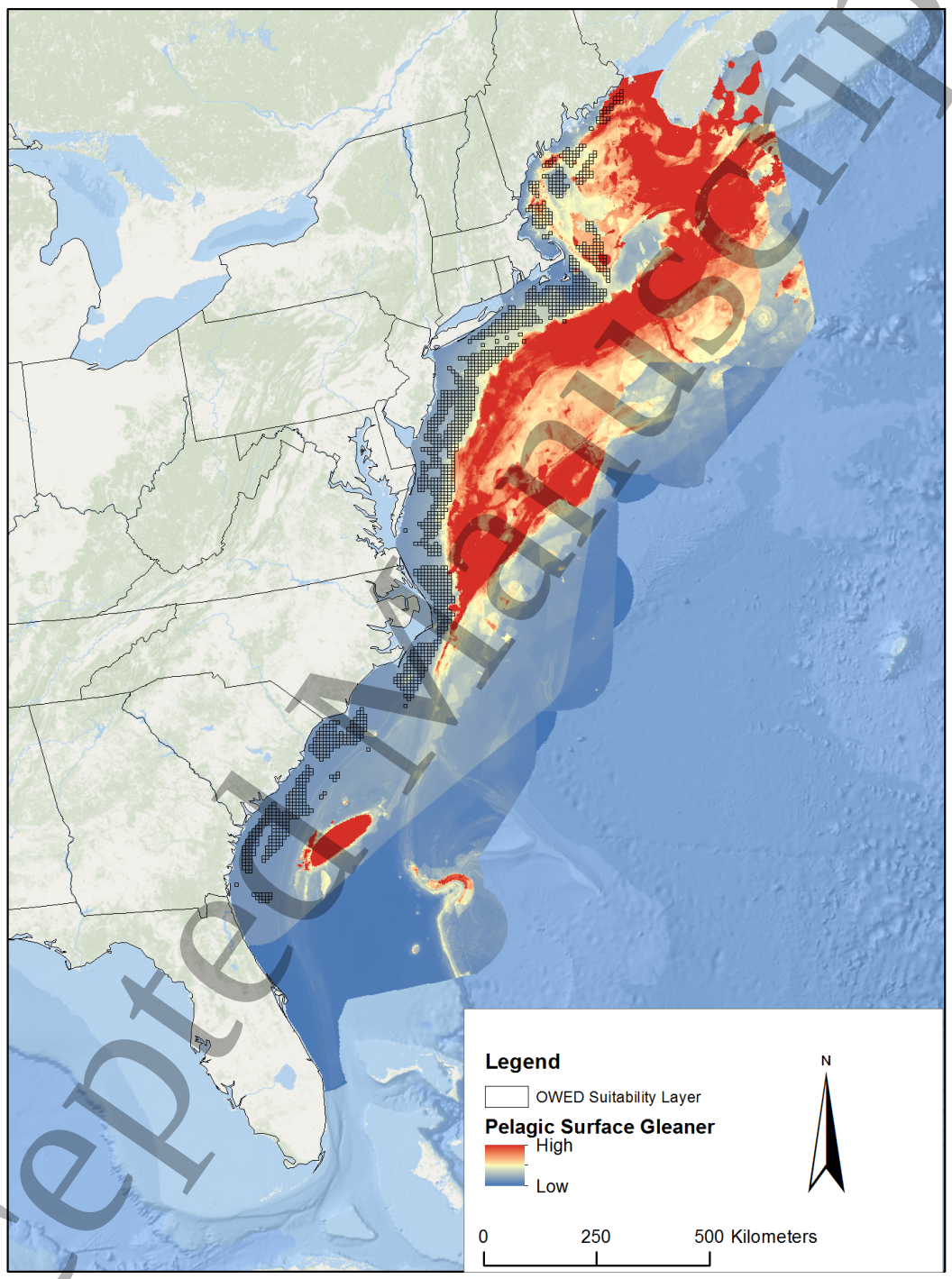

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