Cumulative adverse effects of offshore wind energy development on wildlife

CUMULATIVE ADVERSE EFFECTS OF OFFSHORE WIND ENERGY DEVELOPMENT ON WILDLIFE

A Dissertation Presented

by

MORGAN W. GOODALE

Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
of the requirements for the degree of

DOCTOR OF PHILOSOPHY

September 2018

Environmental Conservation

CUMULATIVE ADVERSE EFFECTS OF OFFSHORE WIND ENERGY DEVELOPMENT ON WILDLIFE

A Dissertation Presented

By

MORGAN W. GOODALE

Approved as to style and content by:

____
Anita Milman, Chair

____
Curtice R. Griffin, Member

____
Charlie M. Schweik, Member

____
Jon G. McGowan, Outside Member

____
Curtice R. Griffin, Department Head
Department of Environmental Conservation

DEDICATION

To my parents, Whitney and Tony Oppersdorff, who have supported me every step of the way in my education and life; and my son, Cedar Goodale, our future.

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to the Chair of my committee, Anita Milman, for her mentoring, guidance, and extraordinary dedication helping me through my PhD process. Not only did Dr. Milman help me through my exams and dissertation process, she also helped me through each step of applying to UMass IGERT Offshore Wind Energy Program, to the Switzer Foundation, and for a National Science Foundation grant. I would also like to thank my committee members, Curtice Griffin, Charlie Schweik, and Jon McGowan, for their incredible support at all stages of my research and for including me in the UMass IGERT Offshore Wind Energy Program. The experiences I had as an IGERT Fellow have reshaped my understanding of all aspects of offshore wind energy development.

My colleagues at Biodiversity Research Institute deserve special recognition. Evan Adams, Andrew Gilbert, and Iain Stenhouse helped me with R coding, statistical analysis, and seabird ecology. In addition, my dissertation would not have been possible without the backing of David Evers and Kate Taylor, who supported me in all ways.

I would also like to thank the federal agencies that provided the seabird data for my analysis. National Oceanic Atmospheric Administration provided the seabird abundance models that were a critical input into my decision support model. In addition, I would like to thank U.S. Fish and Wildlife Service and the Bureau of Ocean

Energy Management for their permission to use Northern Gannet (*Morus bassanus*) satellite telemetry data collected as part of a separate study (BOEM 2017-069 OCS).

My PhD process received vital financial support from the NSF-sponsored IGERT: Offshore Wind Energy Engineering, Environmental Science, and Policy (Grant Number 1068864) and the Switzer Foundation. Finally, my dissertation was only possible with the emotional, intellectual, and editorial support from my wife, Marie Malin.

ABSTRACT

THE CUMULATIVE ADVERSE EFFECTS OF OFFSHORE WIND ENERGY ON WILDLIFE

SEPTEMBER 2018

MORGAN WING GOODALE, B.A., COLORADO COLLEGE

M.PHIL., COLLEGE OF THE ATLANTIC

PH.D., UNIVERSITY OF MASSACHUSETTS AMHERST

Directed by: Anita Milman

Offshore wind energy development is being pursued as a critical component in achieving a low-carbon energy economy. While the adverse effects of one wind farm on a particular wildlife population may be negligible, the aggregate effect of multiple wind farms through space and time could cause wildlife population declines. The risk of cumulative adverse effects (CAE) of offshore wind farms on wildlife is poorly researched and assessment processes are underdeveloped. Assessments of CAE must first calculate the cumulative exposure of a wildlife population to a hazard and then estimate how the exposure will affect the population. Our research responds to the first need by developing a framework to assess CAE and then developing a deterministic, geospatial decision-support model that assesses how wildlife are cumulatively exposed to the hazard of multiple wind farms. We first utilize the model to quantify how Northern Gannet (*Morus bassanus*) would be cumulatively exposed to three different wind farm siting scenarios along the East Coast of the U.S. The findings suggest that Northern Gannets will be cumulatively exposed regardless of siting decisions and avoidance is not an effective mitigation measure. Second, we use the model to assess how seven seabird foraging guilds would be cumulatively exposed to the same three wind farm siting scenarios. The model outputs indicate that no single offshore wind siting decision can reduce 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 reduces cumulative exposure for all guilds.

TABLE OF CONTENTS

Page

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

CHAPTER 1
INTRODUCTION

Worldwide, governments and industries are looking to increase the production of electricity from offshore wind. This movement is driven by a strong interest in diversifying energy sources; reducing the carbon intensity of global energy production as a way to address climate change; and the need to meet growing coastal demands for electricity. However, there are concerns that deployment of multiple offshore farms may lead to declines in wildlife populations.

Offshore wind energy is rapidly expanding along the East Coast of the U.S. The first U.S. offshore wind farm began operating in 2016 (Deepwater Wind 2016); five East Coast states have committed to 8 GW by 2030 (Offshore Wind Biz 2018); and the U.S. federal government has developed a scenario for 86 GW to be installed by 2050 (DOE 2016). Currently, areas are leased from Maine to North Carolina (BOEM 2018), and Massachusetts will issue an 800-MW power purchase agreement in 2018 (Massachusetts Department of Energy Resources 2017). If federal and state wind farm development goals are attained, wildlife will be exposed to thousands of turbines in the next decade (Goodale and Milman 2016).

Single offshore wind farms are demonstrated to adversely affect individual wildlife (Goodale and Milman 2016), but a greater concern is how multiple offshore wind farms, combined with other anthropogenic stressors, will affect wildlife populations through time and space. These cumulative adverse effects (CAE) of offshore wind farms are recognized as an important ecological issue for wildlife (Drewitt and Langston 2006, Fox et al. 2006, Larsen and Guillemette 2007, Boehlert and Gill 2010, Dolman and Simmonds 2010, Masden et al. 2010, Gill et al. 2012, Langston 2013). However, knowledge of CAE of offshore wind farms on wildlife remains relatively unexplored and poorly understood.

CAE is also an important consideration during offshore wind farm permitting. When an offshore wind farm is proposed in the U.S., the National Environmental Policy Act (NEPA) requires that CAE to be assessed in Environmental Impact Statements (EIS) (CEQ 1997). The EIS must describe the affected environment, evaluate alternatives, and assess the direct, indirect, and cumulative effects of the action on the environment. Cumulative effects are defined as "the impact on the environment which results from the incremental impact of the action when added to other past, present, and reasonably foreseeable future actions" (40 CFR §1508.7). The broad and ambiguous definition of cumulative effects leads to inconsistent assessments (MacDonald 2000). Thus, CAE assessments vary within and across regulatory agencies (MMS 2007;2009, BOEM 2012a, Army Corps of Engineers 2014) as well as among NEPA processes (MMS 2007;2009, Army Corps of Engineers 2014). This lack of parity results in assessments that cannot be compared and are considered inadequate (Burris and Canter 1997, Cooper and Canter 1997, Baxter et al. 2001, Cooper and Sheate 2002, Duinker and Greig 2006).

Problems with CAE assessments include: an absence of frameworks to help determine the significance of effects (Berube 2007, British Columbia Forest Practices 2011); an absence of effective methodologies to conduct assessments (Canter and Kamath 1995, Smith 2006, Masden et al. 2010); difficulties evaluating the likelihood of cumulative effects; and no agreed-upon management or mitigation actions. Given this lack of consistency, there is a substantial need to develop a CAE assessment framework as well as an assessment tool that can link individual OWED projects to the regional context to improve integrated decision-making.

To respond to the need to improve the CAE assessment process, we first conduct an interdisciplinary literature synthesis to develop a framework to define the process of CAE. Second, we develop a flexible decision-support model to assess cumulative exposure. Third, we utilize the model to assess the cumulative exposure of seabirds to four different wind farm siting scenarios along the East Coast of the U.S. And finally, we use the assessment to place seabirds into four tiers of likelihood of having cumulative adverse effects and to identify a process for siting offshore wind farms that will reduce CAE on all species. Together these chapters provide stakeholders with clear guidance on how project-specific permitting and regional siting can reduce the CAE of offshore wind energy development on seabirds.

Chapter 2: Cumulative adverse effects of offshore wind energy development on wildlife”

The second chapter is a literature synthesis of how offshore wind farms can cause cumulative adverse effects on wildlife. We begin with a synthesis of ecological research on the direct and indirect effects of OWED. We then focus in on CAE, explaining what it encompasses and why it is important. Next we delineate a framework for determining the scope of CAE assessments. The framework is centered on a conceptual model defining CAE as the process of vulnerable species being exposed to OWED hazards through space and time. We then discuss mechanisms for alleviating CAE and critical uncertainties. This leads to a discussion on how a collaborative stakeholder process could address ongoing policy challenges. This framework, which was published in the *Journal of Environmental Planning and Management*, forms the structure of the remaining dissertation research.

Chapter 3: “Developing a deterministic geospatial decision-support model to assess the cumulative exposure of wildlife to offshore wind energy development patterns”

The third chapter develops a model to partially assess CAE. Assessments of CAE must first calculate the cumulative exposure of a wildlife population to a hazard and then estimate how the exposure will affect the population. Our research responds to the first need by developing a deterministic, geospatial decision-support model that assesses how wildlife are cumulatively exposed to the hazard of multiple offshore wind farms. The model is named “CE model,” i.e., cumulative exposure model.

We derived the model architecture from the framework developed in Chapter 2 (Goodale and Milman 2016) and integrated wind engineering and biological datasets. The CE model estimates the cumulative exposure of wildlife to multiple offshore wind farms by identifying all locations where wind farms could occur; placing wind farms within this suitability layer; and then assessing wildlife cumulative exposure to a series of potential offshore wind farm build-out scenarios.

The first model output is a wildlife cumulative exposure curve for different OWED siting patterns. The output displays the relationship between wildlife cumulative exposure and gigawatts of wind farm production from zero wind farms to full build-out of an area. The second output is a cumulative exposure index that ranks which siting decisions will have the greatest influence on cumulative exposure of wildlife. Together these outputs will provide stakeholders valuable information about how offshore wind farm development patterns will cumulatively expose wildlife, which could be used to guide regional siting decisions.

In this chapter, we provide an overview of the model, describe data inputs and the model analysis process, and explain model outputs. To illustrate the use of the model, we also present and interpret hypothetical model results. We conclude with a discussion on further model development. The paper demonstrates the utility of the CE model, a novel method that has significant value in informing regional and project-specific planning.

Chapter 4: "Assessing the cumulative exposure of Northern Gannet (*Morus bassanus*) to offshore wind energy development along the East Coast of the United States"

The fourth chapter applies the CE model to assess the cumulative exposure of Northern Gannet (*Morus bassanus*) to four offshore wind build-out scenarios along East Coast to determine if siting decisions can reduce exposure rates. The assessment is focused on Northern Gannet because gannets are documented to be vulnerable to offshore wind farms, and a substantial proportion of the North American gannet population could be exposed to wind farms built along the East Coast. The research was spatially bound to the East Coast, which has "outstanding" and "superb" wind power classes (Musial and Ram 2010), and temporally bound by starting at the present with no OWED built and then moving to a nonspecific point in the future when the East Coast has been saturated by OWED. Two independent gannet datasets were used to estimate gannet abundance on the outer continental shelf to ensure the robustness of the analysis.

In this chapter, we first describe the CE model inputs, model process, and the results of the analysis. We then discuss how understanding the relationships between OWED siting decisions and gannet cumulative exposure can guide management actions. We conclude with suggestions on how the CE model outputs can be used in future CAE assessments. The assessment in this chapter takes the first crucial step in addressing the CAE of OWED to gannets and can be directly used to guide site-specific permitting.

Chapter 5: "Assessing the cumulative adverse effects of offshore wind energy development on seabird foraging guilds along the East Coast of the United States"

The fifth chapter utilizes the CE model to assess how offshore wind farm siting decisions will cumulative expose seven seabird guilds, in order to identify seabirds that are more likely to experience CAE. The assessment focuses on seabird guilds because seabirds within the same guild exploit geophysical characteristics of the marine environment (Schreiber and Burger 2001) similar to those required for offshore wind siting. These include distance from shore, bathymetry, and wind speed (Dvorak et al. 2013).

In this chapter we describe the CE model process and present the results of the modeling analysis. We then use this information to examine the relationships between siting decisions and seabird guild exposure. We identify guilds most likely to be cumulatively exposed and recommend a process to minimize CAE for multiple guilds. This chapter's assessment is an important step in reducing the CAE of offshore wind energy development on seabirds as it provides stakeholders with clear guidance on how project-specific permitting and regional siting can reduce CAE.

CHAPTER 2

CUMULATIVE ADVERSE EFFECTS OF OFFSHORE WIND ENERGY DEVELOPMENT ON WILDLIFE*

Abstract

Offshore wind energy development (OWED) is being pursued as a critical component in achieving a low-carbon energy economy. While the potential generating capacity is high, the cumulative effects of expansion of OWED on wildlife remains unclear. Since environmental regulations in many countries require analysis of the cumulative adverse effects (CAE) during permitting processes, this article reviews the state of knowledge on CAE of OWED on wildlife. We synthesize ecological research on the effects of OWED on wildlife; delineate a framework for determining the scope of CAE assessments; describe approaches to avoiding, minimizing and compensating for CAE; and discuss critical uncertainties.

Introduction

Worldwide, governments and industries are looking to increase the production of offshore wind energy. This movement stems from a strong interest in diversifying energy sources, policies aiming to reduce the carbon intensity of global energy production as a way to address climate change, and the need to meet growing coastal demands for electricity. Offshore wind is framed as an energy alternative

---

* Originally published in Journal of Environmental Planning and Management: GOODALE, M. W. & MILMAN, A. 2016. Cumulative adverse effects of offshore wind energy development on wildlife. *Journal of Environmental Planning and Management,* 59, 1-21.

with lower life-cycle adverse effects to the environment (Ram 2011), yet there are concerns that deployment of thousands of offshore turbines may lead to declines in wildlife populations due to cumulative adverse effects (CAE). Understanding the complexities of the effects of offshore wind energy development (OWED aka wind farm) on wildlife, how they accumulate and whether this accumulation causes population level impacts is a pressing multidisciplinary challenge, since over the next decade OWED is expected to significantly expand in Europe and begin in the United States.

Currently, over 6 gigawatts (GW) of offshore wind energy have been deployed in Europe (EWEA 2013) and globally 77.4GW are predicted by 2021 (BTM Consult ApS 2012). The waters of 10 European countries contain 58 wind farms and nearly 2,000 offshore wind turbines (EWEA 2013). Deployment of OWED in the EU has the potential to expand up to 40 GW by 2020 and up to 150 GW by 2030 (CEC 2008). In the UK, 18 GW could be deployed by 2020 and 40 GW by 2030 (UKDECC 2011). Deployment of offshore wind has yet to occur in the US; however, the US National Renewable Energy Laboratory (NREL) estimates the potential capacity of offshore wind power in the US as 4,200 GW (Lopez et al. 2012). The US Department of Energy has set a goal of 54 GW, which would be approximately 5,000-8,000 turbines in the water, deployed OWED by 2030 (DOE 2011).

While taxa dependent, effects to wildlife from OWED are direct (e.g., mortality and injury) or indirect (e.g., general disturbance caused by the turbines and maintenance vessels), and are caused by hazards such as noise from pile driving, boat traffic, and lighting. Yet, the greater concern is how multiple OWEDs, combined with other anthropogenic stressors, will affect wildlife populations through time and space. These CAE are recognized as an important issue for birds (Drewitt and Langston 2006, Fox et al. 2006, Larsen and Guillemette 2007, Masden et al. 2010, Langston 2013), marine mammals (Dolman and Simmonds 2010), fish (Gill et al. 2012), and the environment in general (Boehlert and Gill 2010). However, with the exception of several modeling efforts (see Masden et al. 2010, Poot et al. 2011, Topping and Petersen 2011) and working groups (Norman et al. 2007, King et al. 2009), knowledge of CAE of OWED on wildlife remains relatively unexplored and poorly understood.

Laws in the US, Canada, the UK, and the EU all require environmental assessments as part of permitting and approval processes. While the exact language differs from country to country, the laws explicitly recognize the accumulation through space and time of human actions that degrade the environment; that an attempt to ameliorate combined adverse effects of those actions should be made; and that mitigation measures may be necessary when effects are unavoidable. Thus these countries' decision makers are required to consider the incremental and CAE of anthropogenic actions on the environment and the potential alternatives to those actions (CEQ 1997, Hegmann et al. 1999, Hyder 1999, Cooper 2004). Therefore there is a critical need to better understand CAE from not only a scientific perspective, but also a regulatory or legal perspective.

In this article, we review the state of the knowledge on CAE of OWED on wildlife. Throughout, we will use the term "cumulative adverse effects" or CAE. We will use this in place of the terms "cumulative effects" or "cumulative impacts" that are used in laws and regulations as well as academic papers. Broadly defined, CAE is the accumulation of adverse effects over time and space. We begin with a synthesis of ecological research on the direct and indirect effects of OWED. We then focus in on CAE, explaining what is encompassed in CAE and the importance of CAE. Next we delineate a framework for determining the scope of CAE assessment. We then discuss mechanisms for alleviating CAE and critical uncertainties influencing progress. This leads us to a discussion on how a collaborative stakeholder process could address ongoing policy challenges.

Effects of OWED on Wildlife

Factors Leading to the CAE of OWED (project components and species-related)

Prior to investigating the CAE of OWED on wildlife, it is useful to review the adverse effects of specific elements of offshore wind projects on wildlife. Such adverse effects are a function of the physical hazards of OWED, species' vulnerability (behavioral and life history attributes), and exposure (duration and the geographic extent to which wildlife interact with OWED) (modified from Crichton 1999, Kinlan et al. 2013, Williams et al. in prep). Recognizing that the terms hazards, vulnerability, and exposure are nuanced and have been applied in a variety of manners, we define the terms as used in this paper below.

The hazards OWED present to wildlife are the changes in environment caused by the project components (i.e., turbines and network connections) during each development phase (pre-construction, construction, operation, and decommissioning) (modified from Williams et al. in prep), also described as "impact-producing-factors" (BOEM 2012b, DOE 2013). The primary hazards are: seismic surveys during pre-construction; support structure building (fixed bottom and floating), trenching for electrical cables, and constructing cable landfall during construction; the physical space occupied by the turbines and the entire OWED as well as the electromagnetic fields (EMF) emitted from cables during operation; and yet-to-be determined decommissioning activities (Table 2.1). The state of knowledge on the adverse effects of OWED support structures on wildlife is primarily focused on the noise generated by pile-driven monopiles. The construction of other types of fixed-bottom support structures will generate less noise: gravity-base structures will have no pile driving; the piles of jacket-support structures are substantially smaller and thus have less noise generated during pile driving and in hard soils can be inserted into pre-drilled holes. While the adverse effects of floating offshore turbines on wildlife is poorly understood, wildlife response may differ for slack or tension mooring systems that are tethered to the seafloor with embedded anchors, piles, or gravity bases. Seafloor preparation and decommissioning will also be different with these alternate support structures (J. Manwell personal communication 2014). Exposure to wildlife will also be influenced by turbine spacing, which is determined by turbine size (Manwell et al. 2009). As more efficient/larger turbines are developed, turbines will need to be placed further apart, increasing the footprint of the OWED. How wildlife will respond to increased spacing has yet to be studied. During all operation phases, increased boat traffic and lighting present additional hazards.

A species' vulnerability is determined by the likelihood an individual will interact with and respond to an OWED and that the response will adversely affect the population (modified from Garthe and Huppop 2004, Furness et al. 2013). As such, vulnerability overlaps with what some refer to as "meso- and micro-exposure" (Burger et al. 2011). Our use of the term vulnerability does not encompass whether or not the species' is *a priori* more at risk as may be reflected by the species' conservation status (Furness et al. 2013); rather, the level of a species' vulnerability depends upon behavioral traits of the species that increase its interaction with OWED during breeding, foraging, and migrating. Once an individual encounters an OWED, the behavioral response can either be an attraction or avoidance (macro and micro scales). A species' vulnerability also depends on a its life history and to what extent adverse effects from individual responses to an OWED will lead to demographic change (see Garthe and Huppop 2004, Furness et al. 2013).

Exposure refers to frequency and duration by which individuals interact with OWED over a specific geographic area (modified from Williams et al. in prep). An increase in the number of OWEDs will result in an increase in the exposure of a vulnerable species to the hazards posed by OWEDs.

Adverse Effects By Taxonomic Class

Adverse effects of OWED on wildlife vary by taxonomic group and offshore wind energy development phase (Williams et al. in prep). The primary adverse effects for all species are direct effects from OWED hazards that cause injury or death; indirect effects of behavioral response (attraction and avoidance) to the turbine construction and operation; and/or changes in habitat from all development phases (see Drewitt and Langston 2006, Fox et al. 2006). The OWED hazards most likely to cause adverse effects to fish, sea turtles, and marine mammals are seismic surveys during pre-construction; pile driving during construction; and submerged infrastructure present during operation. The OWED hazards most likely to cause adverse effects for birds are the rotors and the project's footprint, whereas bats will likely be most affected primarily by the turbines (Table 2.2). The specific effect will vary by a species' life history. Below we delineate more specifically the adverse effects of OWED on fish, sea turtles, marine mammals, and birds. As these effects have not been studied comparatively, we describe effects documented by empirical research yet do not provide a relative ranking of adverse effects.

Fish within a close proximity to pre-construction and construction activities will be exposed to noise and pressure hazards. Pre-construction geophysical seismic surveys that use air guns can lead to the direct effect of fish and egg mortality. The surveys may also displace individuals, which can have the indirect effect of localized changes in fisheries (Hirst and Rodhouse 2000). During construction, the hazard of noise from pile driving may cause a decrease in clupeid abundance from the direct effect of injury and mortality (Perrow et al. 2011) as well as hearing loss in fish (Kikuchi 2010); the construction of alternate types of support structures such as gravity bases or jackets will generate substantial less noise and pressure. The turbidity and suspension of sediment from construction of foundations and cable trenching may have indirect effects by causing localized changes in habitat and food resources (Michel et al. 2007, Michel 2013). Indirect effects during operation may include changes in habitat caused by scour protection at the turbine's base. The changes in habitat may lead to regime shifts (Burkhard and Gee 2012) and changes in the biodiversity of the benthic community (Lindeboom et al. 2011); fish aggregations from reef effects (Linley et al. 2007, Inger et al. 2009, Boswell et al. 2010); and localized behavioral response to operational sound (Kikuchi 2010) and electromagnetic field (EMF) emitted from electric cables (Boehlert and Gill 2010, Gill et al. 2012). Research has not conclusively determined if effects during different development phases and from components will affect population trends, but the composition of the ecosystem in the immediate vicinity of the OWED will likely change.

Little is known about the effects of OWED on sea turtles. The hazard of increased vessel traffic during all phases of development may have the direct effect of higher rates of turtle/boat collisions. Pre-construction activities such as geophysical surveys may have direct localized effects of hearing damage and indirect effects such as behavioral changes (MMS 2007). During construction, due to their inability to avoid construction equipment, hatchlings maybe at greater risk of direct mortality from pile driving and trenching (MMS 2007). If explosives are used during construction or decommissioning, turtles may be killed or injured (Continental Shelf Associates 2004). Although light is known to affect sea turtle behavior (Salmon 2003), how adult and juvenile sea turtles will respond to lit construction vessels and turbines is poorly understood.

Similarly, marine mammals may be adversely affected during all stages of OWED. Pre-construction surveys that generate noise can directly affect marine mammals by causing hearing damage and injury and indirectly affect them by causing behavioral responses (MMS 2007). These adverse effects can also be caused by noise generated by pile driving during OWED construction (David 2006, Madsen et al. 2006, McCann 2012), but species could have different responses and there remains uncertainty on the effects of pile driving on marine mammals (Thompson et al. 2010). Additionally, little is known about how marine mammals will respond to the mooring lines of floating turbines, which could create a collision hazard. Seals can be temporally displaced from haul-out sites from pile-driving noise during construction, though to date, no long-term effects have been found (Edren et al. 2010). Once constructed, the effect of the turbines is more uncertain. Porpoises have been displaced from OWEDs (Tougaard et al. 2005), but may habituate to the turbines, or the reef effect may provide an increase in prey availability (Teilmann et al. 2012). During operation the physical structure of the turbines and the noise generated by the turbines may cause cetaceans to avoid the OWED and thus indirectly result in the loss of feeding and mating habitat, and disrupt migratory routes. Floating turbines may lead to fewer indirect effects; however, there could be direct effects if marine mammals collide with mooring lines. Decommissioning activities are not expected to have significant adverse effects (MMS 2007). Vessel traffic during any stage of OWED can increase the opportunity for a marine mammal/boat collisions (McCann 2012) which can cause direct mortality (Waring et al. 2009, Allen et al. 2011) during all development phases. Since large cetaceans are generally absent around operating OWEDs in the U.K. and Europe, actual effects on large cetaceans will not be fully understood until OWEDs are built in the US.

Turbine operation is likely the primary cause of adverse effects on birds. Pre-construction and construction activities are poorly studied, yet since they have lower direct impacts and temporally limited indirect impacts, they are expected to result in fewer adverse effects. Decommissioning activities are expected to have "negligible" effect on birds (MMS 2007). Fox et al. (2006) describes three factors that lead to adverse effects during operation of OWED: direct effects of collision mortality; indirect effects of avoidance response; and physical habitat modification. Collisions generally occur in two ways: birds collide with the superstructure or rotors during operation, or birds are forced to the ground due to the vortex created by the moving rotors (Drewitt and Langton 2006, Fox et al. 2006). While an estimated 573,000 bird are killed a year at terrestrial wind farms in the US (Smallwood 2013), few direct mortalities have been observed at OWED sites (Pettersson 2005, Petersen et al. 2006), with the notable exception of a coastal wind project located directly adjacent to a tern colony in Belgium (Everaert and Stienen 2007). The dearth of empirical evidence on direct mortality may reflect actual low mortality rates, or it may result from methodological challenges in detecting bird fatalities at OWED sites and a lack of extensive post-construction collision studies.

In terms of displacement of birds, while OWED may invoke an avoidance reaction from some species, it may attract or cause no change in behavior in others (Fox et al. 2006, Krijgsveld et al. 2011, Lindeboom et al. 2011). Detecting avoidance response is stymied by challenges in conducting pre- and post-construction studies that have enough statistical power to detect a significant change (Lapena et al. 2013, Maclean et al. 2013). Nonetheless, avoidance responses have been documented for many species of waterbirds (Desholm and Kahlert 2005, Percival 2010, Lindeboom et al. 2011, Plonczkier and Simms 2012). Initial avoidance may cease several years after construction as food resources, behavioral responses, or other factors change (Petersen and Fox 2007, Leonhard et al. 2013). Birds that avoid the area completely experience a *de facto* habitat loss (Drewitt and Langston 2006, Masden et al. 2009, Petersen et al. 2011, Langston 2013).

Little is known about how bats will respond to OWEDs during any development phase. Bats are present in the offshore environment in both Europe (Boshamer and Bekker 2008, Ahlen et al. 2009) and the US (Grady and Olson 2006, Cryan and Brown 2007, Johnson et al. 2011, Hatch et al. 2013, Pelletier et al. 2013a) and have recently been detected at an OWED in the Netherlands (Poerink et al. 2013). In the US the bats detected offshore have primarily been migratory tree bats (Grady and Olson 2006, Cryan and Brown 2007, Hatch et al. 2013). At terrestrial wind projects in the US, 880,000 bats are estimated to be killed annually (Smallwood 2013) from direct collision mortality and barotrauma (Cryan and Barclay 2009). These fatalities, which affect predominantly migratory tree-roosting bats (Kunz et al. 2007), may occur when mating bats are attracted to turbines (Cryan 2008). Thus collision mortality during operation of OWEDs is the most likely direct adverse effect. Effects of decommissioning are unknown but are likely insignificant.

Accumulation of Adverse Effects of OWED on Wildlife

Most research has focused on the effects of a single OWED on wildlife. However, given the scale of projected future deployment of OWED, many authors raise the concern that the effects from a single OWED could accumulate over multiple projects (see Drewitt and Langston 2006, Fox et al. 2006, Larsen and Guillemette 2007, Masden et al. 2009, Dolman and Simmonds 2010, Masden et al. 2010, Gill et al. 2012, Langston 2013). Cumulative adverse effects refers to the combined effects of multiple anthropogenic actions through space and time (MacDonald 2000); it represents a metric of total human impact to the ecosystem. First, the fitness of an individual in a population is reduced via its interaction with a hazard posed by OWED. Second, the effects of multiple OWED on that individual and others accumulate into population level declines (Figure 2.1). In this section, we focus solely on how the presence of multiple OWEDs may result in CAE. Then in below we discuss a broader conceptualization of cumulative adverse effects, which includes anthropogenic hazards beyond OWED.

While scholars vary in the manner in which they categorize adverse effects (Bain et al. 1986, CEQ 1997, Hyder 1999, MacDonald 2000, Cooper 2004, Crain et al. 2008) and a dominant typology has yet to be developed, adverse effects on an individual can occur primarily through direct and indirect pathways (hereafter, referred to as effects pathways). Direct effects are the result of a stimulus-response relationship (Bain et al. 1986, Canter and Kamath 1995), meaning there is a clear cause-effect relationship between the effects on wildlife and an anthropogenic action such as mortality from colliding with a turbine. Indirect effects are second- or third-level effects, and occur away from the project or through multiple effects pathways (Hyder 1999). For example, fish abundance could increase due to a *de facto* fishing exclusion zone at an OWED; this abundance of fish might attract additional birds, which in turn could change the number of collision mortalities.

Adverse effects on individuals can combine interactively causing CAE and thus population level declines. Interacting effects are sometimes referred to as multivariate effects (Bain et al. 1996). Interacting effects may be additive (CAE = a + b), synergistic/supra-additive (CAE > a + b), or countervailing (CAE < a + b), where “a” and “b” represent the effects of separate actions (adapted from Irving et al. 1986, Canter and Kamath 1995, CEQ 1997, Crain et al. 2008). Effects are likely to be additive for long-lived/low-productivity species that experience mortality from multiple OWEDs (Drewitt and Langston 2006) or for wildlife that expend additional energy to avoid multiple wind farms within a migratory corridor (Masden et al. 2009).

Irrespective of the interaction mechanisms, the primary concern is that even when the individual effects of separate actions (a & b above) are below a threshold of harm, cumulative adverse effects may exceed the amount a population can withstand and still remain viable. While, as described above, we have some basic expectations regarding the potential adverse effects of OWED on individual wildlife, in-depth understanding of how those effects translate into population level effects is confounded by significant information gaps (Williams et al. in prep). A paucity of knowledge on the demographic patterns that shape population dynamics confounds the delineation of population baselines. In particular, for many species there is a lack of knowledge on population trends and vital rates (e.g., adult survival), as well as how OWED will affect factors regulating and limiting the populations.

More research has focused on the CAE of OWED on birds than other taxonomic classes. Existing analyses of demographic changes to some species of birds have found little evidence of population-level CAE via direct collision mortality (Poot et al. 2011), displacement (Topping and Petersen 2011), and cumulative habitat loss due to displacement (Busch et al. 2013). Yet not all future build-out scenarios and species of birds have been assessed. Moreover, for other species and taxonomic classes, basic natural history information on when they maybe exposed to OWED hazards and information on micro and macro avoidance rates is lacking. Improving knowledge of the CAE of OWED is complicated by the migratory nature of some species, which are only exposed to OWED during a portion of their life cycle, and by the fact that direct effects such as collision mortality may be significant yet rare, and therefore is hard to measure. As explained below, knowledge of baseline and wildlife responses is essential not only for assessing CAE, but also for development of mitigation strategies.

The Scope of CAE Assessments of OWED on Wildlife

Conceptually, CAE is all encompassing: it includes all effects from all anthropogenic stressors on all species, with no spatial or temporal constraints. Yet in practice, every effect and interaction cannot be understood or analyzed. Limitations of data, analytical methods, resources to conduct assessments, and an understanding of how effects interact constrain the extent and depth of the analysis. A critical step to move from a theoretical discussion of CAE to an applied analysis via an Environmental Impact Statement is to define the scope of assessments.

Through the turn of the century, CAE was not well represented in environmental assessments (Burris and Canter 1997, Cooper and Canter 1997, Baxter et al. 2001, Cooper and Sheate 2002) and the need for greater guidance on CAE assessments was well recognized (Canter and Kamath 1995, MacDonald 2000, Piper 2001, Cooper and Sheate 2002). Governments and academics throughout Europe and North America devised CAE analysis guidelines for environmental assessment regulations (CEQ 1997, Hegmann et al. 1999, Hyder 1999, Cooper 2004). While these guidance documents are non-binding, they provide recommendations for conducting CAE assessments, including determining source, spatial, and temporal scope. Nonetheless, even after development of these guidelines, CAE assessments continue to be challenged in court for having an inadequate analysis scope (Smith 2006, Schultz 2012).

While the guidelines developed for CAE assessment provide a general framework that could be used for any environmental assessment, they do not provide sufficient recommendations on how to address issues specific to OWED and wildlife. Development of a guidance document designed expressly for the OWED industry has been recognized as a critical need in the UK (Renewable UK 2011;2013). Guidelines would provide an applied CAE definition, assessment procedures, and expectations for how CAE assessments are presented in environmental impact statements (Ma et al. 2012). This guidance could complement US Bureau of Ocean Energy Management's (BOEM) current efforts to develop recommendations for environmental surveys at proposed OWEDs.

As per the work in Europe by King et al. (2009), Masden et al. (2010), and others, three inter-related elements that need to be included in an OWED-specific guideline on scoping the CAE of OWED on wildlife are: identification of hazards; evaluation of species' vulnerability, including baselines, effects pathways, and effects thresholds; and delineation of exposure, including spatial and temporal boundaries.

Identification of Hazards Includes:

<u>Understanding the source</u>

CAE result from a variety of anthropogenic stressors. These stressors may be homotypic, i.e., multiple developments of the same type, or heterotypic, i.e., multiple developments of different types (Irving et al. 1986). Adverse effects of OWED are not isolated from other anthropogenic stressors and CAE sources for any given species are likely heterotypic, including but not limited to aquaculture, fishing, linear infrastructure, shipping, military activities, dredging, gravel mining, fossil fuel extraction, pollution, and climate change (MMS 2007, Renewable UK 2013). Accounting for all anthropogenic stressors and understanding how one OWED may incrementally contribute to existing adverse effects is difficult if not impossible. Beyond qualitative assessments, heterotypic source effects have been addressed through proxies, such as existing species management plans, established viable population levels, maximum sustained harvest, or an established trend trajectory. In those cases, heterotypic source effects are accounted for via the population targets, which have theoretically taken into account other stressors on the population (see below discussion on thresholds). Another approach to managing heterotypic sources has been to use ecosystem-based management and ocean zoning that incorporates the adverse effects from multiple sectors into decision making (Halpern et al. 2008).

Understanding the effects pathway

As explained above, the CAE of multiple OWEDs can be additive, synergistic, or countervailing. A lack of empirical evidence on the interactions between adverse effects impedes accurate assessment of CAE. Given these uncertainties, a conservative approach presumes effects are additive (Masden et al. 2010).

Evaluating Species' Vulnerability Includes:

Refining the receptors

While all species that come into contact with OWED will be affected in some manner (Hegmann et al. 1999, Canter 2012), practically understanding CAE requires focused inquiry into the most sensitive receptors, defined as "any ecological or other feature that is sensitive to, or has the potential to be affected by, an action" (Masden et al. 2010, 2). A receptor is also sometimes called a valued ecosystem component (Hegmann et al. 1999). Assessment of CAE of OWED on wildlife thus would focus on species known to be vulnerable to the hazards posed by OWEDs (see Garthe and Huppop 2004, Desholm 2009, Furness et al. 2013, Willmott et al. 2013). The actual species to be included in the assessment will depend on the geographic location of the project and should be selected based upon being listed as a species of concern, being present in an OWED during critical life stages, having behavioral traits that increase exposure, having been detected in protected areas adjacent to a proposed OWED (King et al. 2009, Masden et al. 2010), or being important to stakeholders (Hegmann et al. 1999). Focusing analysis on vulnerable receptors will serve both to understand the adverse effects on species expected to be most vulnerable to OWED hazards, as well as provide insight into how similar species may be affected.

Having clear baselines

Once the receptors have been defined, a baseline needs to be determined for each. A baseline is a metric that describes the state of the receptor prior to the implementation of OWED. Often, population level is used as a baseline metric. A decline of population levels post implementation of OWED relative to the baseline could indicate an adverse effect of the OWED on the receptor. Due to variation in a species' presence over time and over space, determination of the baseline is not straightforward. In many cases there are neither current nor historic data on species abundance in the offshore environment at a particular location (BRP 2006, Geo-Marine Inc. 2010, Thompson et al. 2010, Langston 2013, Pelletier et al. 2013b). In the absence of a historic baseline, monitoring trends can be used to measure the effects of OWED on wildlife (Hyder 1999, Cooper 2004, Masden et al. 2010, Canter 2012).

Stating a threshold

Implicit in measuring CAE against a baseline or in monitoring population trends is the premise that there exists a threshold of adverse effects that should not be exceeded. This threshold will vary from receptor to receptor, depending on the species population dynamics. For example, for species that are rare, long-lived, and have low annual reproduction, the loss of one individual may cross a critical population threshold. Conversely, for species that are common, short lived, and have high annual reproductive output, the loss of several hundred or even a thousand individuals might not cause a decline in the global population.

Delineation of Exposure Includes:

Determining temporal boundaries

The temporal boundary is a critical element in understanding CAE. Three aspects of the temporal boundary include 1) the duration of sustained adverse effects on the receptor, which can be measured via the lifespan of the project from preconstruction through decommissioning (Hegmann et al. 1999); 2) past, present, and future anthropogenic actions that incrementally contribute to CAE (MacDonald 2000); and 3) the life history traits of a receptor that dictate the seasonal and life stage when a receptor is exposed to the action (Masden et al. 2010).

Determining spatial boundaries

Like temporal boundaries, spatial boundaries are an important component to understanding CAE and include the interplay of a biologically relevant geographic unit (e.g., species range, watershed, or ecoregion) and a geographic development envelope (e.g., geopolitical boundaries or an area developed homotypically). Collectively, this creates the spatial area within which a new action is considered along with other anthropogenic actions affecting the receptor. For the biological spatial unit, Masden et al. (2010) specify that the following should be considered: spatial scale of the population being affected (i.e., local, regional, or global); how the population is using the space (e.g., sub-population or entire population); at what life stage the birds are interacting with the project (e.g., migration, breeding, wintering); and the area in which the effect will actually occur. Regarding the development area, MacDonald (2000) suggests that for policy decisions, large-scale assessments are most useful, and for project decisions, a smaller area should be considered. Canter and Kamath (1995, 330) recommend boundaries be based upon "natural interrelationships between biophysical environment features, man-generated interrelationships between socioeconomic environment features, and the geographical locations of expected impacts."

The elements discussed above describe the primary elements to include in scoping guidelines, but would require further refinement and detail. Formalized guidelines would provide consistency and parity between projects, and would facilitate incorporation of project-based assessments into regional decision-making. Guidelines would also provide certainty for developers on the assessment and mitigation permitting requirements.

Mitigating the CAE of OWED on Wildlife

A principal reason for CAE assessment is that through analyzing the potential adverse effects of OWED, mitigation mechanisms can be identified. Mitigation includes avoidance of adverse effects through siting, minimizing the adverse effects when they cannot be avoided through management, and compensating for adverse effects by replacing losses or reducing other anthropogenic stressors. Implementation of mitigation is a challenging policy problem because it requires identification of cause-effect relationships, assignation of responsibility for action, and the selection of a location for compensatory measures.

Avoidance and minimization of adverse effects begins by addressing the direct and indirect effects of individual OWEDs (see Drewitt and Langston 2006 and Cook et al. 2011). Avoidance entails siting OWEDs away from high biological productivity areas of the ocean that are critical habitat for wildlife as well as significant migratory routes. To do so requires both an understanding of how oceanographic features are related to wildlife concentrations (e.g., bathymetry, upwelling areas, and confluence of currents) and where those areas are located. Baseline natural resource surveys can inform efforts by regional decision making entities and government agencies to direct development away from these areas. Minimizing the direct and indirect effects at a project level requires consideration of OWED design (e.g., layout and turbine spacing), changes to turbine design (e.g., size, paint schemes, blade technology, lighting, support structure), use of different operational methodologies (e.g., timing of construction, bubble nets, support vessel travel speed, blade cut-in speed, curtailment during migration), and implementation of adaptive management (e.g., curtailing turbines that are causing the greatest adverse effects).

When adverse effects due to OWED cannot be avoided or sufficiently minimized, mitigation can include compensation. Examples of compensation include protecting or expanding existing breeding habitat, such as seabird nesting islands; reducing mortality of adults of long-lived species, such as in marine mammal boat collisions or fisheries by-catch (birds, sea turtle, non-target vulnerable fish species); or controlling pollutants such as mercury that reduce reproductive success. Whereas many of these compensatory actions may be merited for reasons unrelated to the

OWED and may in fact already be underway, the premise of compensation as a form of mitigation is that it would be designed and implemented to counteract the specific additional effects caused by a particular OWED. While "no net loss" is often a criteria for determining the scope of compensatory mitigation, lags in implementation can lead to a net habitat loss over time (Bendor 2009). Therefore, mitigation will require careful consideration of the temporal nature of impacts and sustained monitoring of mitigation measures to ensure compensation is truly achieved.

The ideal location of compensatory actions will vary by species and by OWED project. In some instances, it may be appropriate for compensation to occur a significant distance away from the hazard. For example, when adverse effects occur within a migratory pathway, compensation near the OWED hazard might be ineffective because there are few mechanisms that could enhance individual survivorship or increase reproductive success at the project site. Yet losses could potentially be compensated for hundreds of kilometers away by enhancing resources at breeding sites to increase reproductive success or by reducing non-OWED hazards near breeding sites and improving individual survivorship. The European Commission *Guidance document on Article 6(4) of the 'Habitats Directive' 92/43/EEC*, recommends compensation should i) occur within the same biogeographic or within the same range, migration route or wintering area for bird species, ii) create the same ecological structure and functions as those lost, and iii) be designed to avoid jeopardizing other conservation objectives. Ideally, compensation is considered first at the project site, second outside of the site but within a common topographical or landscape unit, and third in a different topographic or landscape unit (Habitat 2007).

Given current understandings and technical expertise, predicting adverse effects and measuring the effectiveness of mitigation measures subsequent to their implementation is not yet a reality. Challenges exist particularly with respect to compensation; hence Bronner et al (2013) argue avoidance and minimization should be prioritized. In the marine system, compensation often entails creating habitat for species or ecosystem services that were not originally adversely affected by the original action but are important to stakeholders (Levrel H. et al. 2012). Compensatory actions thereby are not always effective in replacing lost ecological resources (Doyle and Shields 2012, Bronner et al. 2013), and sometimes replication does not succeed (Brown 2001).

A lack of strong evidence between cause (OWED hazards) and effect (population declines) impedes attribution of adverse effects (direct, indirect, or cumulative) to a particular OWED, subsequently hindering management of CAE. If the hazards of a proposed OWED cannot be linked to expected population declines, or the benefits of mitigation measures cannot be satisfactorily demonstrated, it is difficult for responsible statutory agencies to institute regulatory or policy measures to deny siting at a particular location or to compel a developer undertake costly mitigation measures.

Critical Uncertainties

Despite the above described progress towards understanding the effects of OWED on wildlife, a number of uncertainties remain that plague assessment and mitigation activities. While scientific uncertainties arising from incomplete understandings of cause-effect relationships leading to adverse effects are critical barriers, uncertainties in policy processes also hinder progress. These uncertainties are connected in that reducing scientific uncertainties is reliant upon collection, sharing, and analysis of data, the responsibility for which remains distinctly unclear. Moreover, both improved understandings of cause-effect relationships and governance processes are needed to attribute responsibility for mitigation actions.

As described above, major limitations to determining these cause-effect relationships arise from significant data gaps. Knowledge of basic parameters, such as population levels, trends, and vital rates, confounds delineation of baseline populations and determining rates of population decline. Thus there is a paucity of information on baseline conditions (Smith 2006). Data from monitoring that can be used to iteratively assess CAE (Schultz 2010) could help improve the knowledge base. Yet responsibility for data collection, species monitoring, data sharing, and analysis needs to be clarified (Piper 2001).

From a policy perspective, a key issue is attribution of responsibility for collecting, storing, and analyzing the data on the multiplicity of stressors and receptors to be included in CAE assessments. There are financial and technical constraints to what a single OWED developer can achieve (Piper 2001). Moreover, the data needed for a CAE assessment may be proprietary and not publically available or compiled. As such, it is also difficult for a single developer to incorporate consideration of the impacts of other potential projects into a CAE assessment. This points to the need for regional efforts by government, or non-government organizations that compile information. Such efforts could both increase the ability of scientific studies to improve understandings of effects pathways and improve decision-making by enabling regulators to conduct regional assessments of the interactions across multiple OWED projects.

Collaborative governance processes, private-public partnerships, and stakeholder processes have emerged to engage with these unanswered questions regarding the uncertainty of cause-effect relationships and attribution of responsibility. These processes move towards a "pragmatic approach" of CAE assessments as described by Parkins (2011). The pragmatic approach depolarizes decision-making and is grounded in deliberative democracy where all participants engage in rigorous debate and are willing to revise their position. This is in contrast to the common form of cumulative effects assessments dominated by either a "technocratic approach" that is focused on analytical, data driven modeling, or the "decisionistic" approach in which influential players make unilateral decisions based upon their own political interests (Parkins 2011). A pragmatic approach would also allow for a broader integrated risk analysis that incorporates the climate change mitigative qualities of OWED and the adverse effect from fossil-fuel energy decision making (Ram 2011). Example of such approaches include the multidisciplinary stakeholder processes of the Collaborative Offshore Wind Research Into The Environment (COWRIE) and the Strategic Ornithological Support Services (SOSS) in the UK, We@Sea in Europe, and the National Wind Coordinating Committee (NWCC) in the US. Each of these processes has brought together developers, regulators, and NGO leaders to identify and respond to key environmental issues around wind projects. Bringing together this group of stakeholders has changed the nature of regulatory processes, shifting the emphasis from who/which OWED is responsible to what the OWED community as a whole can do to reduce CAE. These groups reduce uncertainty for the regulated community and seek to minimize CAE of OWED to wildlife by establishing best practices (see Drewitt and Langston 2006); agreeing on assessment scope via early dialog between stakeholders and the government (Renewable UK 2013); facilitating the sharing of data collected at particular projects; focusing research on critical information gaps; and determining reasonable mitigation measures.

Discussion

If countries in the US and Europe meet their 2030 goals for offshore wind energy, thousands of turbines in coastal and offshore waters will be deployed. This future build-out is likely to have adverse effects on wildlife. In the above review, we explained that the direct and indirect effects of OWED on wildlife are a function of hazards (changes to the environment by OWED), vulnerability (the likelihood a species will interact and respond to an OWED), and exposure (the duration that individuals interact with OWED over a specific geographic area). These individual adverse effects accumulate additively, synergistically, or in a countervailing manner through an increase of spatial and temporal exposure. To prevent population declines, it is essential that we develop effective practices for the assessment and mitigation of these CAE.

Yet our review and analysis of the assessment of CAE of OWED on wildlife illuminates a number of inter-related challenges with assessment and compensatory mitigation of CAE. Insufficient baseline and wildlife response data impede identifying effects pathways and accumulation resulting from both homo- and heterotypic hazards and their interactions. Technology and financial limitations (e.g., detecting collision mortality of birds and bats over the open ocean) constrain determination of direct effects. Identification of indirect effects (e.g., reduced individual fitness from avoidance response leading to lower reproductive success) is hampered by the fact that such effects may be separated spatial and temporally from an OWED project. Moreover, since CAE occurs through incremental accumulation of adverse effects, the effects caused by one project may in isolation not lead to population declines, but when combined with effects from other homo- and heterotypic sources (e.g., minerals extraction, fishing, climate change) would cause a population decline. Lastly, since population dynamics are highly complex and factors that adversely affect one species may be inconsequential to others (see Newton 2013), the factors causing CAE will vary significantly from one species or taxonomic group to another.

Assessment of CAE of OWED on wildlife is further complicated by a lack of clarity regarding what constitutes CAE and the extent of factors (temporal, special boundaries, species to be included, etc.) to be considered in the analysis. Guidelines for CAE assessments, which aim to address questions on scoping, are broad and guidelines specific to the CAE of OWED on wildlife need to be developed.

Resolution of the challenges of CAE assessment and mitigation is both a scientific and a policy conundrum. From a science perspective, greater knowledge and data is needed about wildlife populations and how they respond to OWED. Methodological improvements also need to be made on assessment of CAE. Yet the need for improving the science is compounded by the policy issue of responsibility. Currently in the US the onus for a CAE assessment for a specific project falls *de facto* to the OWED project developer, who, in the process of addressing disclosure requirements, sets the stage for scientific improvements. Yet there are limits both to the information available to a developer and to the resources the developer can put towards CAE assessment. While a developer will have detailed information about their actions, baseline population level data and information on concurrent hazards, including other projects planned or under construction, may be beyond the purview of the developer. This information gap suggests CAE assessment may be best accomplished through a two-stage process in which the developer assesses certain elements of CAE, and regional scale assessments fall to a regulating governing body.

A second science and policy issue arises in relation to the burden of mitigation. Due to CAE accumulating from a variety of both hetero- and homotypic hazards and uncertainty in effects pathways, attribution of responsibility for action is unclear. A sector-specific approach to CAE assessment of OWED on wildlife could enable the burden of mitigation to be assigned on a project-by-project basis, yet such an approach would discount heterotypic effects (e.g., fisheries bycatch). Until science progresses to the point where effects can be specifically attributed to each hazard, resolution of this issue will be, of necessity, a political determination.

Given that the offshore wind industry is still in a nascent stage, there is no immediate answer to these policy conundrums. The deployment of additional turbines will provide the opportunity to improve the understandings of wildlife response to OWED, through *in situ* studies by developers as well as regional baseline research. Nonetheless, due to the complexity of CAE, uncertainties will still remain. Thus there is a need for more meaningful engagement on the topic of how to manage CAE in the face of uncertainty. The private-public collaborations in the UK and Europe (COWRIE, SOSS, or WE@SEA) discussed above are a start in this direction. Collaborative governance efforts could assist in developing consistent research questions, standard methodologies, and data sharing mechanisms, allowing stakeholders to iteratively inform each other of new understandings of adverse effects that accumulate to cause CAE. A notable challenge, however, is how to achieve this sharing of information while simultaneously protecting companies' proprietary information.

In sum, the development of OWED in the US and the expansion of current capacity in the UK and Europe has significant momentum. Mitigating adverse effects that accumulate to affect populations will require clear definitions and thresholds, delegation of responsibility, careful analysis, a deliberative regulatory process, and strong private-public partnerships.

Table 2.1. Primary OWED hazards to wildlife: Cause.

Development phase	Development component	Hazard source	Hazard
Preconstruction	Turbines	Seismic profiling	Noise, pressure
	Network Connection	Seismic profiling	Noise, pressure
Construction	Turbines	Pile driving	Noise, pressure, turbidity, sedimentation, physical alteration of habitat
	Network Connection	Trenching	Turbidity, sedimentation, physical alteration of habitat
Operation	Turbines	Turbines, wind farm footprint, mooring lines	Disturbed air space, turbulence, noise, permanently altered habitat
	Network Connection	Electrical cable	EMF
Decommissioning	Turbines	Decommissioning activities	Unknown
	Network Connection	Decommissioning activities	Unknown
All phases	All components	Boat traffic, lighting	Disturbed marine habitat, noise, turbulence, light

Table 2.2. Primary adverse effects of OWED hazards to wildlife: Effect.

Taxon	Vulnerable characteristic	Vulnerable life stage	Primary exposure	Adverse effect
Fish	Sensitive to habitat alterations, EMF, and noise; present at all OWEDs	All	All	Mortality, injury, displacement, habitat alteration, reef effect
Sea turtle	Sensitive to EMF and noise; inability to escape boat hazards; widespread abundance.	All but nesting	All	Mortality, injury, behavioral alteration
Marine mammal	Long-lived/high adult survival/low annual reproductive rate; widespread abundance; sensitive to sound; inability to escape boat hazards	All	Construction	Mortality, injury, hearing damage from noise, behavioral alteration
Bird	Long-lived/high adult survival/low annual reproductive rate; fly at rotor height; attraction to and avoidance of turbines	Breeding, migrating, wintering	Operation	Mortality, injury, displacement
Bat	Long-lived/high adult survival/low annual reproductive rate; attraction to turbines	Migrating	Operation	Mortality

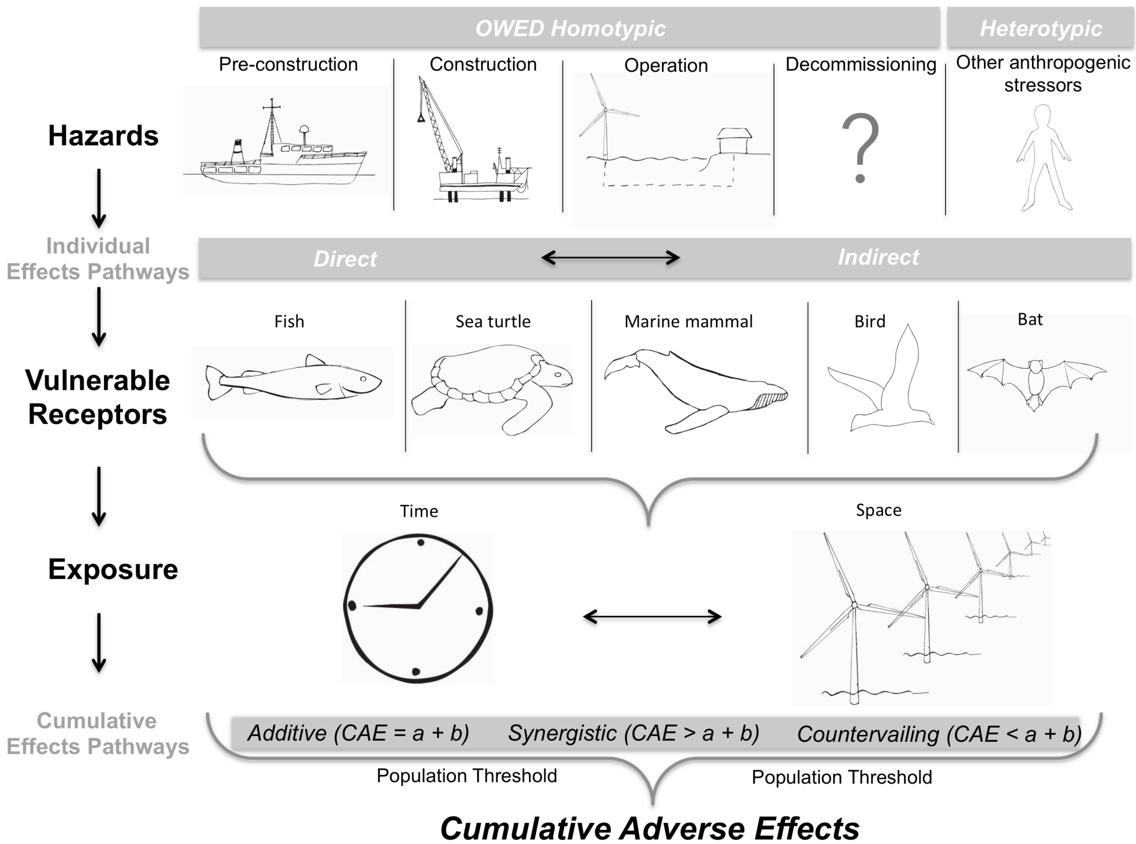


Figure 2.1. The process of the cumulative adverse effects of offshore wind energy development on wildlife. Homotypic OWED hazards, as well as other heterotypic sources, directly/indirectly adversely affect vulnerable receptors. These adverse effects accumulate as vulnerable receptors are repeatedly exposed through time and space to the OWED hazards via additive, synergistic, and countervailing pathways. The adverse effects of the exposure of vulnerable receptors to OWED hazards can then accumulate to a degree that a population threshold is passed.

CHAPTER 3

DEVELOPING A DETERMINISTIC GEOSPATIAL DECISION-SUPPORT MODEL TO ASSESS THE CUMULATIVE EXPOSURE OF WILDLIFE TO OFFSHORE WIND ENERGY DEVELOPMENT PATTERNS

Abstract

Assessments of cumulative adverse effects (CAE) must first calculate the cumulative exposure of a wildlife population to a hazard and then estimate how the exposure will affect the population. Our research responds to the first need by developing a deterministic, geospatial decision-support model designed to assess how wildlife are cumulatively exposed to the hazard of multiple offshore wind energy developments (OWEDs). The model assesses cumulative exposure by identifying all locations where OWED could occur, placing wind farms within this suitability layer, and then overlaying wind engineering and biological data sets. The first model output is a wildlife cumulative exposure curve for different OWED siting decisions. The second output is a cumulative exposure index that ranks which OWED siting decisions will have the greatest influence on wildlife cumulative exposure. Together these outputs will provide stakeholders valuable information about how OWED patterns will cumulatively expose wildlife, which could be used to guide regional siting decisions.

Introduction

Worldwide, governments and industries are looking to increase the production of electricity from offshore wind. This movement stems from a strong interest in diversifying energy sources, reducing the carbon intensity of global energy production as a way to address climate change, and the need to meet growing coastal demands for electricity. Offshore wind is framed as an energy alternative with lower life-cycle adverse effects to the environment than fossil fuel electricity production (Ram 2011); however, there are concerns that deployment of offshore turbines may lead to declines in wildlife populations. While today there is only one, five-turbine (0.03 gigawatts [GW]) offshore wind project in the U.S. (Deepwater Wind 2016), the U.S. National Renewable Energy Laboratory (NREL) estimates the potential capacity of offshore wind power in the U.S. to be 4,200 GW (Lopez et al. 2012). The U.S. Department of Energy (DOE) has set a goal of 54 GW installed by 2030 (DOE 2011); and DOE has developed a scenario for 86GW to be installed by 2050 (DOE 2016). Reaching the 54 GW goal would lead to approximately 5,000-8,000 turbines deployed in U.S. waters (Goodale and Milman 2016). The prospect of thousands of turbines in U.S. oceans means that understanding the complexities of the effects of offshore wind energy development on wildlife is a pressing and immediate multidisciplinary challenge.

While taxa dependent, effects to wildlife from offshore wind energy development (OWED) are direct (e.g., mortality) or indirect (e.g., general disturbance caused by the turbines; Goodale and Milman 2016). The adverse effects of a single OWED are important, but a greater concern is how multiple OWEDs, combined with other anthropogenic stressors, will affect wildlife populations through time and space. These cumulative adverse effects (CAE) of OWED on wildlife are recognized as an important issue for birds (Drewitt and Langston 2006, Fox et al. 2006, Larsen and

Guillemette 2007, Masden et al. 2010, Langston 2013); marine mammals (Dolman and Simmonds 2010); fish (Gill et al. 2012); and the environment in general (Boehlert and Gill 2010).

The risk of CAE of OWED on wildlife is poorly researched and processes for assessing the risk of CAE within permitting processes are underdeveloped (Burris and Canter 1997, Cooper and Canter 1997, Baxter et al. 2001, Cooper and Sheate 2002, Duinker and Greig 2006). Consequently, CAE assessments vary within and across regulatory agencies (MMS 2007;2009, BOEM 2012a, Army Corps of Engineers 2014) as well as between National Environmental Policy Act (NEPA) processes (MMS 2007;2009, Army Corps of Engineers 2014). Uncertainty about how to conduct assessments and evaluate CAE is a cause for delays in OWED permitting and the source of inconsistency in how CAE is addressed in environmental assessments (Masden et al. 2015, Willsteed et al. 2017). With the exception of several modeling efforts (see Masden et al. 2010, Poot et al. 2011, Topping and Petersen 2011) and working groups (Norman et al. 2007, King et al. 2009), knowledge of CAE of OWED on wildlife remains relatively unexplored. Existing efforts are limited to conceptual models (Masden et al. 2010, Willsteed et al. 2017), geographically limited scopes (Poot et al. 2011), single species (Topping and Petersen 2011), and finite development scenarios (Busch et al. 2013). Therefore, there is a need to develop new processes for assessing CAE.

Assessments of CAE must calculate the cumulative exposure of a wildlife population to a hazard and then estimate how the exposure will affect the population (Goodale and Milman 2016). Our research responds to the first need by developing a customizable deterministic, geospatial decision support model ("CE model") that analyzes the relationships between OWED siting decisions and cumulative wildlife exposure. The CE model estimates the cumulative exposure of wildlife to the homotypic stressor of OWED by identifying all locations where OWED could occur, placing wind farms within this suitability layer, and then overlaying wind engineering and biological data sets to develop two outputs. The first model output, the cumulative exposure (CE) curve, is a graphical representation of how OWED siting decisions affect wildlife cumulative exposure. The second model output, the CE index, identifies the OWED siting decisions that will cause highest initial rates of cumulative exposure.

In this paper, we provide an overview of the model, describe data inputs and the model analysis process, and explain model outputs. To illustrate the use of the model, we also present and interpret hypothetical model results. We conclude with a discussion on further model development. The paper demonstrates the utility of the CE model, a novel method that has significant value in informing regional and project-specific planning.

Model Description

Overview of the Model

To assess the cumulative exposure of wildlife to OWED, the CE model undertakes a series of sequential calculations (Figure 3.1). The initial step is to establish the spatial scope of analysis (CEQ 1997, Canter 2012, Willsteed et al. 2017). An "OWED building suitability layer" is developed, which sets the spatial scope of the analysis using jurisdictional boundaries, wind engineering constraints, and/or ecologically relevant areas. After the suitability layer is determined, the model uses an average wind farm size (determined by the user) to fit a "wind farm grid" within the suitability layer. Next, "wildlife relative abundance indices" are developed from existing individual tracking and survey data. The model then spatially joins the wildlife relative abundance indices, and layers representing the elements stakeholders consider when siting OWED (hereafter "siting factors"), to the wind farm grid using a coordinate reference system that reduces area distortion. The spatial join calculates the total number of wildlife (e.g., 245 Northern Gannet [*Morus bassanus*]) and an average siting factor value (e.g., 7.8 m/s wind speed or 24 m water depth) for each wind farm within the wind farm grid. The model then orders factors by favorability and calculates the cumulative exposure of wildlife to each siting factor. Results from this calculation are used to plot the CE curve and calculate the CE index. The CE curve is temporally bound by starting at the present with the assumption of zero OWED built, and moving to a nonspecific point in the future when the OWED suitability layer has been saturated by wind farms. The model is scripted in the R programming environment (R Core Team 2015) and requires 21 packages for the analysis (Appendix A).

Model Inputs

The CE model relates OWED siting decisions to wildlife abundance data using two input parameters types: siting factors and wildlife relative abundance index data. The siting factors are separated into three categories: exclusions, constraints, and decision factors. "Exclusions" are specific areas of the ocean that have physical hazards (e.g., unexploded ordinance), have specific regulatory exclusions (e.g., shipping lanes), or have been identified as having conflict with military activities. "Constraints" are OWED siting considerations that have thresholds beyond which OWED is no longer viable either technologically or economically (e.g., wind speed less than 7 m/s). "Decision factors" are factors that will influence, but not dictate, where developers consider siting OWED projects (i.e., hurricane risk and proximity to high energy use areas).

Wildlife relative abundance index data are raster indices of wildlife abundance. The values in the raster must be a relative abundance metric modeled from satellite tracking or survey data. The raster surfaces must have full coverage of the area being considered for development. If the raster surface does not include the entire study area, then the CE model would consider areas with no data to have no wildlife.

Model Process

The OWED building suitability layer (i.e., where development is possible) is created by combining siting factor exclusions and constraints using Boolean map-layering (O'Sullivan and Unwin 2014). Boolean logic assigns true (1) and false (0) values to each cell for each siting factor layer included in the analysis. The siting factors are then multiplied together using raster math and all areas coded to false are excluded from development. Given the high uncertainty about which siting factors will be most important for OWED siting (Musial and Ram 2010, Schwartz et al. 2010), Boolean logic provides simplicity and transparency and reduces the number of input assumptions. The assumptions in Boolean layering are that relationships between layers are Boolean, that inputs do not have measurement error, categorical attributes are exactly known, and that boundaries within an input layer are certain (O'Sullivan and Unwin 2014). Since Boolean layering requires establishing an absolute suitable/unsuitable boundary (values of 1 and 0 respectively; e.g., development cannot occur in water depths greater than 200 m), error in the values of input layers can lead to the erroneous inclusion or exclusion of development areas. An overly constrained OWED suitability layer would exclude areas from development that may actually be developed (Type II error), and thus exclude areas where wildlife may actually be exposed to development, leading to an underestimate of the exposure. Therefore, for each siting factor constraint, Boolean values are selected that allow for the inclusion of a greater area for OWED development to ensure that all possible locations of development are included in the assessment. Within the building suitability layer, the model creates a wind farm grid using three input parameters: wind turbine size (e.g., 6 MW), wind turbine spacing (e.g., 8 rotor diameters), and overall wind farm capacity (e.g., 300 MW). Using the wind farm area, a grid of square-shaped wind farms is fit within the OWED suitability layer. There are areas at the edges of the suitability layer that have the potential for OWED that are excluded from the analysis because the CE model will only accept full-size wind farms.

If individual tracking data are available, the model calculates utilization distributions (UDs) using continuous-time movement modeling (ctmm R package; Calabrese et al. 2016) to create a raster surface of wildlife exposure. The raw satellite data are preprocessed with the Douglas Argos-Filter (DAF) Algorithm (Douglas et al. 2012) and subsetted to use the best daily Argos location class (ARGOS 2016). The ctmm method is used because it includes autocorrelation in the bandwidth estimate, which reduces underestimating animal home range (Fleming et al. 2015). By incorporating autocorrelation into the analysis, the final UD has greater smoothing and thus will create a larger overall home range, reducing the potential for a Type II error in the cumulative exposure estimate. The UD can be rescaled to create a relative abundance index (Wakefield et al. 2013, Cleasby et al. 2015) to match the scale used by other wildlife inputs such as seabird abundance models developed by Kinlan et al. (2016). The raster UD outputs and/or survey models inputted into the CE model, such as those developed by Kinlan et al. (2016), are then converted to polygons, the required input for the spatial join.

Using a spatial join function, the model calculates a mean siting factor (e.g., 7.8 m/s wind speed) and abundance index value for each species (e.g., 124 Northern Gannets, *Morus bassanus*) for each wind farm within the OWED suitability layer grid. The calculation is conducted by converting each siting factor constraint, decision factor, and wildlife abundance layer from a raster to a polygon. Using a many-to-one polygon within polygon spatial overlay (i.e., join function), each siting factor layer is merged with the wind farm grid using a mean function and each wildlife relative abundance index layer is merged using a sum function.

The model calculates the cumulative sum of wildlife exposure for each siting factor and species. First, wildlife cumulative exposure is calculated presuming wind farm siting avoids wildlife concentration areas by ordering the wind farm grid from low to high number of animals and calculating the cumulative sum of animals exposed. This is repeated for each species. Second, wildlife exposure is calculated presuming wind farm siting was optimized independently for each siting factor. Siting factors are ordered independently in a sequence that minimizes the levelized cost of electricity (LCOE) for that factor (e.g., build in the windiest places first, or shallow places first) and then the cumulative sum of animals exposed is calculated. The GW of production capacity is assigned to each wind farm (default 0.3), and the cumulative sum of production is calculated assuming the entire wind farm grid is built. The result from these calculations is one table that estimates cumulative exposure of each species/siting factor combination inputted into the CE model. The model uses the table to plot the CE curve and calculate the CE index (described below).

Model Outputs

Cumulative exposure (CE) curve

The first model output is a cumulative exposure curve for each siting factor/species combination, including avoiding wildlife exposure (Figure 3.2). The output displays the relationship between wildlife cumulative exposure (y-axis) and GW of OWED production (x-axis) from zero OWED to full build-out of the OWED suitability layer. If GW of OWED development (x-axis, Figure 3.2) is a proxy for time, then the curve represents a rate that wildlife will be cumulatively exposed based upon how OWEDs are sited. The closer the curve is to the x-axis, the lower the initial rate of exposure (i.e., Type III); the closer the curve is to the y-axis, the higher the initial rate of exposure (i.e., Type I).

Cumulative exposure (CE) index

The second model output is the CE index that identifies the siting decisions that will cumulatively expose wildlife at a higher rate. An index value for each species/siting factor combination is developed by subtracting the area below the siting factor curve from the area below the wildlife avoidance curve (Figure 3.3). The area is normalized to a metric between 0-1 by dividing the area calculation by the total area of the plot. The closer the value is to 1, the higher the initial rate of cumulative exposure.

Example CE Model Analysis

To illustrate model outputs and how they can be interpreted, below we display the results from an example analysis. The example model outputs are based upon an OWED suitability layer in a generic location with the area required to fit 200, 500 MW wind farms for a total production capacity of 100 GW. The analysis uses fictitious wildlife relative abundance index data for three species (A, B, & C) with different distribution patterns. Species A is a coastal species with a northerly bias distribution (e.g., seaduck), Species B is a common, broadly distributed species (e.g., gull), and Species C is a pelagic species (e.g., shearwater). Cumulative sum of exposure is then hypothetically calculated for two siting factors: distance from shore and wind speed.

The example outputs demonstrates how the CE model simplifies the complexity of cumulative exposure into easily interpreted graphs and metrics (Figure 3.4). In this example, the CE curve indicates that Species A will be cumulatively exposed at a higher initial rate when OWED is sited close to shore and at a slightly lower rate when projects are built in high wind areas; Species B will be cumulatively exposed at a similar rate for both siting decisions; and Species C will be cumulatively exposed at a higher rate when projects are built in high wind areas and at a lower rate when built close to shore. For Species A and B, the CE index range indicates that siting decisions have less influence on cumulative exposure, whereas for Species C, siting decisions are more important.

Discussion

The CE model will have direct application in assessing cumulative adverse effects of offshore wind energy development on wildlife. The CE model takes the first step towards evaluating CAE by assessing how wildlife will be cumulatively exposed to OWED siting patterns. The CE model builds upon past conceptual efforts to frame and scope CAE (CEQ 1997, Masden et al. 2010, Goodale and Milman 2016, Willsteed et al. 2017) by developing outputs that will aid stakeholders in understanding how wildlife may be cumulatively exposed to alternative future OWED patterns. Specifically, the CE model outputs identify: a) the OWED siting decisions that are most likely to cumulatively expose particular species; b) the siting decisions that can successfully avoid cumulatively exposing particular species; and c) the species that will be cumulatively exposed regardless of siting decisions. Stakeholders can use the model outputs to place project-specific species exposure within the context of future exposure patterns.

Cumulative effects analysis must include past, present, and reasonable foreseeable future actions (CEQ 1997); yet, the number of future wind farms and pattern of development remains uncertain. Future OWED could be limited to the only existing wind farm (Deepwater Wind 2016), or be constrained to Wind Energy Areas (BOEM 2018), or be expanded to a much broader area (DOE 2016). The CE model distills into a simple index how these alternative OWED siting scenarios and patterns could contribute to CAE. The CE index measurement represents the percentage that an OWED siting decision (e.g., prioritize building in shallow areas) diverges from siting decisions that avoid exposing wildlife. The closer the index is to 1, the higher the initial rate (e.g., number of individuals exposed per GW of OWED) that wildlife will be exposed to development. Conversely, the closer the index is to 0, the lower the initial rate of exposure to development. Thus, the CE index clearly shows the OWED siting decisions that will expose wildlife at the highest initial rate.

The CE index also shows, on species-specific or guild level, if OWED siting decisions are effective in avoiding cumulative exposure. When multiple OWED development decisions are analyzed simultaneously (e.g., prioritize building close to shore or in shallow areas or in high wind resource areas), the greater the statistical range of the CE index for a particular guild or species, the greater the influence OWED siting decisions will have on cumulative exposure. A low index range indicates that cumulative exposure rates will be similar for a species regardless of OWED siting decisions and does not mean the birds will be at low risk of exposure. A low CE range can be the result of a species occupying a large geographic range—e.g., generalists gulls—and indicate that the species will likely be exposed to OWED regardless of where they are sited. Therefore, for each species, the CE index provides critical information on both the siting decisions that will lead to high or low cumulative exposure as well as if siting decisions have the power to reduce cumulative exposure.

The hypothetical results demonstrate how the CE model can inform decision-making. For Species A the model outputs indicate that building close to shore would lead to greater cumulative exposure, but that neither OWED siting decision leads to effective avoidance of species concentration areas. In contrast, for Species C, building close to shore will effectively avoid exposing the birds in large numbers for the first 50 GW of development, whereas building in high wind areas to achieve the same 50 GW will expose nearly 75% of the population. Species B follow the pattern of a species that has a broad distribution throughout the OWED suitability layer. Specifically, since the curve that represents avoiding bird concentration areas (green) has a steep initial slope, the CE curve for Species C shows that siting decisions will not be effective in reducing exposure.

The value of the CE model outputs becomes evident when combined with prior knowledge of species' behavioral and population vulnerability to OWED (Garthe and Huppop 2004, Desholm 2009, Furness et al. 2013, Goodale and Stenhouse 2016). For example, if Species A was not considered vulnerable to OWED development and had a stable population, then decision makers could generally dismiss the species as being at risk of CAE, even though they would be cumulatively exposed to both development patterns. If Species B was considered vulnerable to collision with offshore wind turbines, the CE model outputs show avoidance is not an effective mitigation strategy and that all projects, regardless of site, should consider minimization measures such as reducing lighting. Finally, if Species C was an endangered species, the CE model outputs could quickly guide regulators on the rigor of analysis needed for individual projects. In this example, projects being built close to shore might receive less scrutiny than projects built in high wind-resource areas.

The hypothetical results represent a simplistic example of the CE model outputs, but the model is scripted to be used in any geographic location, be tailored to any OWED build-out scenario, and accept unlimited wildlife and OWED siting decision inputs. Thus, the model can be used to determine a consistent scope of CAE analysis for a region, a critical need identified for CAE assessments (Willsteed et al. 2017). In addition, the CE model can reduce uncertainty in CAE assessments (Masden et al. 2015, Willsteed et al. 2017, Stelzenmüller et al. 2018) by forecasting simultaneously unlimited species/development combinations. In a complex analysis, the CE index provides clear metrics for stakeholders to evaluate and explore if there are OWED siting decisions that can reduce the potential of CAE and maximize OWED capacity.

Model Extensions and Opportunities

The CE model could be modified to include stochasticity and become an online decision tool. Currently, the model only allows for a deterministic pattern of development for each siting factor through ordering. Stochasticity could be added to the model process by selecting sites for development in a probabilistic manner weighted by the relevant properties of the site. This process would allow the CE model to simulate the variance presence in the site selection process and properly quantify the uncertainty inherent in the model.

Stochasticity could also be added by including intra- and inter-annual variation in species abundance. The CE model is currently designed to assess the cumulative annual exposure for a species; yet, species are highly mobile and their use of the marine ecosystem varies seasonally and annually. The CE model could be modified to accept raster layers for each season and/or year of available data for each species and then to create an aggregated cumulative exposure curve. These modifications would capture the natural variability in OWED siting decisions and wildlife abundance.

In addition, the CE model code could be integrated into an interactive web-based decision-support model using R Shiny (RStudio 2017) to allow stakeholders to conduct their own cumulative exposure assessments. As OWED progresses in the U.S., the online tool could begin to estimate the cumulative exposure based upon existing and proposed projects, and then forecast how future OWED siting decisions would contribute to cumulative exposure. We developed an example of an online decision tool for Northern Gannets: https://cae-owed-seabird.shinyapps.io/survey/.

Conclusions

We developed a novel method for assessing cumulative exposure of wildlife to OWED siting patterns. The CE model's structure allows users to apply the model to any geographic location and explore how changing assumptions affect cumulative exposure assessments. The CE model takes the first step towards evaluating CAE, and provides decision makers with clear guidance, by species, on the efficacy of avoiding cumulative exposure of wildlife through siting decisions, which has significant value in informing regional planning efforts an directing species-specific mitigation efforts.

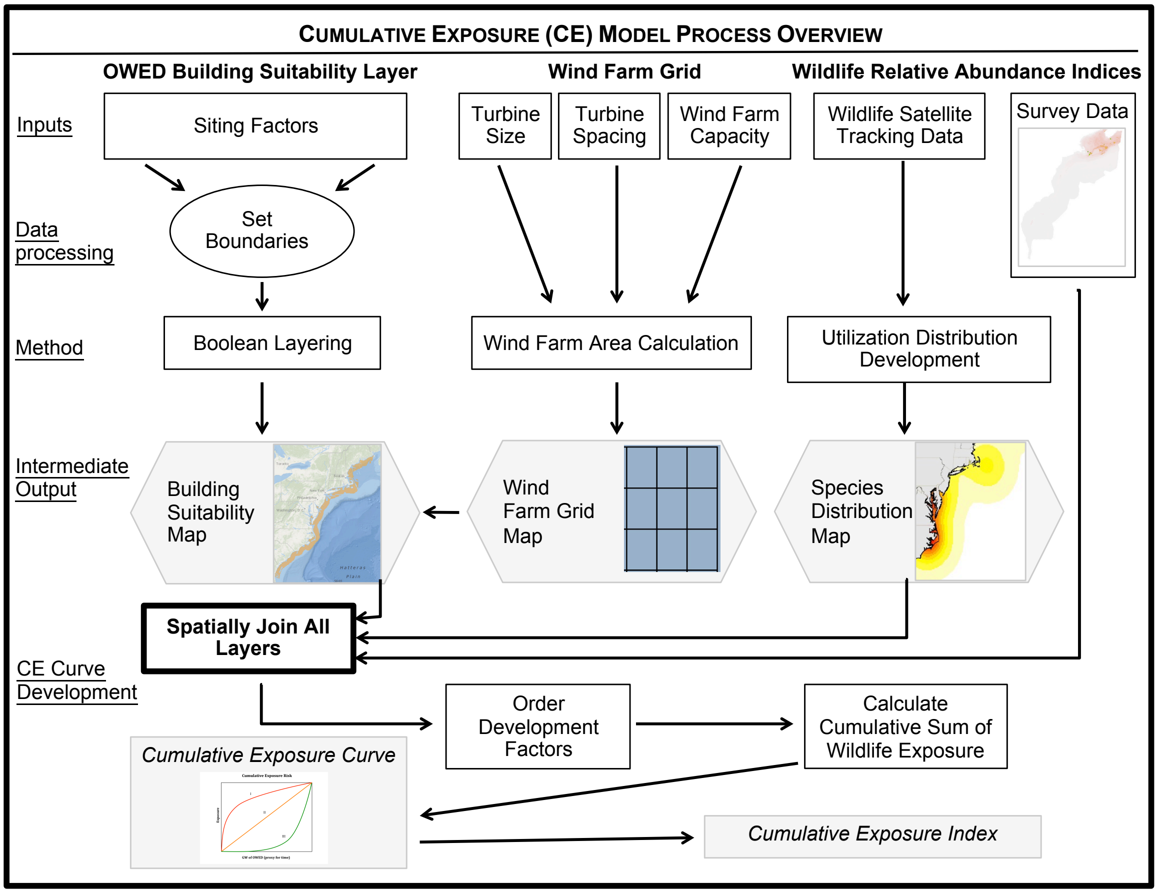


Figure 3.1. The CE model creates an OWED building suitability layer (i.e., where is development possible); fits a wind farm grid within the suitability layer; creates a species distribution map from individual tracking data; spatially joins wildlife layers and siting factors to the wind farm grid; sorts siting factors by favorability; and creates two outputs: cumulative exposure curve and cumulative exposure index.

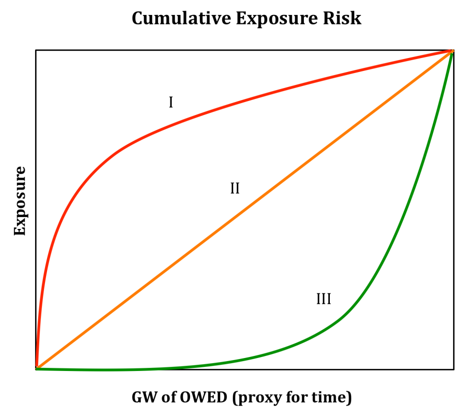


Figure 3.2. Conceptual representation of cumulative exposure: A Type I curve is high initial exposure rate, a Type II is a constant exposure rate, and a Type III is a low initial exposure rate. The Y-axis will be the number of individuals exposed from a hypothetical population.

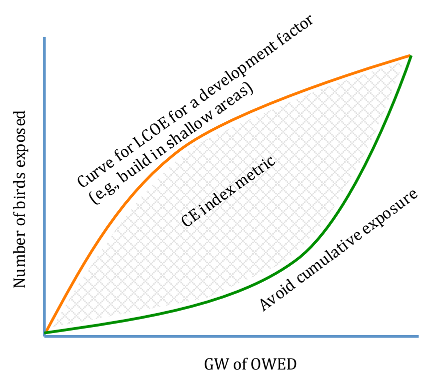


Figure 3.3. The CE index is the area (grey hatched area) between a curve for a particular development decision (e.g., building in shallow areas; orange line) and the curve for siting OWED in areas with the least wildlife abundance (green line). The index indicates the percentage an OWED siting decision diverges from avoiding exposing wildlife.

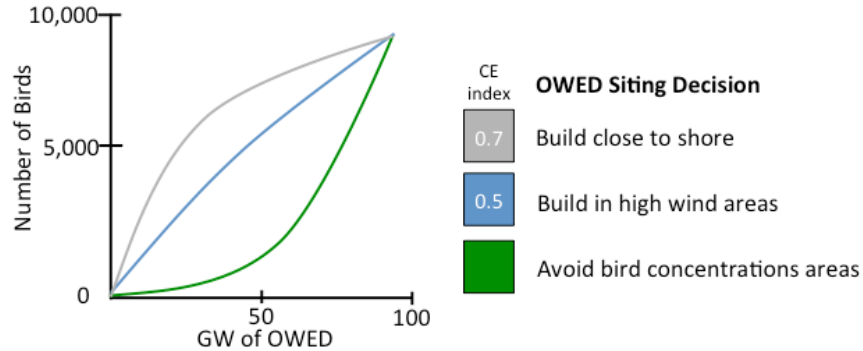
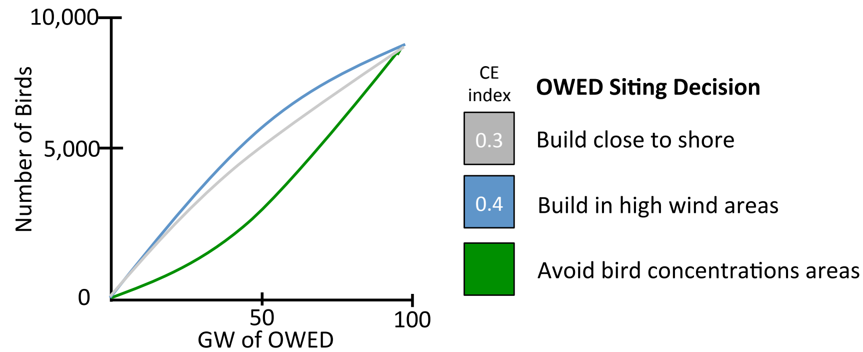
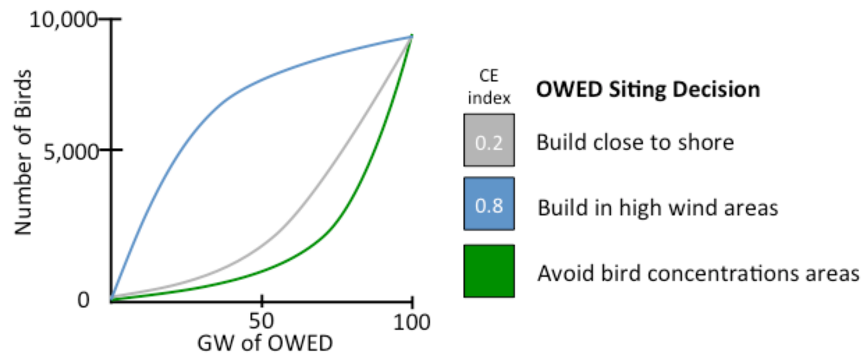
Species	CE Index Range	CE Curve
A	0.2	
B	0.1	
C	0.6	

Figure 3.4. An example of the CE curves and index (displayed in legend box) produced for three hypothetical species (A, B, & C) exposed to two different siting decisions. For all species the green curve represents selecting areas for development that always have the lowest wildlife abundance.

CHAPTER 4

ASSESSING THE CUMULATIVE EXPOSURE OF NORTHERN GANNET (*MORUS BASSANUS*) TO OFFSHORE WIND ENERGY DEVELOPMENT ALONG THE EAST COAST OF THE UNITED STATES

Abstract

Offshore wind farms are rapidly being permitted along the East Coast of the U.S. The exposure of Northern Gannet (*Morus bassanus*) to multiple wind farms could impact the population because gannets are vulnerable to both displacement and collision. A critical question is if wind farm siting decisions can reduce gannet cumulative exposure. To research this question, we quantified how three different wind farm siting scenarios would cumulatively expose gannets. Two independent gannet abundance datasets were used to ensure the robustness of the analysis. The results indicate that for initial development, projects sited close to shore and in shallow areas exposed gannets at the highest rates, but no siting decisions effectively avoided exposing gannets due to the birds' broad distribution through the outer continental shelf. The findings suggest that gannets will be cumulatively exposed regardless of siting decisions and avoidance is not an effective mitigation measure.

Introduction

Concerns about the adverse effects of offshore wind energy development (OWED) on seabirds are increasing because OWED is rapidly expanding in the U.S. The U.S. Department of Energy (DOE) has set a goal of 54 gigawatt (GW) installed by 2030 (DOE 2011), and DOE has developed a scenario for 86 GW to be installed by 2050 (DOE 2016). The first U.S. offshore wind farm began operating in 2016 (Deepwater

Wind 2016) and areas are currently leased from North Carolina to Maine along the East Coast of the U.S. (BOEM 2018). If DOE's development goals are achieved, seabirds could be cumulatively exposed to thousands of turbines installed in the next decade (Goodale and Milman 2016).

The potential adverse effects of OWED on seabirds are effective habitat loss due to displacement and mortality due to collision (Drewitt and Langston 2006, Fox et al. 2006, Goodale and Milman 2016). The risk of adverse effects occurs when vulnerable species are exposed to wind farm hazards. Species are vulnerable to displacement when they avoid wind farms (Furness et al. 2013, Dierschke et al. 2016, Goodale and Milman 2016) and vulnerable to collision when flight behaviors increase the likelihood that a bird will be struck by a turbine blade (Furness et al. 2013).

Northern Gannet (*Morus bassanus;* hereafter "gannet") is a seabird consistently identified as being vulnerable to both displacement and collision. Gannets are considered to be vulnerable to displacement from habitat because studies indicate the birds avoid wind farms (Krijgsveld et al. 2011, Cook et al. 2012, Hartman et al. 2012, Vanermen et al. 2015, Dierschke et al. 2016, Garthe et al. 2017). Yet, when gannets enter a wind farm they may also be vulnerable to collision because they have the potential to fly within the rotor-swept zone (Furness et al. 2013, Garthe et al. 2014, Cleasby et al. 2015). Gannets also have demographic vulnerability (Goodale and Stenhouse 2016), increasing the likelihood that the loss of individuals will affect the population, because gannets are long-lived, have high adult survivorship, and lay only one egg per year (Mowbray 2002, Chardine et al. 2013). Combined, the behavior and demographic vulnerability suggests that gannets may be adversely affected by OWED (Brabant et al. 2015).

A substantial proportion of the North American gannet population have the potential to be exposed to OWED along the East Coat of the U.S. Gannets breed exclusively in six colonies in southeastern Canada, which represents approximately 27% of the global population (Chardine et al. 2013). In the fall the birds migrate through the Gulf of Maine and primarily winter along the Atlantic and Gulf of Mexico outer continental shelf (Mowbray 2002, Stenhouse et al. 2017). Immature birds can continue to move throughout the outer continental shelf and remain in the southern portion of their range until they reach maturity (Mowbray 2002). Thus, widespread OWED along the East Coast of the U.S. has the potential to cumulatively expose the gannet population. Due to the gannets' vulnerability, this cumulative exposure could lead to cumulative adverse effects (CAE), a concern also identified in Europe (Poot et al. 2011, WWT 2012, Brabant et al. 2015, Cleasby et al. 2015).

While CAE is recognized as a concern for gannets, there has been no research in the U.S. on how OWED siting decisions will affect gannet cumulative exposure. Understanding these relationships is necessary to support efforts to reduce CAE because there is substantial uncertainty on the spatiotemporal patterns of future development (Goodale and Milman 2016). The temporal scope of CAE analysis includes past, present, and future development (Goodale and Milman 2016). In the

U.S., the past development is limited to five turbines off Block Island; the present is Wind Energy Areas (WEAs) identified by the federal government (BOEM 2017); and the future is undefined. Beyond the WEAs, the locations of future wind farms remain unknown and, within existing and future leased areas, the order in which the projects will be built is uncertain. Wind farms may be sited close to shore to reduce the construction costs, or projects may be built in areas with the highest wind resources to maximize energy production (Dvorak et al. 2013). Predicting if the population will be adversely affected by future development cannot be done with certainty since gannets are not uniformly distributed across the marine ecosystem (Stenhouse et al. 2017), and incremental exposure patterns are dependent upon the OWED siting decisions. Yet, the uncertainty provides an opportunity to site projects in a manner that optimizes energy production and reduces gannet exposure.

We used the cumulative exposure model ("CE model"; Goodale 2018) to assess cumulative exposure of gannets to three alternate wind farm siting scenarios along the East Coast of the U.S. to determine if specific siting decisions can reduce exposure rates. The CE model estimates the locations of all potential wind farms in a prescribed area and then assesses how alternate future wind farm development scenarios will incrementally expose wildlife populations. Two independent datasets were used to estimate gannet abundance on the outer continental shelf to ensure the robustness of the analysis. In this paper, we first describe the CE model inputs, model process, and the results of the analysis; we then discuss how understanding the relationships between OWED siting decisions and gannet cumulative exposure can guide management actions; and we conclude with suggestions on how the CE model outputs can be used in future CAE assessments. Our assessment takes the first crucial step in addressing the CAE of OWED to gannets and can be directly used to guide site-specific permitting.

Methods

Model Overview

The CE model (Goodale 2018), a geospatial decision-support model that assesses wildlife exposure to alternate development scenarios, was used to assess gannet cumulative exposure to OWED siting decisions along the East Coast of the U.S. The CE model developed an "OWED suitability layer" (areas available for development), placed a wind farm grid within the suitability layer, and spatially joined to the wind farm grid the gannet abundance datasets and three layers representing key OWED siting decisions (hereafter "siting factors"). The first model output was a gannet cumulative exposure curve for different OWED siting decisions. The second output was a cumulative exposure index that ranked which OWED siting decisions will have the greatest influence on gannet cumulative exposure.

Model Inputs

Two independent gannet abundance datasets were used to ensure the robustness of the analysis: satellite telemetry and modeled survey data. The satellite telemetry data, provided by U.S. Fish and Wildlife Service, were collected during a four-year collaborative project with multiple federal, academic, and non-profit institutions

(Spiegel et al. 2017). NOAA provided relative abundance models developed from surveys conducted from 1978-2014 along the entire East Coast of the U.S., which included observations of 17,270 gannets. The gannet population was defined as the total number of birds exposed to the OWED suitability layer; therefore, for this assessment, complete build out of the suitability layer led to 100% exposure of the population.

Both satellite telemetry and survey data were used to estimate gannet population abundance patterns to account for the spatiotemporal variability in gannet distribution and abundance. The telemetry data provided fine resolution data on the movement of individual animals (Hebblewhite and Haydon 2010), allowing for the development of utilization distributions, which were scaled up to predict abundance patterns of a population. Survey data provided count data for the region, which, when related to environmental covariates, was used to predict abundance patterns of the population (Curtice et al. 2016). The satellite data estimated gannet abundance based upon accurate positions of individuals collected over approximately one year, and the modeled survey data estimated abundance by averaging count data over 36 years. By evaluating gannet cumulative exposure from both datasets, we were able to partially account for inter- and intra-annual variability in gannet movements, environmental stochasticity, and deficiencies in each dataset. Using both datasets to triangulate on the siting decisions most likely to influence gannet exposure increased the robustness of our analysis and reduced uncertainty in our evaluation.

Three factors commonly considered in OWED siting were selected as model inputs: distance from shore, bathymetry, and wind speed. Each siting factor chosen as a model input strongly influences where offshore wind farms are sited and are critical considerations in lowering the levelized cost of electricity (LCOE) (Schwartz et al. 2010, Dvorak et al. 2013). The further a project is from shore the greater the costs of the grid connection and construction/maintenance (Jacobsen et al. 2016); the deeper the water the greater the cost of foundations (Musial and Ram 2010); and the higher the wind velocity the greater the power production (Manwell et al. 2009). These siting factors are often not positively correlated, and in some cases have inverse LCOE relationships: wind speed generally increases with distance from shore. Consequently, there is not one optimum siting pattern for developers to use. The siting factors we selected were not intended to be all-inclusive, and stakeholders will consider other political, economic, social, legal, technical, physical, and environmental factors during OWED siting.

Model Process

The spatiotemporal scope of analysis was defined to demarcate areas where birds will be exposed to future wind farm development. The analysis was spatially bound to areas along the East Coast, which is the of focus of the Department of Interior's "Smart from the Start" offshore wind planning process (Farquhar 2011). The CE model was temporally bound by starting at the present, with no wind farms built, and then moved to a nonspecific point in the future when the East Coast has been saturated by OWED. Six exclusion layers and three constraint layers were used in the Boolean map-layering to develop the OWED suitability layer. For each siting factor constraint, Boolean values were chosen that included all possible areas where siting could expose gannets (Table 4.1). Within the OWED suitability layer, a grid was placed representing 300-MW wind farms, comprised of 6-MW turbines (Siemens 2016) spaced 8 rotor diameters apart (Jonkman et al. 2009). The output from the CE model was an OWED suitability layer that had a 450 GW capacity spread over 1,500 wind farms (Figure 4.1).

Gannet abundance data and siting factors were combined to predict gannet cumulative exposure to future OWED. Initially, utilization distributions (UD) were developed from the satellite positions of 46 gannets captured in the mid-Atlantic of the U.S. (Spiegel et al. 2017) using an auto-correlated kernel density estimate method (Fleming and Calabrese 2016). By incorporating autocorrelation into the bandwidth estimate, the final UD has greater smoothing and thus will create a larger overall home range, reducing the potential for a Type II error in our exposure estimate. The NOAA gannet abundance models, developed by NOAA using spatial predictive modeling (Kinlan et al. 2016), did not require further analysis and could be used as inputs into the CE model. Then the gannet abundance models and the three siting factors were spatially joined with the OWED suitability layer and the production capacity was assigned to each wind farm (0.3 GW). The resulting table was ordered in sequence for each siting factor based upon reducing the LCOE (Green and Vasilakos 2011) and for the number of gannets from low to high. The CE model calculated the cumulative exposure for each siting factor and gannet abundance dataset combination for plotting the CE curves and calculating the CE index.

The CE curve plotted the relationship between wildlife cumulative exposure and GW of OWED production from zero OWED to full build-out of the OWED suitability layer. The closer the curve is to the x-axis, the lower the initial rate of exposure, and the closer the curve is to the y-axis, the higher the initial rate of exposure. The CE index for each siting factor combination was developed by subtracting the area below the development factor curve from the area below the wildlife avoidance curve. The maximum value of the CE index is 1. The closer the value is to 1 for a siting factor, the steeper the initial portion of the CE curve and higher the initial rate of cumulative exposure. The greater the statistical range of the CE index, the greater the influence OWED siting decisions will have on cumulative exposure. A low index range indicates that cumulative exposure rates will be similar for gannets regardless of OWED siting decisions.

An ANOVA was used to test if the CE index changed based upon gannet abundance datasets. There was no significant difference between the datasets, which allowed them to be interpreted together and increased the robustness of the analysis. Statistical analysis was performed using R version 3.3.1 (R Core Team 2015).

Results

Our CE model predicted that siting decisions can reduce gannet cumulative exposure rates for initial development of the OWED suitability layer, but for complete build-out no one siting factor consistently reduced exposure (Figure 4.2). The CE curves and index were similar for both the survey and satellite gannet abundance datasets ($F[1,4] = 2.78$, $p = 0.17$), and both datasets had the same range (0.04). The modeled satellite data had a marginally higher CE index (Figure 4.3) because the red avoidance curve is initially closer to the x-axis, indicating there may be more locations available for siting that avoid exposure than the modeled survey data predicted. As complete development is reached, exposing 100% of the gannets, the bathymetry and wind speed CE curves peak earlier with the satellite dataset, suggesting that as wind farms saturate the East Coast, shifting development closer to shore may be more successful at reducing exposure.

With up to ~ 225 GW of OWED, the CE curves suggested that projects sited close to shore and in shallow waters will expose a higher proportion of the gannet population than projects developed in high-wind areas (Figure 4.2). By ~ 225 GW of development, the CE curves converged, indicating that all three siting factors are exposing the same number of birds. As development progressed through the OWED suitability layer to 100% exposure of the gannet population, exposure rates increased steadily as both wind speed and water depth increased, but exposure continued on a linear slope as distance from shore increased. Overall, the CE curves followed a fairly linear, one-to-one relationship for all siting factors, with gannet exposure steadily increasing with each new wind farm developed.

Overall, as development progressed from no wind farms to complete development of the East Coast, there was no particular siting decision that consistently avoided exposing gannets (Figure 4.3). While the CE index indicated that prioritizing building close to shore would expose birds at a slightly higher rate, the low statistical range of the CE index (both abundance datasets) demonstrated that there was little difference between the exposure rates for each siting factor. The small difference in cumulative exposure patterns is caused by gannets' broad distribution along the outer continental shelf. The red avoidance curve, which increased relatively rapidly with OWED, suggests that there are few areas where OWED can be sited without exposing gannets.

Discussion

Gannet abundance along the East Coast of the U.S. is variable as the birds forage throughout the outer continental shelf on surface-schooling pelagic fish (Mowbray 2002, Fifield et al. 2014), which is influenced by environmental conditions (Buchheister et al. 2016). The two gannet abundance datasets had strong agreement and predicted similar exposure patterns for both initial development and complete build-out of the OWED suitability layer. From both an individual movement and regional scale, the datasets indicated gannets are concentrated close to shore in the mid-Atlantic and are only passing through the Gulf of Maine during migration

(Kinlan et al. 2016, Stenhouse et al. 2017). The primary difference between the datasets was that the satellite data indicated slightly more areas with low gannet abundance within the OWED suitability layer than the survey data.

Initially, siting decisions can reduce gannet exposure because of the interrelationships between gannet abundance patterns and OWED siting factors. Gannet abundance is concentrated in coastal areas in the mid-Atlantic (NOAA 2016; Stenhouse 2015), where there is a strong relationship between bathymetry and distance from shore (Williams et al. 2015). In contrast, gannet abundance is lower in the Gulf of Maine (Kinlan et al. 2016), where there is the highest wind resource (Schwartz et al. 2010). Therefore, for initial build-out, siting projects close to shore and in shallower waters will expose gannets at a higher rate than siting projects in the high-wind resource areas located in the Gulf of Maine. This findings is in general agreement with European studies that show gannets will be exposed in higher numbers to OWED in coastal areas (Busch et al. 2013, Garthe et al. 2017).

Once build-out reaches approximately 225 GW, the CE curves converge, suggesting that all scenarios have the same cumulative effect on gannets at this level of build-out. After that point, the scenario of building close to shore becomes the development pathway that has the least cumulative effect. The converging of CE curves indicates that prioritizing a single siting factor through full build-out will not reduce effects. Furthermore, the similar shapes and slopes of the CE curves across siting factors after 225 GW indicates that gannets will be exposed at relatively similar rates regardless of siting decision. This finding reflects the birds' broad distribution throughout the outer continental shelf (Mowbray 2002, Fifield et al. 2014, Stenhouse et al. 2015), and the occurrence of few, if any, locations where wind farms can be sited without gannets. Consequently, we suggest that avoidance mitigation cannot effectively reduce cumulative exposure, and thus cumulative effects for full build-out of the East Coast. Therefore, effective wind farm design measures that reduce collision and displacement risk for all planned and future projects needs to be developed to reduce potential CAE for gannets.

Currently, our CE model only examines exposure. In the future, as knowledge of the effects of habitat loss and collision mortality improves (Busch et al. 2013), the CE model outputs could also be used to estimate effects to the gannet population. Mortality caused by OWED siting decisions could be estimated using a collision risk model (Band 2012, Masden and Cook 2016), and adverse effects caused by displacement could be calculated by developing a model that connects habitat loss to gannet fitness and reproductive success. Combined, this information could feed into a population model, results from which could be used to guide management efforts in current and future permitting efforts to reduce CAE.

Conclusions

Our analysis suggests that siting decisions can reduce gannet exposure rates during the initial build-out phase; however, avoidance will not be effective at mitigating potential CAE with full build-out along the East Coast. Thus, on a project-by-project scale, every design measure should be incorporated to minimize the adverse effects. For example, collision risk could be decreased by reducing lighting and perching sites (USACE 2012, Langston 2013), and displacement risk could be decreased by configuring turbines within a wind farm to provide flight corridors (see Krijgsveld 2014). Ultimately, the most effective CAE mitigation measure for gannets is to minimize the adverse effects of each wind farm to each individual bird.

Table 4.1. Siting factors used as inputs to create OWED suitability layer. "Exclusions" are specific areas of the ocean that have physical hazards, have specific regulatory exclusions (e.g., shipping lanes), or have been identified as having conflict with military activities. "Constraints" are OWED siting considerations that have thresholds beyond which OWED is no longer viable either technologically or economically.

Category	Factor	OWED suitability layer values	LCOE sort order	Data source
Exclusion	Danger zones and restricted areas[1]	All = 0	NA	http://marinecadastre.gov/
Exclusion	Dept. of Defense wind exclusions areas	All = 0	NA	http://marinecadastre.gov/
Exclusion	Ocean disposal sites[2]	All = 0	NA	http://marinecadastre.gov/
Exclusion	Shipping lanes[3]	All = 0	NA	http://marinecadastre.gov/
Exclusion	Unexploded ordnance[4]	All = 0	NA	http://marinecadastre.gov/
Exclusion	State waters as defined by Submerged Lands Act	All = 0	NA	http://marinecadastre.gov/
Constraint	Wind speed	< 7 m/s = 0 > 7 m/s = 1	High to low	http://marinecadastre.gov/
Constraint	Bathymetry	> 200 m = 0 0-199 m = 1	Shallow to deep	http://marinecadastre.gov/
Constraint	Distance from shore	0-5.6 & > 92.6 km = 0 5.6-92.6 km = 1	Close to far	Created using Euclidean distance function in ArcGIS

[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
[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

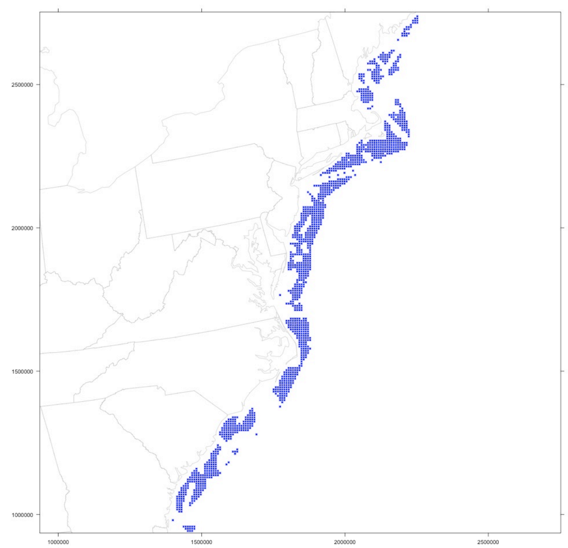
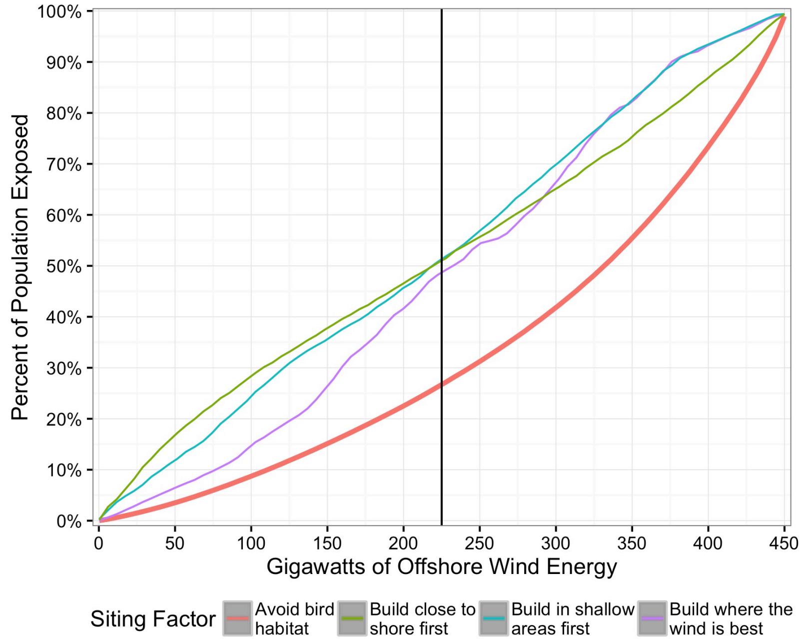


Figure 4.1. OWED suitability layer that represents all areas where wind farms can be built along the East Coast of the U.S.

Modeled Survey Data



Modeled Satellite Data

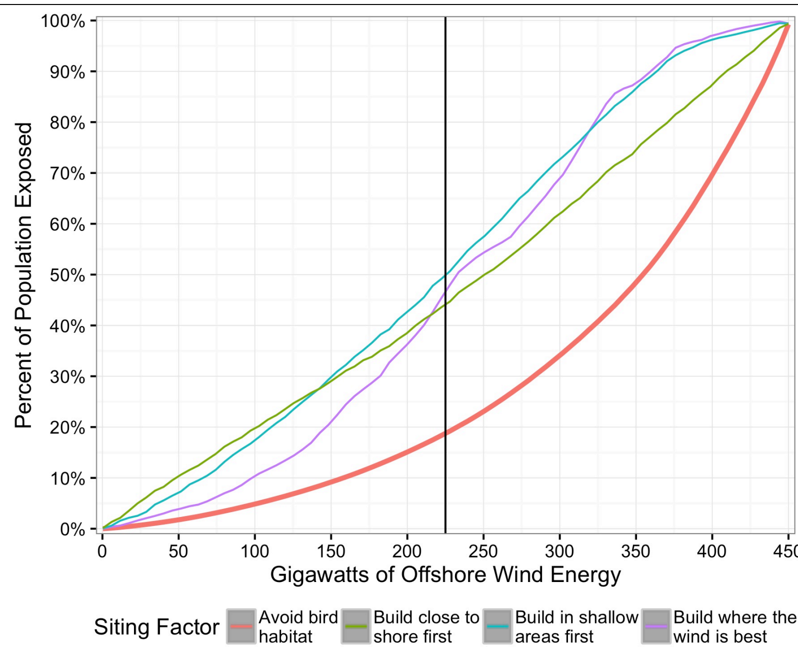


Figure 4.2. Gannet cumulative exposure curves for three siting factors. For the first 225 GW (black line) of development, projects sited close to shore and in shallow waters will expose gannets at a higher proportion of the population than projects developed in high-wind areas; yet, throughout build-out, no one factor consistently reduces exposure.

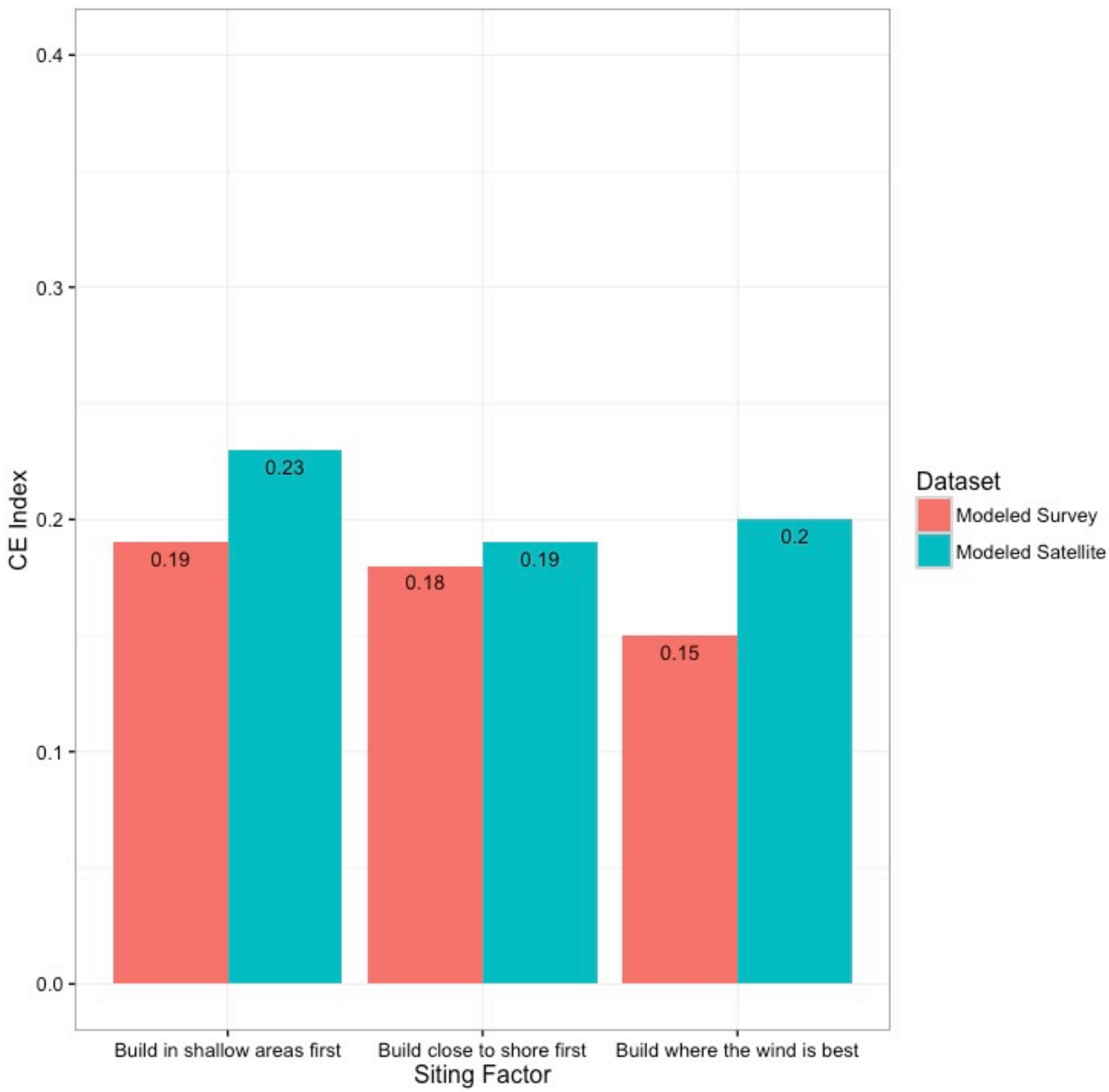


Figure 4.3. CE index values of modeled survey and modeled satellite gannet abundance datasets for three OWED siting factors. Prioritizing building in shallow areas slightly increased gannet exposure rates, but not significantly.

CHAPTER 5

ASSESSING THE CUMULATIVE ADVERSE EFFECTS OF OFFSHORE WIND ENERGY DEVELOPMENT ON SEABIRD FORAGING GUILDS ALONG THE EAST COAST OF THE UNITED STATES

Abstract

Offshore wind farms are rapidly being permitted along the East Coast of the U.S., which could cumulatively affect seabirds. The seabird guilds most likely to be at risk of cumulative effects have not been identified. To address this need, we quantified how three different wind farm siting scenarios would cumulatively expose seven seabird foraging guilds. The coastal bottom gleaner guild would be exposed at similar rates regardless of siting decision, while other coastal guilds would be exposed at high rates when projects are built in shallow areas and close to shore. 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 reduces cumulative exposure for all guilds.

Introduction

Offshore wind energy development is rapidly expanding along the East Coast of the U.S. The first U.S. offshore wind farm began operating in 2016 (Deepwater Wind 2016) and marine development areas for offshore wind energy have been leased from Maine to North Carolina (BOEM 2018). The U.S. federal government is planning for 86 GW of offshore wind to be installed by 2050 (DOE 2016), with hundreds of wind turbines installed during the next decade (Goodale and Milman 2016).

Globally, governments are pursuing offshore wind to address climate change (Ram 2011), but wind farms also have the potential to adversely affect seabirds (Langston 2013). Research in Europe has found that offshore wind farms can adversely affect seabirds in two ways: through direct mortality and through 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). Such mortalities were recorded at wind turbines built adjacent to tern and gull colonies (Everaert and Stienen 2007). Displacement occurs when birds consistently avoid wind farms that 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). This macro-avoidance 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).

Though the adverse effects of an individual wind farm are important, of greater concern is how the development of multiple future offshore wind farms along the East Coast of the U.S. will cumulatively affect seabird populations. U.S. laws and regulations require assessment of these cumulative adverse effects (CAE) during the permitting process (CEQ 1997; Hyder 1999; Hegmann et al. 1999; Cooper 2004). CAE assessments must determine the effects to seabird populations from each new wind farm combined with effects from past, present, and reasonably foreseeable future actions (40 C.F.R. §1508.7).

The CAE of offshore wind farm development will depend on how the location of offshore wind farm development interacts with seabird use areas. Seabird guild distributions are heterogeneous and species will be differentially exposed depending on their foraging, reproductive, and migratory strategy. Coastal birds (e.g., gulls) typically forage within sight of land, while inshore species (e.g., terns, auks) feed out of sight of land but within the continental shelf of the East Coast. Pelagic species (e.g., petrels and shearwaters) 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).

Understanding the relationship between seabird guild exposure and wind farm siting decisions is necessary to support CAE assessments and develop effective mitigation measures (Drewitt and Langston 2006). Avoidance 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 at risk while increasing exposure for other groups.

To date, there has been no research relating exposure of seabird guilds to future wind farm siting. This paper addresses this gap by answering two questions: which seabird guilds are most likely to be at risk of CAE from such development and could any set of wind farm siting decisions serve to reduce CAE for all 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 2018). Below we describe the CE model process and present the results of the modeling analysis. We then use this information to examine the relationships between siting decisions and seabird guild exposure. We identify guilds most likely to be cumulatively exposed and recommend a process to minimize CAE for multiple guilds. This assessment is an important step in reducing the CAE of offshore wind energy development on seabirds as it 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

The CE model (Goodale 2018), a geospatial decision-support model that assesses wildlife exposure to alternate offshore wind development scenarios, was used to assess the cumulative exposure of seven seabird guilds to three offshore wind energy development (OWED) siting scenarios along the East Coast of the U.S. The CE model estimates the locations of all potential wind farms in an area and then assesses how different future wind farm development decisions would incrementally expose each seabird guild. As detailed below, the CE model identified areas available for development ("OWED suitability layer"), and then used that layer to create scenarios of how potential wind farm build out may occur. The model then overlays seabird abundance datasets with the wind farm build out scenarios to evaluate exposure.

OWED suitability layer

The OWED suitability layer was developed to bound the analysis to areas where seabirds would likely be exposed to future wind farm development. The suitability layer was spatially bound 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 the Boolean map-layering to develop the OWED suitability layer (Table 5.1). The Boolean values chosen included all possible areas where siting could expose the seabird guilds. A wind farm grid, representing 300-MW wind farms, was placed in the OWED suitability layer. The grid was developed using 6-MW turbines (Siemens 2016) that were spaced 8 rotor diameters apart (Jonkman et al. 2009). The final OWED suitability layer had a 450-GW capacity (Figure 5.1).

OWED build-out scenarios

Wind farm siting is a tradeoff between distance from shore, bathymetry, and wind speed as well as other environmental and socioeconomic factors. Increased distance from shore and greater water depth strongly influence 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 has the potential to 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 farms remains unknown because there is no single offshore wind farm siting strategy that optimizes LCOE. This uncertainty around future development provides an opportunity to site projects in a manner that reduces both the LCOE and the exposure of seabird guilds most at risk to development.

Three siting factors (i.e., key elements considered when siting offshore wind farms) were spatially joined with the OWED suitability layer and the 300-MW production capacity was assigned to each wind farm. The selected siting factor model inputs were distance from shore, bathymetry, and wind speed, which all strongly influence the cost of developing offshore wind farms (i.e., LCOE)(Schwartz et al. 2010, Dvorak et al. 2013). Generally, the further a project is from shore, the greater the costs

(Jacobsen et al. 2016); the deeper the water, the greater the costs (Musial and Ram 2010); and the higher the wind velocity, the greater the power production (Manwell et al. 2009) and the lower the overall project costs.

Seabird abundance

Seabird abundance models for 36 species (Table 5.2) were spatially joined with the OWED suitability layer. The seabird abundance estimates were developed by the National Oceanic and Atmospheric Administration (NOAA) from survey data collected from 1978-2014 along the entire East Coast of the U.S. using spatial predictive modeling (Kinlan et al. 2016). Audubon Shearwater (*Puffinus lherminieri*), Black-capped Petrel (*Pterodroma hasitata*), Black Guillemot (*Cepphus grylle*), and Common Eider (*Somateria mollissima*) were excluded from the analysis due to errors identified in the abundance models (Curtice et al. 2016). The individual species were binned into guild groupings relevant to offshore wind siting (Table 5.2) based upon foraging guilds described by De Graaf et al. (1985) and foraging strategies identified in species accounts (Rodewald 2015). Due to comparable foraging strategies, species within the same guild generally have similar vulnerabilities to offshore wind farms (Furness et al. 2013, Wade et al. 2016) and may be similarly exposed to development. 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). These guilds encompass all guilds likely to be exposed to offshore wind farms along the East Coast.

The seabird populations were defined as the total number of birds included in the NOAA models (Figure 5.1); therefore, depending upon the spatial distribution of each species, complete build-out of the suitability layer exposed varying proportions of the population. The proportion of each species' population within each wind farm was calculated along with the average for each guild to provide a generalized exposure metric. The table that resulted from the spatial join was ordered sequentially, for each siting factor, to reflect the lowest LCOE (Green and Vasilakos 2011), and for each species and guild from low to high abundance. The CE model calculated the cumulative exposure for species and guild/siting factor combination for plotting the CE curves and calculating the CE index.

Model Outputs

The model outputs were a cumulative exposure curve for each seabird guild/siting factor combination and a cumulative exposure index that identified the siting decisions that had the greatest influence on seabird cumulative exposure. The CE curve plotted 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 was to the y-axis, the higher the initial rate of exposure; the closer the curve was 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. The CE index for each species/siting factor combination was developed by subtracting the area below the development factor curve from the area below the avoidance curve. The closer the CE index is to 1 for a siting factor, 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 factor, while also providing insight into which siting factors will expose the birds the most.

While the curves can be interpreted at any point of development, 86 GW of development was selected as a point to estimate guild exposure to siting factors because it represents ~20% of the OWED suitability layer and DOE's 2050 scenario. The guild exposure patterns for full development of the OWED suitability layer were evaluated by viewing the relationship between siting factor and avoidance curves, and with box-plots displaying the distribution of the CE index by siting factor, with each box representing all species within a guild. All plots were developed using R version 3.3.1 (R Core Team 2015).

Results

Our 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 (Figure 5.2 & 5.3). For the first 86 GW of development (~20% of the OWED suitability layer), 8-14% of the coastal bottom gleaner populations 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 are exposed to projects sited close to shore and in shallow water, and 1-2% of the populations are exposed to projects built in high-wind areas. For the pelagic guilds, siting in shallow areas exposed <1% of the populations; siting close to shore exposed 1-3% of the populations; and siting in high-wind areas exposed 2-5% of the populations. For full development of the OWED suitability layer, the proportion of the populations 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.

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 5.3). 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 the wind speed curve did not follow the avoidance curve, and beyond ~75 GW of development exposure rapidly increased in high-wind areas. 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, 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. Of the pelagic guilds, the pelagic surface gleaners had the least difference between the CE curves because the guild is comprised of species with northerly and southerly biased distributions.

Discussion

Our CE 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 factors yield opposite exposure patterns for coastal and pelagic guilds.

The relationships between guild exposure and siting factor are partially driven by the two dominant spatial trends in the siting factor data that align with seabird distributions: near-shore to offshore and north to south. 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 consistently 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 directly south of Cape Cod, Massachusetts, an area heavily used by sea ducks. Consequently, a high percentage of the coastal bottom gleaner populations in this area will be exposed to both initial and full 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).

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 (Kinlan et al. 2016). Due to the assumptions used to create the OWED suitability layer, the CE model predicts wind farm development to avoid many offshore concentrations of pelagic birds. 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 5.4). The tiers are ordered from higher to lower likelihood of CAE based upon guild cumulative exposure patterns and evidence of vulnerability to adverse effects of offshore wind farms. 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 most 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 adversely 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, Furness et al. 2013, Dierschke et al. 2016). Some coastal diver species are vulnerable to displacement and others are vulnerable to collision: Red-throated Loons (*Gavia stellata*) are documented to be permanently displaced by wind farms (Percival 2010, Lindeboom et al. 2011); Common Loons (*Gavia immer*) are predicted to have high displacement vulnerability (Furness et al. 2013); and Double-crested Cormorants (*Phalacrocorax auritus*) are considered 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 (Furness et al. 2013), and Northern Gannet (*Morus bassanus*) is vulnerable to collision as well as displacement (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 no documented vulnerability 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.

From our CE model outputs and a visual assessment of the NOAA abundance models (Northeast Ocean Data Portal 2018), we predict that exposure can be reduced for Tier 1 guilds by siting projects either offshore; in the Gulf of Maine; or in the region from the Wind Energy Area (WEA) in Massachusetts to the central point of Long

Island. Exposure can be reduced for Tier 2 guilds by siting projects offshore, and for Tier 3 and 4 guilds by siting in shallow areas and south of Long Island.

However, 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). Recent and ongoing survey efforts along the East Coast of the U.S. now make regional hotspot mapping possible (Winiarski et al. 2014, Veit 2015, Williams et al. 2015, GOMCES 2016, NYSERDA 2016, Veit et al. 2016). Hotspots should be identified first for species in Tier 1 and 2, which are more likely to experience CAE.

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 separated. 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 rather than additional ones between Massachusetts and New Jersey.

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.

Table 5.1. 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	OWED suitability layer values	LCOE sort order	Data source
Exclusion	Danger zones and restricted areas[1]	All = 0	NA	http://marinecadastre.gov/
Exclusion	Dept. of Defense wind exclusions areas	All = 0	NA	http://marinecadastre.gov/
Exclusion	Ocean disposal sites[2]	All = 0	NA	http://marinecadastre.gov/
Exclusion	Shipping lanes[3]	All = 0	NA	http://marinecadastre.gov/
Exclusion	Unexploded ordnance[4]	All = 0	NA	http://marinecadastre.gov/
Exclusion	State waters as defined by Submerged Lands Act	All = 0	NA	http://marinecadastre.gov/
Constraint	Wind speed	< 7 m/s = 0 > 7 m/s = 1	High to low	http://marinecadastre.gov/
Constraint	Bathymetry	> 200 m = 0 0-199 m = 1	Shallow to deep	http://marinecadastre.gov/
Constraint	Distance from shore	0-5.6 & > 92.6 km = 0 5.6-92.6 km = 1	Close to far	Created using Euclidean distance function in ArcGIS

[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

[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

Table 5.2. 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*

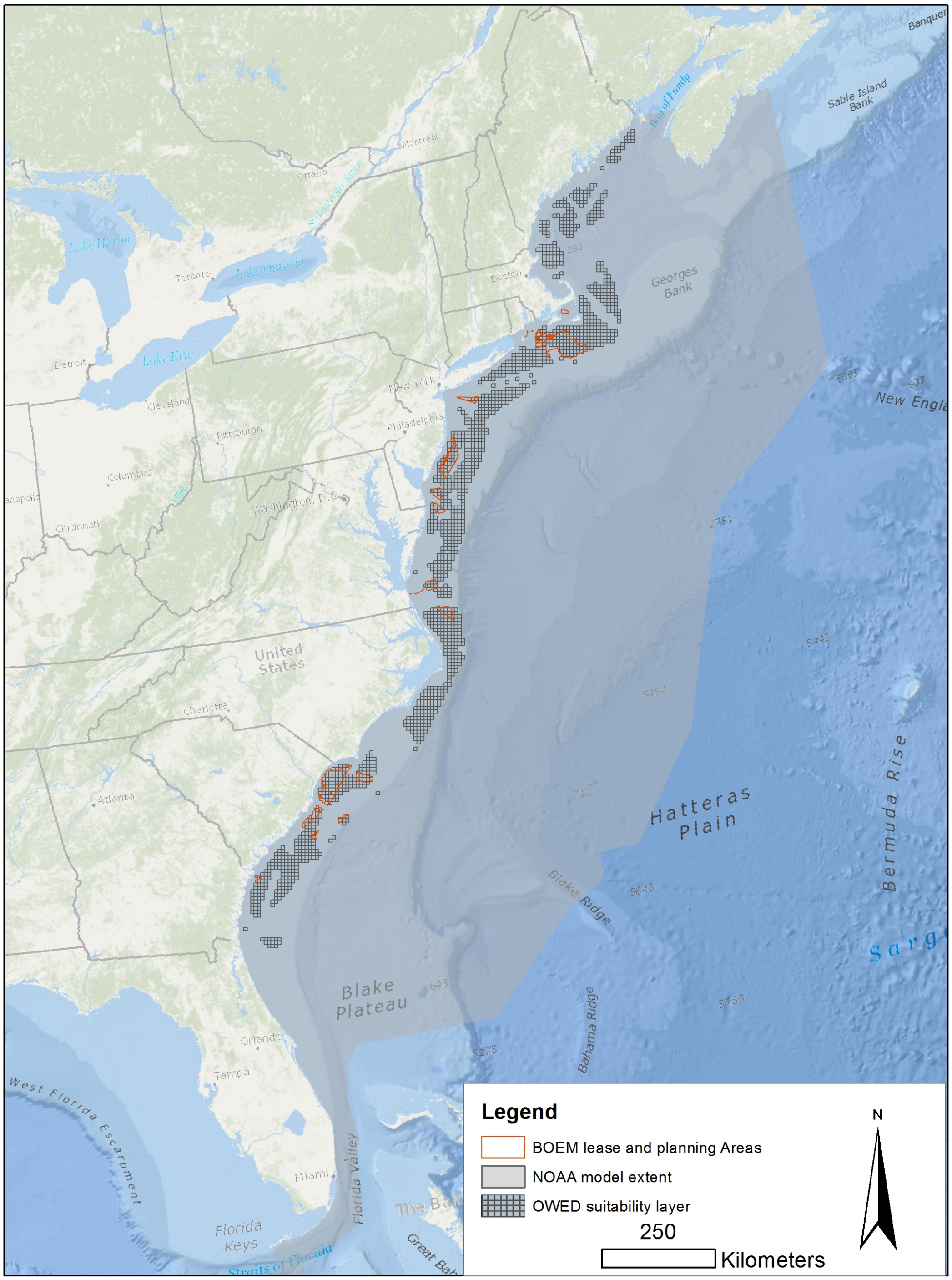
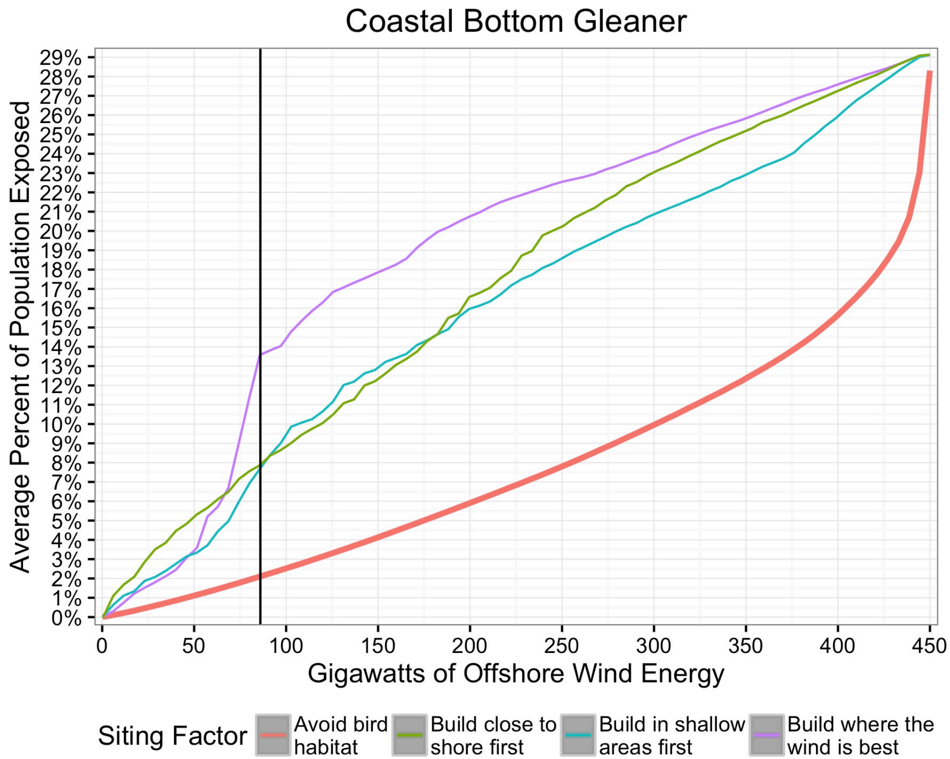
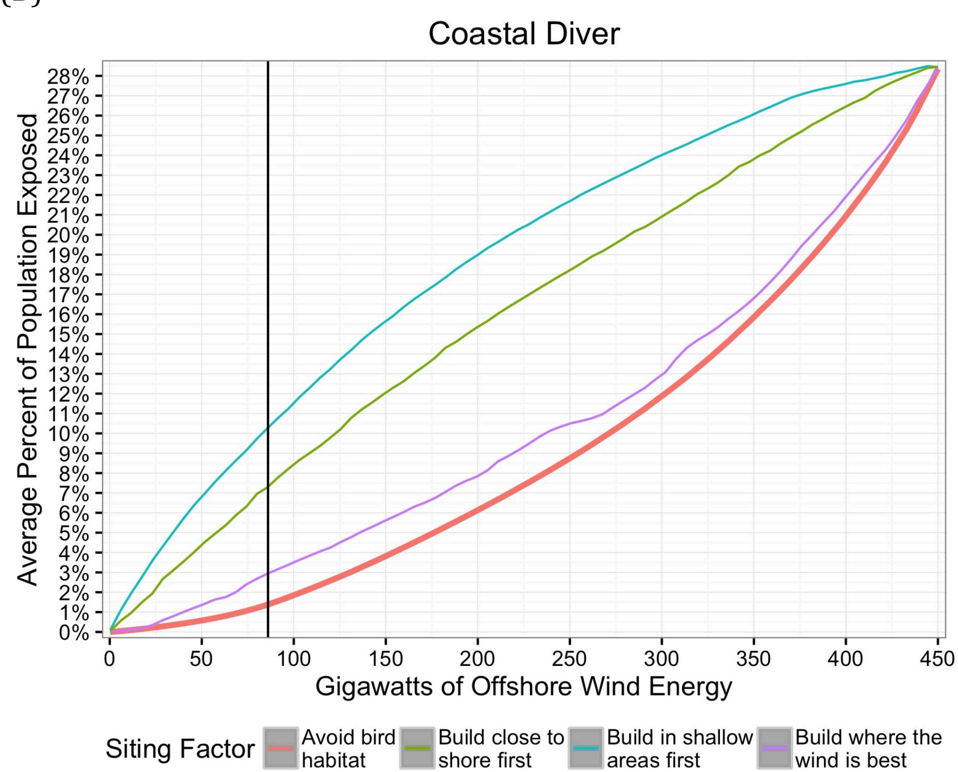


Figure 5.1. OWED suitability layer that represents all areas where wind farms can be built along the East Coast of the U.S. and the full coverage area of the NOAA models used to define the population in the analysis.

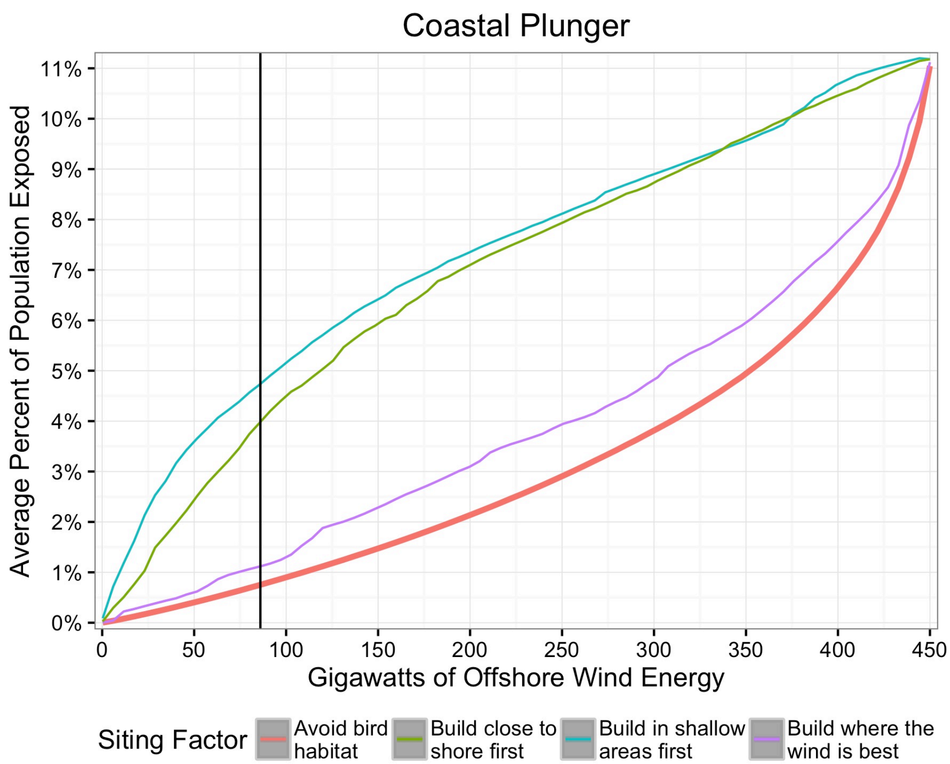
(A)


Coastal Bottom Gleaner
Average Percent of Population Exposed
0% 1% 2% 3% 4% 5% 6% 7% 8% 9% 10% 11% 12% 13% 14% 15% 16% 17% 18% 19% 20% 21% 22% 23% 24% 25% 26% 27% 28% 29%
0 50 100 150 200 250 300 350 400 450
Gigawatts of Offshore Wind Energy
Siting Factor
Avoid bird habitat
Build close to shore first
Build in shallow areas first
Build where the wind is best

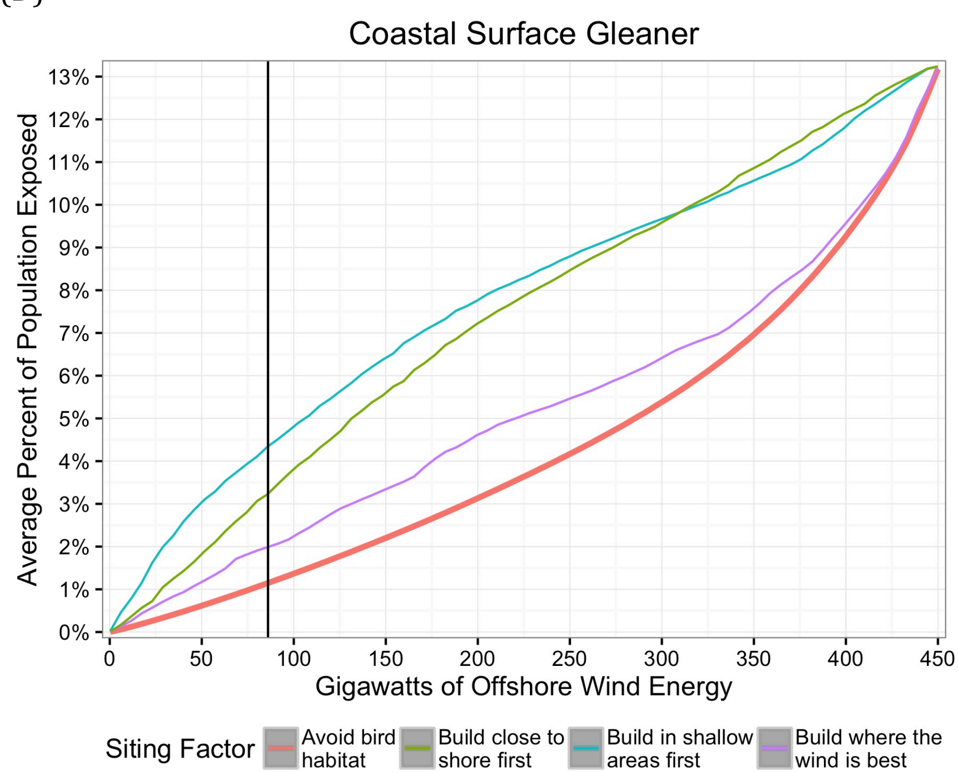
(B)


Coastal Diver
Average Percent of Population Exposed
0% 1% 2% 3% 4% 5% 6% 7% 8% 9% 10% 11% 12% 13% 14% 15% 16% 17% 18% 19% 20% 21% 22% 23% 24% 25% 26% 27% 28%
0 50 100 150 200 250 300 350 400 450
Gigawatts of Offshore Wind Energy
Siting Factor
Avoid bird habitat
Build close to shore first
Build in shallow areas first
Build where the wind is best

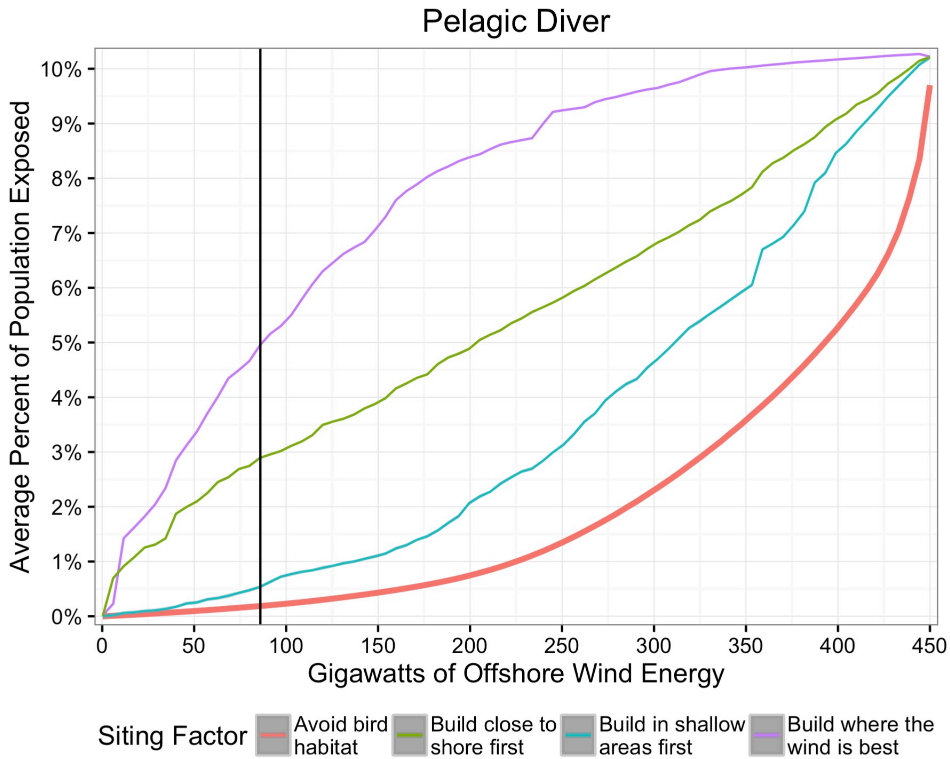
(C)


Coastal Plunger
Average Percent of Population Exposed
11%
10%
9%
8%
7%
6%
5%
4%
3%
2%
1%
0%
0
50
100
150
200
250
300
350
400
450
Gigawatts of Offshore Wind Energy
Siting Factor
Avoid bird habitat
Build close to shore first
Build in shallow areas first
Build where the wind is best

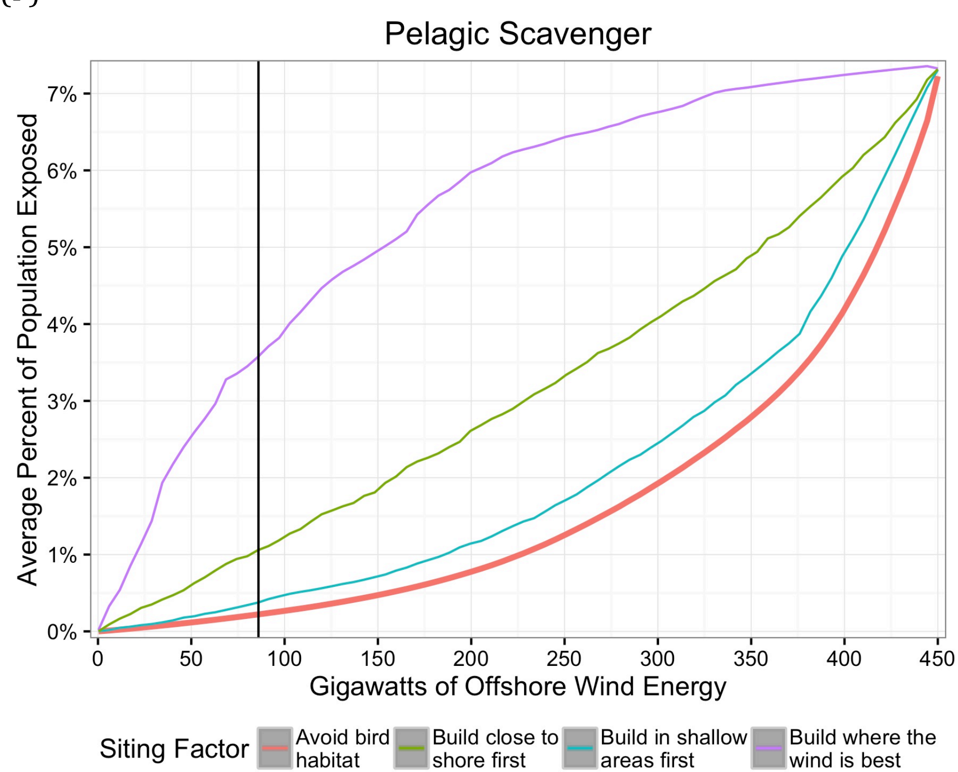
(D)


Coastal Surface Gleaner
Average Percent of Population Exposed
13%
12%
11%
10%
9%
8%
7%
6%
5%
4%
3%
2%
1%
0%
0
50
100
150
200
250
300
350
400
450
Gigawatts of Offshore Wind Energy
Siting Factor
Avoid bird habitat
Build close to shore first
Build in shallow areas first
Build where the wind is best

(E)


Pelagic Diver
Average Percent of Population Exposed
10%
9%
8%
7%
6%
5%
4%
3%
2%
1%
0%
0
50
100
150
200
250
300
350
400
450
Gigawatts of Offshore Wind Energy
Siting Factor
Avoid bird habitat
Build close to shore first
Build in shallow areas first
Build where the wind is best

(F)


Pelagic Scavenger
Average Percent of Population Exposed
7%
6%
5%
4%
3%
2%
1%
0%
0
50
100
150
200
250
300
350
400
450
Gigawatts of Offshore Wind Energy
Siting Factor
Avoid bird habitat
Build close to shore first
Build in shallow areas first
Build where the wind is best

(G)

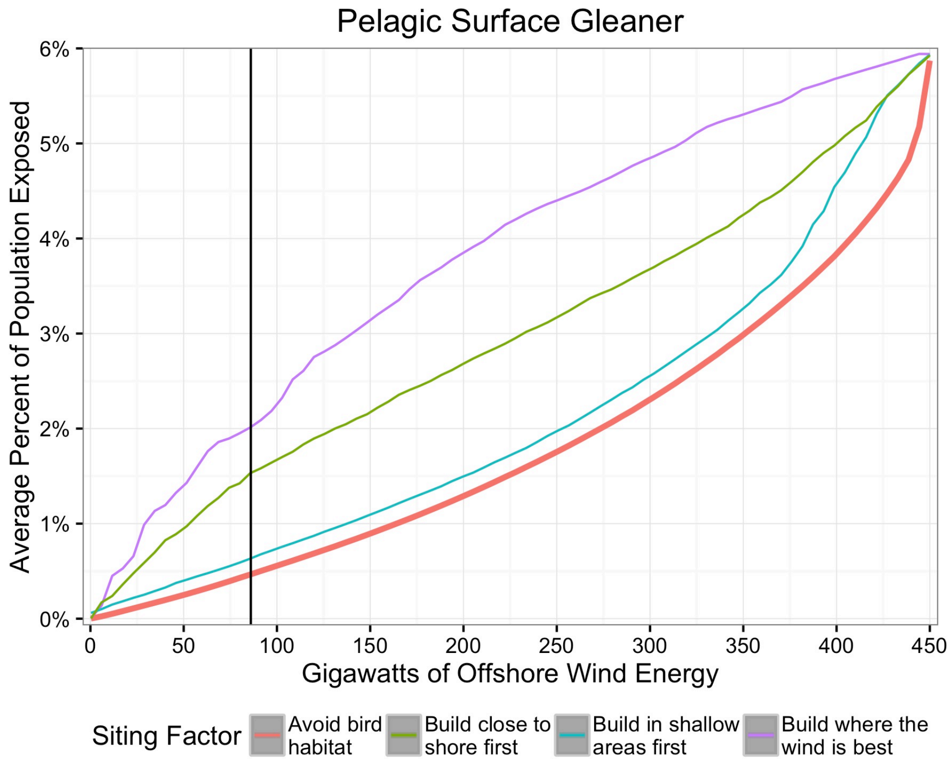


Figure 5.2. (A-G). Relationships between siting factors and guilds. The y-axis scale varies for each graph because the maximum exposure of a guild is dictated by a guild's species composition. The black vertical line represents 86 GW (~20% development of OWED suitability layer). With the exception of 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.

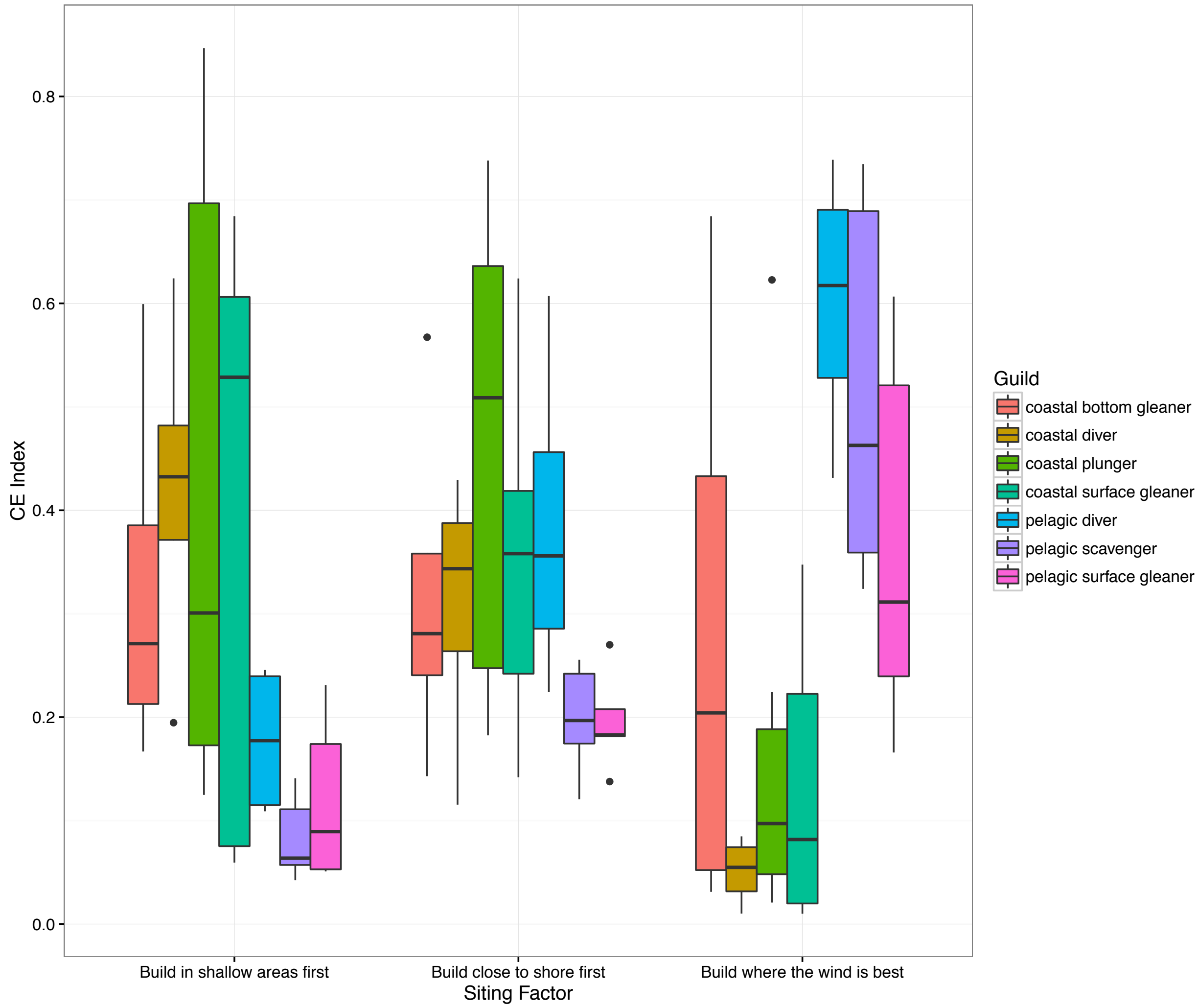


Figure 5.3. Distribution of the CE index by guild for each OWED siting factor. The results indicated that pelagic seabird guilds will be exposed at higher rates when projects are built in high-wind areas while coastal seabird guilds will be exposed at higher rates when projects are built in shallow areas. Distance from shore had the least influence on exposure.

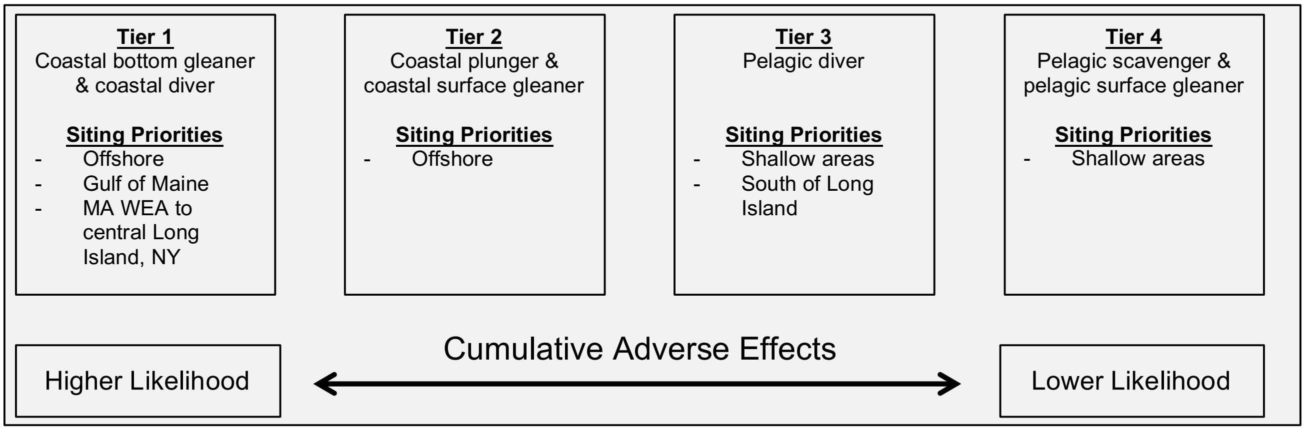


Figure 5.4. Seabird guild tiers to be considered during CAE assessments, and siting priorities to reduce exposure. Tier 1 & 2 guilds have the highest likelihood of CAE because of relatively high cumulative exposure to offshore wind farms along the East Coast of the U.S. and documented vulnerability to 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 because of low cumulative exposure rates and no documented vulnerability to offshore wind farms.

CHAPTER 6
CONCLUSIONS

Our research has provided new insight into how to frame, assess, evaluate, and manage the cumulative adverse effects (CAE) of offshore wind farms on wildlife. In Chapter 2 we framed CAE; in Chapter 3 we developed a novel method to assess CAE by assessing cumulative exposure; in Chapter 4 we assessed cumulative exposure of a vulnerable species; and in Chapter 5 we evaluated which seabirds guilds are most likely at risk of CAE.

We framed CAE as the exposure of vulnerable species to multiple hazards through space and time. Through our assessment we identified that no one offshore wind farm siting scenario along the East Coast of the U.S. can reduce cumulative exposure for all seabird guilds and species simultaneously. These results suggest that, aside from avoiding persistent aggregations of seabirds, siting has limited utility in reducing cumulative exposure.

We evaluated the likelihood of a seabird guild being at risk of CAE based upon guild cumulative exposure patterns and evidence of vulnerability to adverse effects of offshore wind farms. We identified that CAE is most likely for coastal bottom gleaners (seaducks) and coastal divers (loons, cormorants, and grebes), which are identified as being vulnerable to displacement and potential habitat loss; as well as for coastal plungers (terns, pelican, gannet) and coastal surface gleaners (gulls), which are vulnerable to collision. CAE is less likely for pelagic species that had lower overall exposure offshore to wind farm development along the East Coast and less evidence of vulnerability. The evaluation suggests that cumulative habitat loss may be a greater concern than cumulative collision mortality.

Our results demonstrate that no one siting decision can avoid exposing all the guilds when the suitability layer is saturated with wind farms. However, assuming that all areas suitable for offshore wind farms will not be built, we recommend the following siting process to reduce CAE across multiple guilds: 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.

The first siting decision is to avoid persistent aggregations of seabirds in areas with high food availability (i.e., “hotspots”). Avoiding hotspots will reduce potential adverse effects to birds by directing development into areas of lower conservation value. Next, wind farms should be dispersed throughout all areas suitable for wind farm development rather than clumped in certain areas. Dispersing development north to south and from near-shore to offshore will spread cumulative exposure over all species. While all species would be exposed at some level, the assumption is that the exposure rate for any one species would not lead to levels of cumulative mortality or cumulative habitat loss that would adversely affect the population. If projects are clumped, then the exposure will be significantly higher for some species and lower or non-existent for other species.

Next, wind farms should be sited with the greatest possible distance between them. Greater distance will primarily ensure that collision mortality is not concentrated among the sub-populations of individual species, and will potentially provide movement corridors between the wind farms. Dispersing development has the potential to increase the levelized cost of electricity because concentrated development allows for economies of scale, but siting strategies that reduce the CAE on seabirds will likely increase the public acceptance of projects, reduce pre- and post-monitoring required by regulators, and increase certainty for developers.

Overall, the research presented in this dissertation has increased the understanding of the CAE of offshore wind energy on wildlife and can be used to inform decision-making. The research can be used to support project-specific environmental impact statements by providing a spatial scope for assessments; providing insight into the efficacy of avoidance mitigation; and identifying which species groups are more likely to be at risk of CAE and thus should be the focus of mitigation efforts. The CE model can be used to support the identification of future Wind Energy Areas by identifying areas that reduce the levelized cost of electricity while decreasing exposure for species more likely to be at risk of CAE. In the future, the CE model could be used to analyze the exposure of other taxonomic groups such as marine mammals, sea turtles, and fish in order to assess if there are wind farm development scenarios that simultaneously increase or decrease the cumulative exposure across such groups.

The challenge now is to relate cumulative exposure to effects on populations by using collision risk models and modeling the effects of habitat loss. The difficulty is that there are assumptions in the CE model, in collision risk models, and in population models, as well as uncertainty around how to assess the adverse effects of habitat loss, all of which increase error in a population risk assessment. A further complication is that a full CAE assessment should include all heterotypic stressors such as climate change, overfishing, and plastic pollution. Understanding how all these stressors combine to affect populations could only be accomplished with estimates of the mortality caused by each stressor as well as precise knowledge of species-specific population numbers and vital rates. We will likely never have the capability, resources, or knowledge to make such calculations, and thus will not be able to truly quantify CAE. Consequently, an assessment of CAE that converts cumulative exposure to CAE, and includes all heterotypic stressors, must be qualitative and will be subjective.

Embracing the subjective nature of CAE is critical for a transparent process as we move from assessing to evaluating to managing CAE. Our research takes the first step towards an informed qualitative assessment by providing stakeholders with metrics on how different OWED patterns will cumulatively expose wildlife.

APPENDIX A

R PACKAGES (LIBRARIES) USED IN THE CE MODEL

Package	Function	Citation
snow	Parallel processing	Luke Tierney, A. J. Rossini, Na Li and H. Sevcikova (2016). snow: Simple Network of Workstations. R package version 0.4-2. https://CRAN.R-project.org/package=snow
snowfall	Parallel processing	Jochen Knaus (2015). snowfall: Easier cluster computing (based on snow).. R package version 1.84-6.1. https://CRAN.R-project.org/package=snowfall
ggplot2	Plotting	H. Wickham. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York, 2009.
plyr	Data manipulation	Hadley Wickham (2011). The Split-Apply-Combine Strategy for Data Analysis. Journal of Statistical Software, 40(1), 1-29. URL http://www.jstatsoft.org/v40/i01/.
dplyr	Data manipulation	Hadley Wickham and Romain Francois (2016). dplyr: A Grammar of Data Manipulation. R package version 0.5.0. https://CRAN.R-project.org/package=dplyr
data.table	Data manipulation	M Dowle, A Srinivasan, T Short, S Lianoglou with contributions from R Saporta and E Antonyan (2015). data.table: Extension of Data.frame. R package version 1.9.6. https://CRAN.R-project.org/package=data.table
flux	Data calculations	Gerald Jurasinski, Franziska Koebsch, Anke Guenther and Sascha Beetz (2014). flux: Flux rate calculation from dynamic closed chamber measurements. R package version 0.3-0. https://CRAN.R-project.org/package=flux
GISTools	GIS	Gerald Jurasinski, Franziska Koebsch, Anke Guenther and Sascha Beetz (2014). flux: Flux rate calculation from dynamic closed chamber measurements. R package version 0.3-0. https://CRAN.R-project.org/package=flux
raster	GIS raster	Robert J. Hijmans (2016). raster: Geographic Data Analysis and Modeling. R package version 2.5-8. https://CRAN.R-project.org/package=raster
rgdal	GIS	Roger Bivand, Tim Keitt and Barry Rowlingson (2016). rgdal: Bindings for the Geospatial Data Abstraction Library. R package version 1.1-10. https://CRAN.R-project.org/package=rgdal
sp	GIS	Pebesma, E.J., R.S. Bivand, 2005. Classes and methods for spatial data in R. R News 5 (2), http://cran.r-project.org/doc/Rnews/.
rgeos	GIS	Roger Bivand and Colin Rundel (2016). rgeos: Interface to Geometry Engine - Open Source (GEOS). R package version 0.3-21. https://CRAN.R-project.org/package=rgeos
ggmap	GIS	D. Kahle and H. Wickham. ggmap: Spatial Visualization with ggplot2. The R Journal, 5(1), 144-161. URL http://journal.r-project.org/archive/2013-1/kahle-wickham.pdf
gridExtra	Graphics	Baptiste Auguie (2016). gridExtra: Miscellaneous Functions for "Grid" Graphics. R package version 2.2.1. https://CRAN.R-project.org/package=gridExtra
dismo	Species distribution mapping	Robert J. Hijmans, Steven Phillips, John Leathwick and Jane Elith (2016). dismo: Species Distribution Modeling. R package version 1.1-1. https://CRAN.R-project.org/package=dismo
pastecs	Analysis of space-time data	Philippe Grosjean and Frederic Ibanez (2014). pastecs: Package for Analysis of Space-Time Ecological Series. R package version 1.3-18. https://CRAN.R-project.org/package=pastecs
ctmm	Movement modeling	Chris H. Fleming and J. M. Calabrese (2016). ctmm: Continuous-Time Movement Modeling. R package version 0.3.3.

Package	Function	Citation
		https://CRAN.R-project.org/package=ctmm
move	Movement modeling	Bart Kranstauber and Marco Smolla (2016). move: Visualizing and Analyzing Animal Track Data. R package version 2.1.0. https://CRAN.R-project.org/package=move
effects	GLM plotting	John Fox (2003). Effect Displays in R for Generalised Linear Models. Journal of Statistical Software, 8(15), 1-27. URL http://www.jstatsoft.org/v08/i15/.
multcomp	Statistical analysis	Torsten Hothorn, Frank Bretz and Peter Westfall (2008). Simultaneous Inference in General Parametric Models. Biometrical Journal 50(3), 346--363.
piecewiseSEM	Statistical analysis	Lefcheck, Jonathan S. (2015) piecewiseSEM: Piecewise structural equation modeling in R for ecology, evolution, and systematics. Methods in Ecology and Evolution. 7(5): 573-579. DOI: 10.1111/2041-210X.12512

APPENDIX B
CE INDEX BY SPECIES

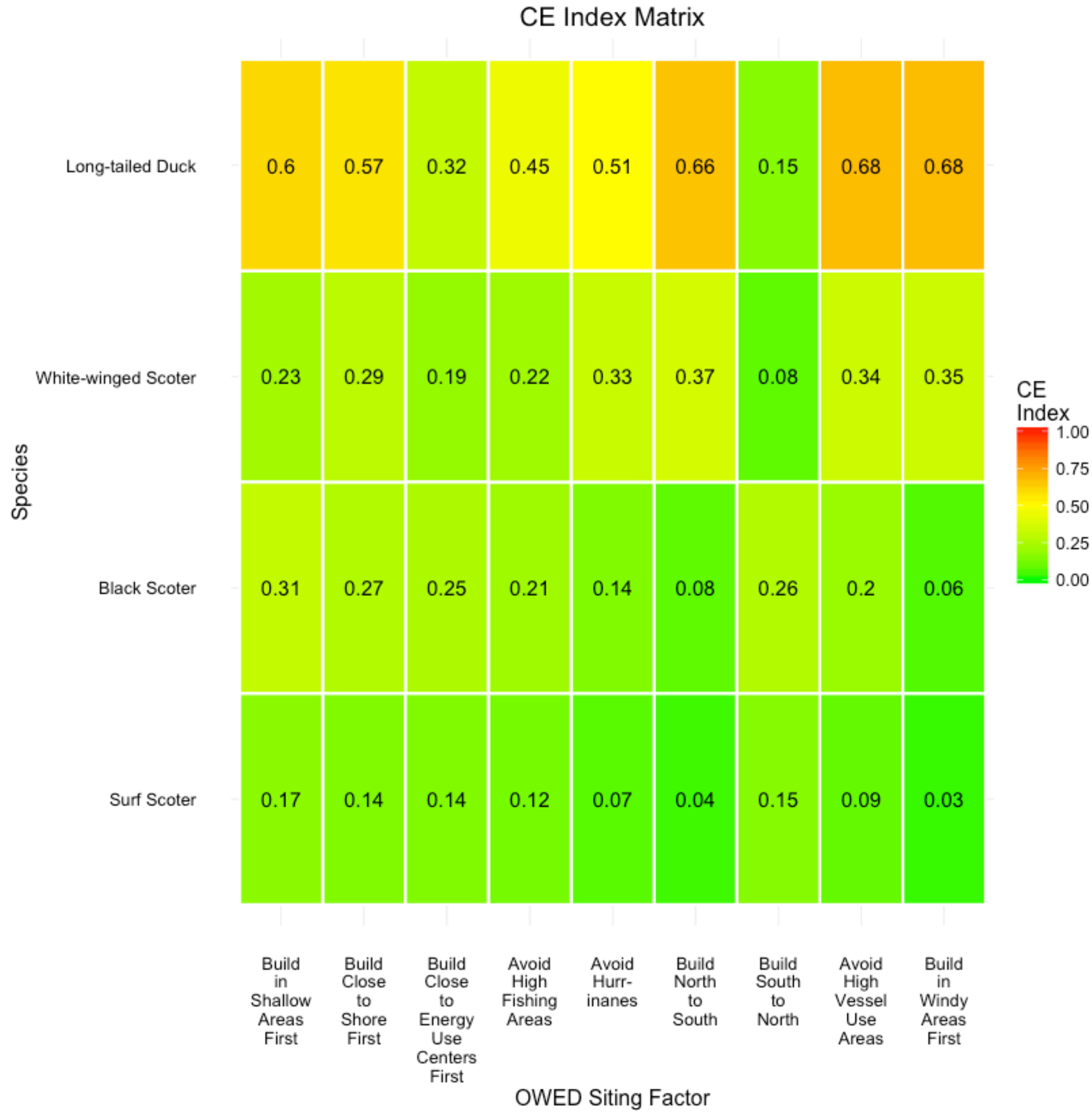
We used the CE model (detailed in Chapter 2) to assess the cumulative exposure of 36 seabird species (Chapter 4) to seven OWED siting factors (Table 1). The siting factors included physical constraints as well as decisions factors (additional factors stakeholders consider during wind farm siting). We also calculated the CE index for a development scenario beginning in the north and ending in the south as well as beginning in the south and ending in the north to provide insight into the latitudinal relationships between siting factors and seabird abundance. The species-specific results are grouped by foraging guild: 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).

Table 1. Siting factors used to develop the CE index. “Constraints” are OWED siting considerations that have thresholds beyond which OWED is no longer viable either technologically or economically. “Decision factors” are factors that will influence, but not dictate, where developers consider siting OWED projects.

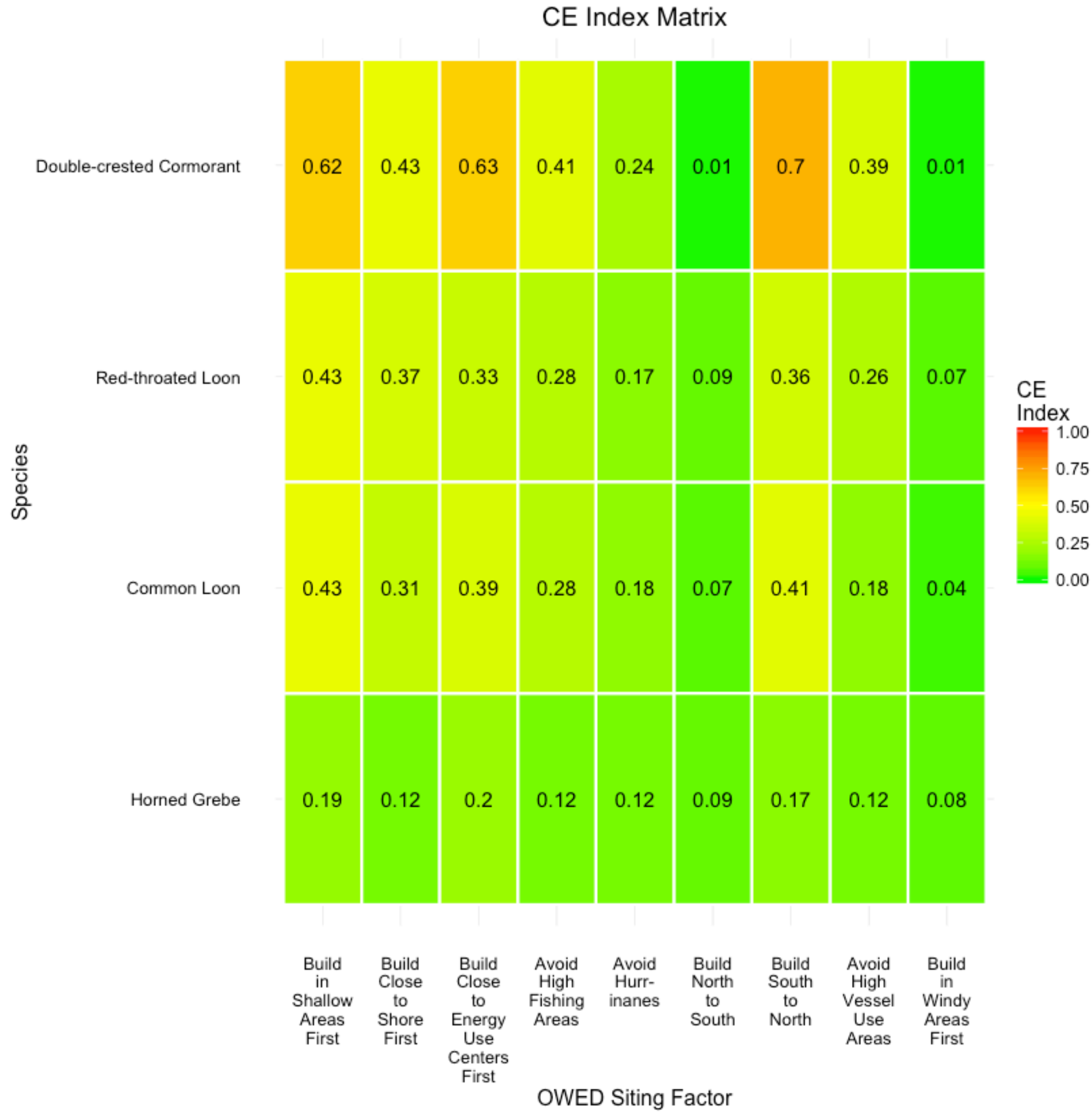
Category	**Factor**	**LCOE* sort order**	**Data source**
Constraint	Wind speed	High to low	http://marinecadastre.gov/
Constraint	Bathymetry	Shallow to deep	http://marinecadastre.gov/
Constraint	Distance from shore	Close to far	Created using Euclidean distance function in ArcGIS (ESRI 2016)
Decision factor	Tropical cyclone exposure	Low to high	http://marinecadastre.gov/
Decision factor	Energy use	High to low	www.census.gov/ and http://www.eia.gov/state/
Decision factor	Atlantic fishing revenue intensity	Low to High	http://marinecadastre.gov/
Decision factor	2011 Vessel traffic (AIS)	Low to High	http://marinecadastre.gov/

*The order development factors are sorted to reduce the levelized cost of electricity (LCOE)

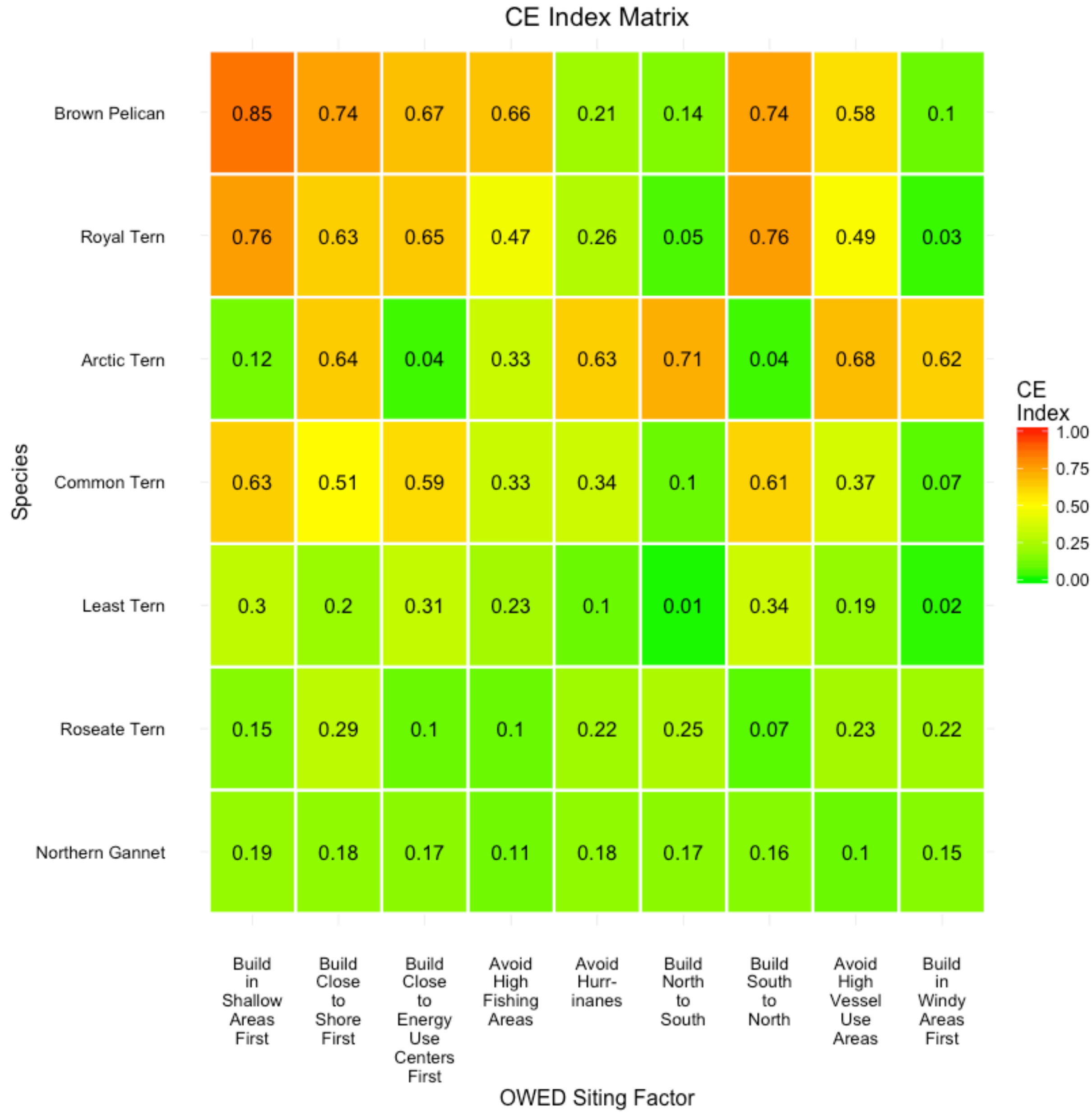
Coastal Bottom Gleaner



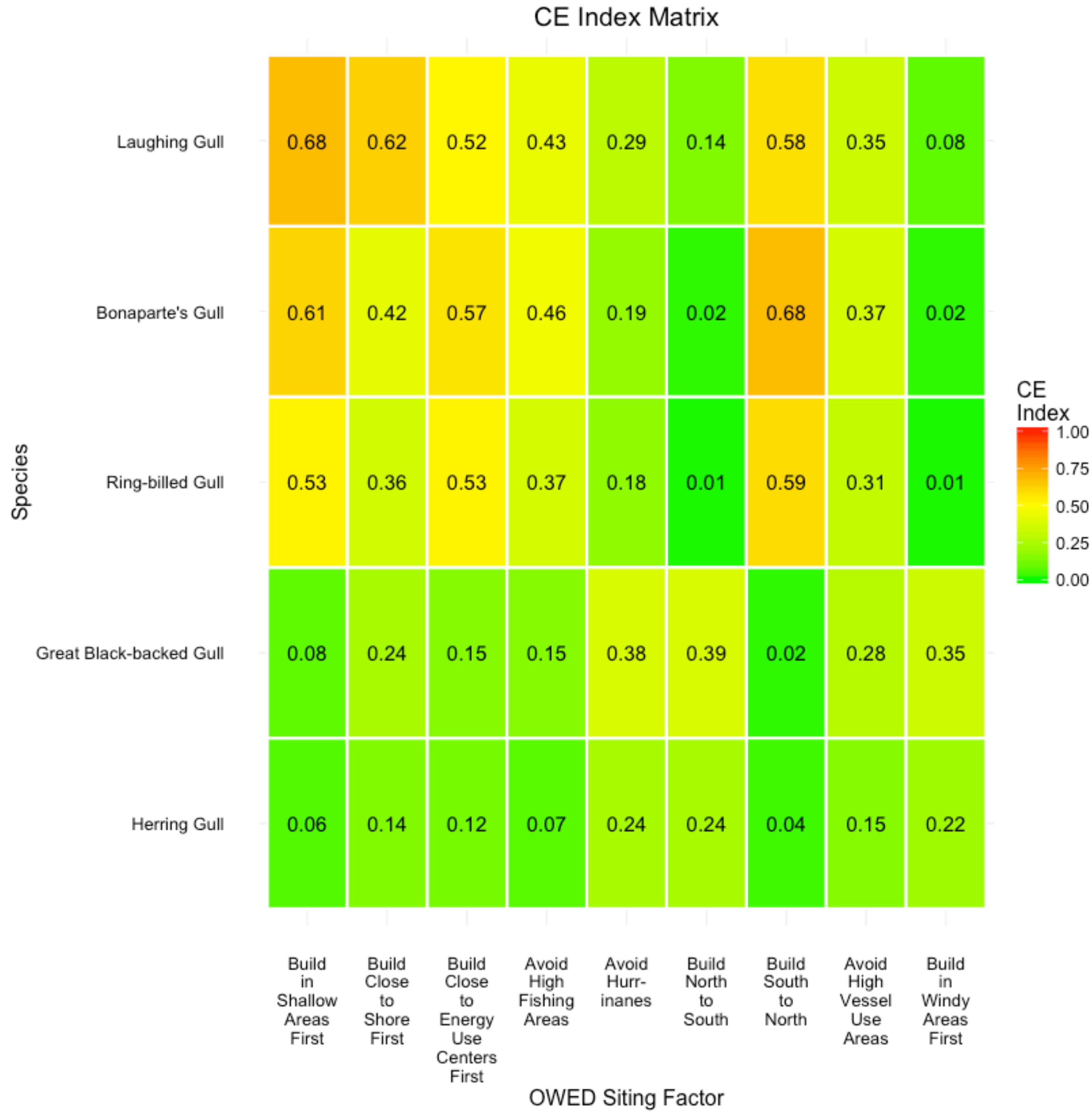
Coastal Diver



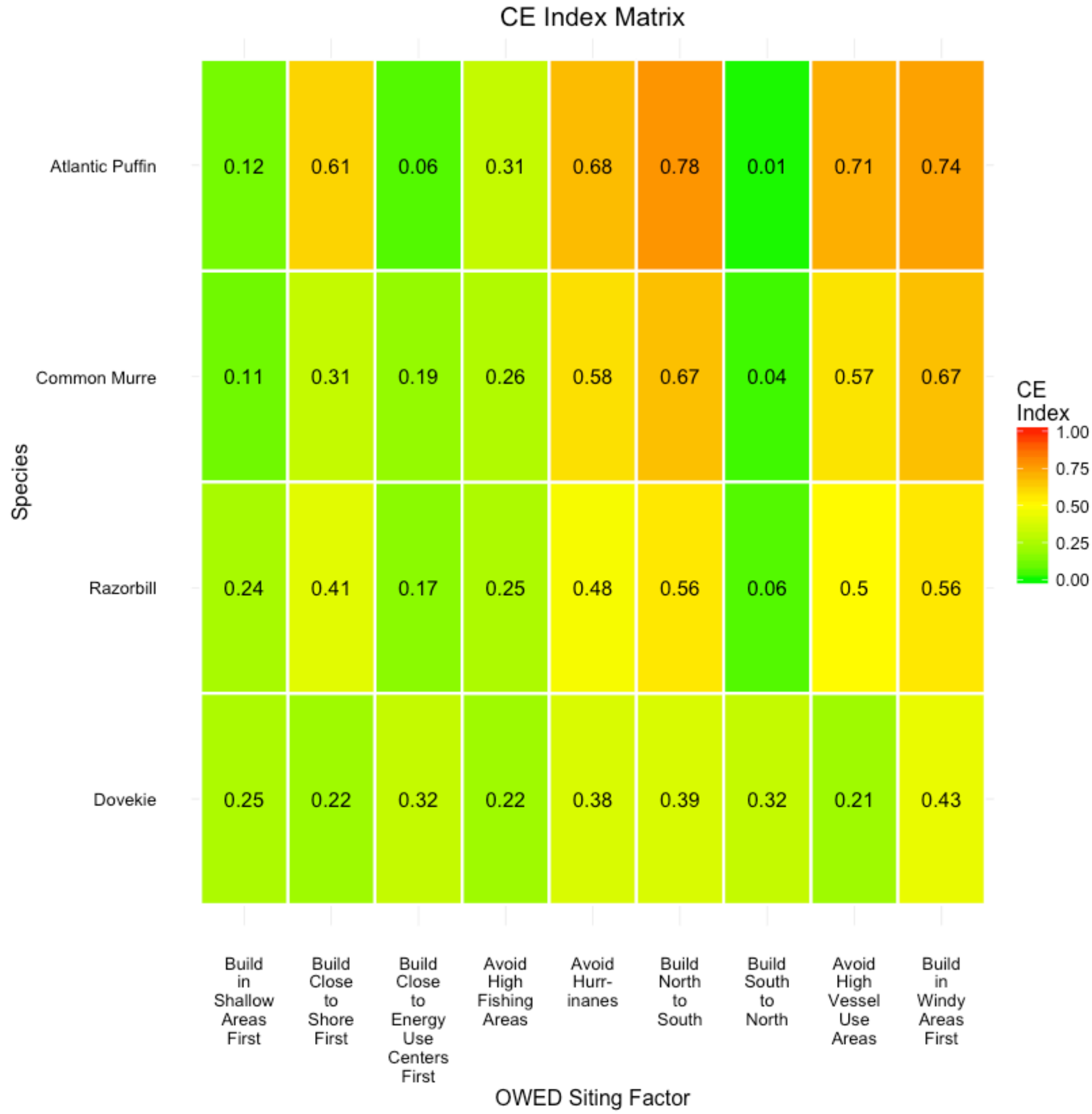
Coastal Plunger



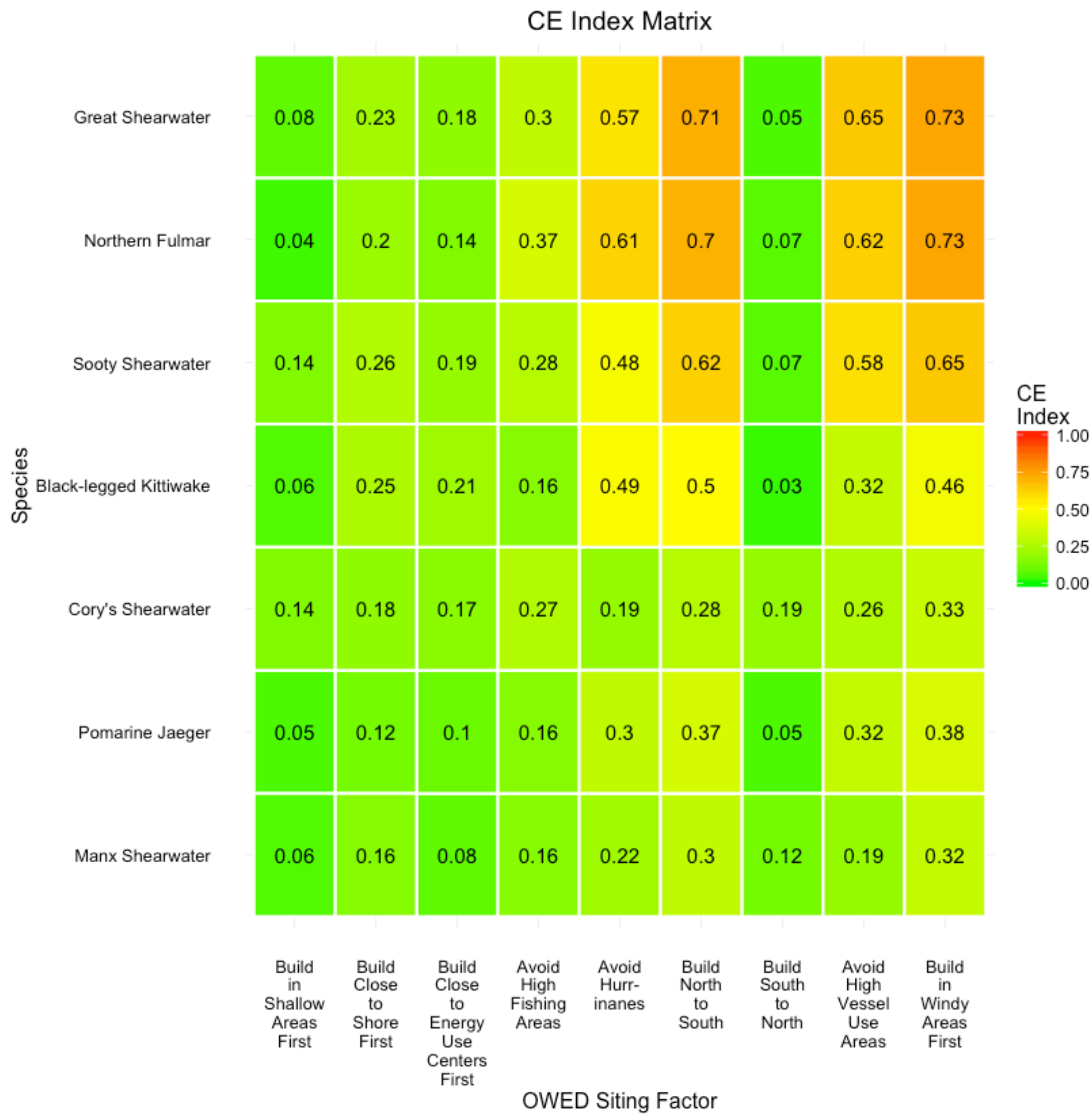
<u>Coastal Surface Gleaner</u>



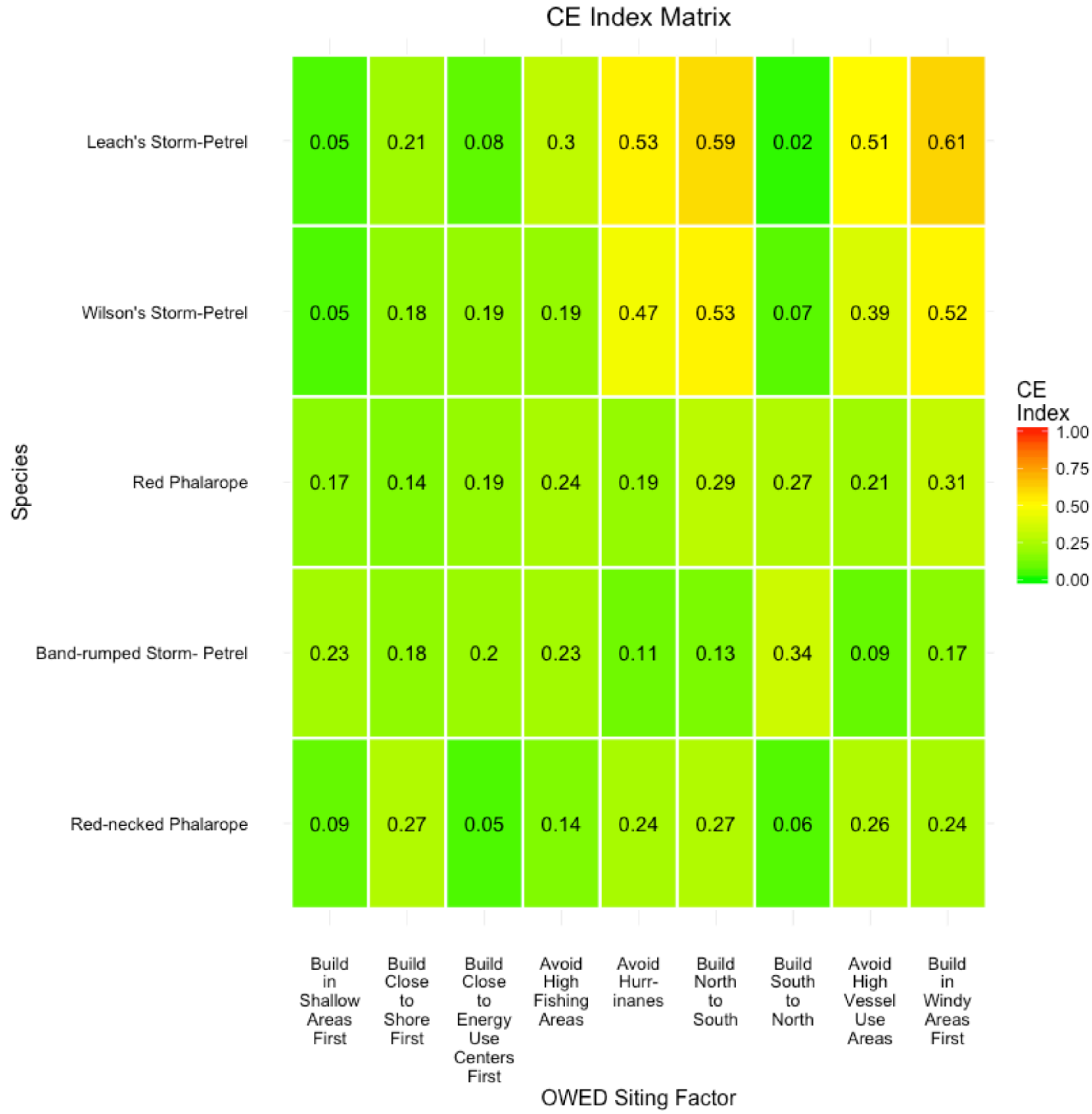
Pelagic Diver



Pelagic Scavenger



Pelagic Surface Gleaner



REFERENCES

Ahlen, I., H. J. Baagoe, and L. Bach. 2009. Behavior of Scandinavian bats during migration and foraging at sea. Journal of Mammalogy 90:1318-1323.

Allen, B. M., R. P. Angliss, and P. R. Wade. 2011. Alaska marine mammal stock assessments, 2010. Alaska Fisheries Science Center, National Marine Mammal Laboratory, U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service. Seattle, Washington

Anderson, E. M., Rian D. Dickson, Erika K. Lok, Eric C. Palm, Jean-Pierre L. Savard, Daniel Bordage and Austin Reed. 2015. Surf Scoter (Melanitta perspicillata), The Birds of North America (P. G. Rodewald, Ed.). Ithaca: Cornell Lab of Ornithology; Retrieved from the Birds of North America: https://birdsna.org/Species-Account/bna/species/sursco.

ARGOS. 2016. Location Classes. http://www.argos-system.org/manual/3-location/34_location_classes.htm

Army Corps of Engineers. 2014. Block Island Environmental Assessment. http://www.nae.usace.army.mil/Portals/74/docs/Topics/DeepwaterWind/EA17Sep2014.pdf

Bain, M. B., J. S. Irving, R. D. Olsen, E. A. Stull, and G. W. Witmer. 1986. Cumulative impact assessment: Evaluating the environmental effects of multiple human developments. Argonne National Laboratory, Energy Environmental Systems Division

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.

Baxter, W., W. A. Ross, and H. Spaling. 2001. Improving the practice of cumulative effects assessment in Canada. Impact Assessment and Project Appraisal 19:253-262.

Bendor, T. 2009. A dynamic analysis of the wetland mitigation process and its effects on no net loss policy. Landscape and Urgan Planning 89:17-27.

Berube, M. 2007. Cumulative effects assessments at Hydro-Quebec: what have we learned? Impact Assessment and Project Appraisal 25:101-109.

Boehlert, G., and A. Gill. 2010. Environmental and ecological effects of ocean renewable energy development: A current synthesis. Oceanography 23:68-81.

BOEM. 2012a. Commercial Wind Lease Issuance and Site Assessment Activities on the Atlantic Outer Continental Shelf Offshore Rhode Island and Massachusetts Environmental Assessment. http://www.boem.gov/uploadedFiles/BOEM/Renewable_Energy_Program/State_Activities/BOEM RI_MA_Revised EA_22May2013.pdf

_____. 2012b. Commercial wind lease issuance and site assessment activities on the Atlantic Outer Continental Shelf offshore Rhode Island and Massachusetts: Environmental Assessment. U.S. Department of the Interior Bureau of Ocean Energy Management Office of Renewable Energy Programs. http://www.boem.gov/uploadedFiles/BOEM/Renewable_Energy_Program/Smart_from_the_Start/BOEM_RI_MA_EA_2012-070.pdf

_____. 2014. Commercial Wind Lease Issuance and Site Assessment Activities on the Atlantic Outer Continental Shelf Offshore Massachusetts. https://http://www.boem.gov/Revised-MA-EA-2014/

_____. 2017. Atlantic OCS Renerable Energy: Massachusetts to South Carolina. https://http://www.boem.gov/uploadedImages/BOEM/Renewable_Energy_Program/Mapping_and_Data/ocs_wpa.jpg

_____. 2018. BOEM state activities. https://http://www.boem.gov/Renewable-Energy-State-Activities/

Boshamer, J. P. C., and J. P. Bekker. 2008. Nathusius' pipistrelles (Pipistrellus nathusii) and other species of bats on offshore platforms in the Dutch sector of the North Sea. Lutra. 51:17-36.

Boswell, K. M., R. J. D. Wells, J. H. Cowan Jr, and C. A. Wilson. 2010. Biomass, density, and size distributions of fishes associated with large-scale artificial reef complex in the Gulf of Mexico. Bulletin of Marine Science 86:879-889.

Brabant, R., N. Vanermen, E. W. M. Stienen, and S. Degraer. 2015. Towards a cumulative collision risk assessment of local and migrating birds in North Sea offshore wind farms. Hydrobiologia 756:63-74.

British Columbia Forest Practices, B. 2011. Cumulative effects from assessment towards management. http://site.ebrary.com/id/10484517

Bronner, C. E., A. M. Bartlett, D. C. Lambert, A. J. Rabideau, S. L. Whiteway, and S. J. Bennett. 2013. An assessment of U.S. stream compensatory mitigation policy: Necessary changes to protect ecosystem functions and services. Journal of the American Water Resources Association 49:449-462.

Brown, S. C. V. P. L. M. 2001. Effectiveness of compensatory wetland mitigation in Massachusetts, USA. Wetlands 21:508-518.

BRP. 2006. State of New Jersey Blue Ribbon Panel on Development of Wind Turbine Facilities in Coastal Waters final report. Prepared for Gov. Jon S. Corzine, Trenton, New Jersey by Blue Ribbon Panel on Development of Wind Turbine Facilities in Coastal Waters, Trenton, New Jersey.

BTM Consult ApS. 2012. International wind energy development: Offshore report 2013. Navigant Consulting, Inc., Chicago, Illinois USA. http://www.navigantresearch.com/wordpress/wp-content/uploads/2012/11/Offshore-Wind-2013-Exec-Summary-Excerpt.pdf

Buchheister, A., T. J. Miller, E. D. Houde, D. H. Secor, and R. J. Latour. 2016. Spatial and temporal dynamics of Atlantic menhaden (Brevoortia tyrannus) recruitment in the Northwest Atlantic Ocean. ICES Journal of Marine Science 73:1147-1159.

Burger, J., C. Gordon, J. Lawrence, J. Newman, G. Forcey, and L. Vlietstra. 2011. Risk evaluation for federally listed (roseate tern, piping plover) or candidate (red knot) bird species in offshore waters: A first step for managing the potential impacts of wind facility development on the Atlantic Outer Continental Shelf. Renewable Energy 36:338-351.

Burkhard, B., and K. Gee. 2012. Establishing the resilience of a coastal-marine social-ecological system to the installation of offshore wind farms. Ecology and Society 17:32.

Burris, R. K., and L. W. Canter. 1997. Cumulative impacts are not properly addressed in environmental assessments. Environmental Impact Assessment Review 17:5-18.

Busch, M., A. Kannen, S. Garthe, and M. Jessopp. 2013. Consequences of a cumulative perspective on marine environmental impacts: Offshore wind farming and seabirds at North Sea scale in context of the EU Marine Strategy Framework Directive. Ocean and Coastal Management 71:213-224.

Calabrese, J. M., C. H. Fleming, and E. Gurarie. 2016. ctmm: an r package for analyzing animal relocation data as a continuous-time stochastic process. Methods in Ecology and Evolution 7:1124-1132.

Canter, L. W. 2012. Guidance on cumulative effects analysis in environmental assessments and environmental impact statements. http://nero.noaa.gov/nepa/docs/nmfsneronepaguidancecumulativeimpacts.pdf

Canter, L. W., and J. Kamath. 1995. Questionnaire checklist for cumulative impacts. Environmental Impact Assessment Review 15:311-339.

CEC. 2008. Offshore Wind Energy: Action needed to deliver on the Energy Policy Objectives for 2020 and beyond. Commission of the European Communities http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2008:0768:FIN:EN:PDF

CEQ. 1997. Considering cumulative effects under the National Environmental Policy Act. https://http://www.energy.gov/sites/prod/files/nepapub/nepa_documents/RedDont/G-CEQ-ConsidCumulEffects.pdf

Chardine, J. W., J. F. Rail, and S. Wilhelm. 2013. Population dynamics of Northern gannets in North America, 1984–2009. Journal of Field Ornithology 84:187-192.

Cleasby, I. R., E. D. Wakefield, S. Bearhop, T. W. Bodey, S. C. Votier, and K. C. Hamer. 2015. Three-dimensional tracking of a wide-ranging marine predator: flight heights and vulnerability to offshore wind farms. Journal of Applied Ecology 52:1474-1482.

Continental Shelf Associates. 2004. Explosive removal of offshore structures information synthesis report. U.S. Dept. of the Interior Minerals Management Service, Gulf of Mexico OCS Region, New Orleans, Louisiana

Cook, A. S. C. P., A. Johnston, L. J. Wright, and N. H. K. Burton. 2012. A review of flight heights and avoidance rates of birds in relation to offshore wind farms. Strategic Ornithological Support Services Project SOSS-02.

Cooper, L. M. 2004. Guidelines for cumulative effects assessment in SEA of Plans. EPMG occasional paper 04/LMC/CEA. Imperial College London

Cooper, L. M., and W. R. Sheate. 2002. Cumulative effects assessment: A review of UK environmental impact statements. Environmental Impact Assessment Review 22:403.

Cooper, T. A., and L. W. Canter. 1997. Documentation of cumulative impacts in environmental impact statements. Environmental Impact Assessment Review 17:385-411.

Crain, C. M., K. Kroeker, and B. S. Halpern. 2008. Interactive and cumulative effects of multiple human stressors in marine systems. Ecology Letters 11:1304-1315.

Crichton, D. 1999. The risk triangle. Pages 102-103 *in* J. Ingleton, editor. Natural Disaster Management. Tudor Rose, London.

Cryan, P. M. 2008. Mating behavior as a possible cause of bat fatalities at wind turbines. Journal of Wildlife Management Journal of Wildlife Management 72:845-849.

Cryan, P. M., and R. M. R. Barclay. 2009. Causes of bat fatalities at wind turbines: Hypotheses and predictions. Journal of Mammalogy 90:1330-1340.

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

Curtice, C., J. Cleart, E. Schumchenia, and P. Halpin. 2016. Marine-life Data and Analysis Team ("MDAT") technical report on the methods and development of marine-life data to support regional ocean planning and management. Prepared on behalf of the Marine-life Data and Analysis Team (MDAT). http://seamap.env.duke.edu/models/MDAT/MDAT-Technical-Report-v1_1.pdf

David, J. A. 2006. Likely sensitivity of bottlenose dolphins to pile-driving noise. Water and Environment Journal 20:48-54.

De Graaf, R. M., N. G. Tilghman, and S. H. Anderson. 1985. Foraging guilds of North American birds. Environmental Management 9:493-536.

Deepwater Wind. 2016. Block Island Wind Farm. http://dwwind.com/project/block-island-wind-farm/

Desholm, M. 2009. Avian sensitivity to mortality: Prioritising migratory bird species for assessment at proposed wind farms. Journal of Environmental Management 90:2672-2679.

Desholm, M., and J. Kahlert. 2005. Avian collision risk at an offshore wind farm. Biological Letters 1:296-298.

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

DOE. 2011. A national offshore wind strategy: Creating an offshore wind energy industry in the United States. Department of Energy. http://www1.eere.energy.gov/wind/pdfs/national_offshore_wind_strategy.pdf

_____. 2013. Financial Assistance Request for Information: environmental research and observations at the first U.S. offshore wind facilities. Department of Energy. Request For Information: DE-FOA-0000911 CFDA Number: 81.087. http://www1.eere.energy.gov/wind/m/financial_opps_detail.html?sol_id=595

_____. 2016. National offshore wind strategy: Facilitating the development of the offshore wind industry in the United States. http://energy.gov/sites/prod/files/2016/09/f33/National-Offshore-Wind-Strategy-report-09082016.pdf

Dolman, S., and M. Simmonds. 2010. Towards best environmental practice for cetacean conservation in developing Scotland's marine renewable energy. Marine Policy 34:1021-1027.

Douglas, D. C., R. Weinzierl, S. C. Davidson, R. Kays, M. Wikelski, and G. Bohrer. 2012. Moderating Argos location errors in animal tracking data. Methods in Ecology and Evolution 3:999-1007.

Doyle, M. W., and D. F. Shields. 2012. Compensatory mitigation for streams under the Clean Water Act: Reassessing science and redirecting policy. American Water Resource Association 48:494-509.

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

Duinker, P., and L. Greig. 2006. The Impotence of Cumulative Effects Assessment in Canada: Ailments and Ideas for Redeployment. Environmental Management 37:153-161.

Dvorak, M. J., B. A. Corcoran, J. E. Ten Hoeve, N. G. McIntyre, and M. Z. Jacobson. 2013. US East Coast offshore wind energy resources and their relationship to peak−time electricity demand. Wind Energy 16:977-997.

Edren, S. M. C., S. M. Andersen, J. Teilmann, J. Carstensen, P. B. Harders, R. Dietz, and L. A. Miller. 2010. The effect of a large Danish offshore wind farm on harbor and gray seal haul-out behavior. Marine Mammal Science 26:614-634.

ESRI. 2016. ArcGIS Desktop: Release 10.x. Redlands, CA: Environmental Systems Research Institute.

Everaert, J., and E. W. M. Stienen. 2007. Impact of wind turbines on birds in Zeebrugge (Belgium). Biodiversity and Conservation 16:3345-3359.

EWEA. 2013. The European offshore wind industry: Key trends and statistics 2012. European Wind Energy Association.

Farquhar, N. 2011. Atlantic Offshore Wind Development. http://www.boem.gov/uploadedFiles/BOEM/Renewable_Energy_Program/State_Activities/DOIInitiatives032411.pdf

Fifield, D. A., W. A. Montevecchi, S. Garthe, G. J. Robertson, U. Kubetzki, and J.-F. Rail. 2014. Migratory Tactics and Wintering Areas of Northern Gannets (Morus bassanus) Breeding in North America. Ornithological Monographs:1-63.

Fleming, C. H., and J. M. Calabrese. 2016. ctmm: Continuous-Time Movement Modeling. R package version 0.3.3. https://CRAN.R-project.org/package=ctmm

Fleming, C. H., W. F. Fagan, T. Mueller, K. A. Olson, P. Leimgruber, and J. M. Calabrese. 2015. Rigorous home range estimation with movement data: a new autocorrelated kernel density estimator. Ecology 96:1182-1188.

Fox, A. D., M. Desholm, J. Kahlert, T. K. Christensen, and I. B. Krag Petersen. 2006. Information needs to support environmental impact assessment of the effects of European marine offshore wind farms on birds. Ibis 148:129-144.

Furness, R. W., and P. Monaghan. 1987. Seabird ecology. Blackie, New York, U.S.A.

Furness, R. W., H. M. Wade, and E. A. Masden. 2013. Assessing vulnerability of marine bird populations to offshore wind farms. Journal of Environmental Management 119:56-66.

Garthe, S., N. Guse, W. A. Montevecchi, J.-F. Rail, and F. Grégoire. 2014. The daily catch: Flight altitude and diving behavior of northern gannets feeding on Atlantic mackerel. Journal of Sea Research 85:456-462.

Garthe, S., and O. Huppop. 2004. Scaling possible adverse effects of marine wind farms on seabirds: Developing and applying a vulnerability index. Journal of Applied Ecology 41:724-734.

Garthe, S., N. Markones, and A.-M. Corman. 2017. Possible impacts of offshore wind farms on seabirds: a pilot study in Northern Gannets in the southern North Sea. Journal of Ornithology 158:345-349.

Gaston, A. J. 2004. Seabirds: a natural history. Yale University Press.

Geo-Marine Inc. 2010. New Jersey Department of Environmental Protection baseline studies. Final Report.

Gill, A. B., M. Bartlett, and F. Thomsen. 2012. Potential interactions between diadromous fishes of U.K. conservation importance and the electromagnetic fields and subsea noise from marine renewable energy developments. Journal of fish biology 81:664-695.

GOMCES. 2016. Gulf of Maine Coastal Ecosystem Survey. https://gomces.wordpress.com/

Goodale, M. W. 2018. Developing a deterministic geospatial decision-support model to assess the cumulative exposure of wildlife to offshore wind energy development patterns. PhD, University of Massachusetts.

Goodale, M. W., and A. Milman. 2016. Cumulative adverse effects of offshore wind energy development on wildlife. Journal of Environmental Planning and Management 59:1-21.

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

Grady, F. V., and S. L. Olson. 2006. Fossil bats from quaternary deposits on Bermuda (chiroptera: vespertilionidae). Journal of Mammalogy 87:148-152.

Green, R., and N. Vasilakos. 2011. The economics of offshore wind. Energy Policy 39:496-502.

Habitat, E. 2007. Guidance document on Article 6(4) of the 'Habitats Directive' 92/43/EEC. European Commission. http://ec.europa.eu/environment/nature/natura2000/management/docs/art6/guidance_art6_4_en.pdf

Halpern, B. S., K. L. McLeod, A. A. Rosenberg, and L. B. Crowder. 2008. Managing for cumulative impacts in ecosystem-based management through ocean zoning. Ocean and Coastal Management 51:203-211.

Hartman, J. C., K. L. Krijgsveld, M. J. M. Poot, R. C. Fijn, M. F. Leopold, and S. Dirksen. 2012. Effects on birds of Offshore Wind farm Egmond aan Zee (OWEZ).

Hatch, S. K., E. E. Connelly, T. J. Divoll, I. J. Stenhouse, and K. A. Williams. 2013. Offshore observations of eastern red bats (Lasiurus borealis) in the Mid-Atlantic United States using multiple survey methods. Biodiversity Research Institute. PLoS ONE 8:e83803.

Hebblewhite, M., and D. T. Haydon. 2010. Distinguishing technology from biology: a critical review of the use of GPS telemetry data in ecology. Philosophical Transactions of the Royal Society B: Biological Sciences 365:2303-2312.

Hegmann, G., C. Cocklin, R. Creasey, S. Dupuis, A. Kennedy, L. Kingsley, W. Ross, H. Spaling, and D. Stalker. 1999. Cumulative effects assessment practitioners guide. AXYS Environmental Consulting Ltd. Report 0660177099 9780660177090.http://www.ceaa-acee.gc.ca/Content/4/3/9/43952694-0363-4B1E-B2B3-47365FAF1ED7/Cumulative_Effects_Assessment_Practitioners_Guide.pdf

Hirst, A. G., and P. G. Rodhouse. 2000. Impacts of geophysical seismic surveying on fishing success. Reviews in Fish Biology and Fisheries 10:113-118.

Hyder, P. L. C. 1999. Consulting guidelines for the assessment of indirect and cumulative impacts as well as impact interactions. Brussels: EC DGX1 Environment, Nuclear Safety and Civil Protection

Inger, R., M. J. Attrill, S. Bearhop, A. C. Broderick, W. J. Grecian, D. J. Hodgson, C. Mills, E. Sheehan, S. C. Votier, M. J. Witt, and B. J. Godley. 2009. Marine renewable energy: Potential benefits to biodiversity? An urgent call for research. Journal of Applied Ecology 46:1145-1153.

Irving, J. S., M. B. Bain, E. A. Stull, and G. W. Witmer. 1986. Cumulative impacts: real or imagined. Argonne National Lab. Annual meeting of the Idaho Chapter of the American Fisheries Society, Boise I.D. U.S.A.

Jacobsen, H. K., C. Wolter, and P. Hevia-Koch. Nearshore Versus Offshore: Comparative Cost and Competitive Advantages. International Association for Energy Economics, 2016 2016.

Johnson, J. B., J. E. Gates, and N. P. Zegre. 2011. Monitoring seasonal bat activity on a coastal barrier island in Maryland, USA. Environmental Monitoring and Assessment 173:1-4.

Johnston, A., A. S. C. P. Cook, L. J. Wright, E. M. Humphreys, and N. H. K. Burton. 2014. Modelling flight heights of marine birds to more accurately assess collision risk with offshore wind turbines. Journal of Applied Ecology 51:31-41.

Jonkman, J., S. Butterfield, W. Musial, and G. Scott. 2009. Definition of a 5-MW Reference Wind Turbine for Offshore System Development. Technical Report. NREL/TP-500-38060. National Renewable Energy Laboratory

Kikuchi, R. 2010. Risk formulation for the sonic effects of offshore wind farms on fish in the EU region. Marine Pollution Bulletin 60:172-177.

King, S., I. M. D. Maclean, T. Norman, and A. Prior. 2009. Developing guidance on ornithological cumulative impact assessment for offshore wind farm developers. COWRIE. Report 9780955750151 0955750156.http://www.offshorewindfarms.co.uk/Assets/CIA Report Final Combined.pdf

Kinlan, B., R. Rakin, and C. Caldow. 2013. Predictive models of at-sea marine bird occurrence and abundance in the Mid-Atlantic. http://www.acjv.org/Marine_Bird_page/workshop_2013/Kinlan_NOAA_NCCOS_Mid-Atlantic_Predictive_Modeling.pdf

Kinlan, B. P., A. J. Winship, T. P. White, and J. Christensen. 2016. Modeling At-Sea Occurrence and Abundance of Marine Birds to Support Atlantic Marine Renewable Energy Planning: Phase I Report. U.S. Department of the Interior, Bureau of Ocean Energy Management, Office of Renewable Energy Programs, Sterling, VA. OCS Study BOEM 2016-039. xvii+113 pp. https://coastalscience.noaa.gov/projects/detail?key=279

Krijgsveld, K. L. 2014. Avoidance behavior of birds around offshore wind farms: Overview of knowledge including effects of configuration. Report Bureau Waardenburg.

Krijgsveld, K. L., R. C. Fijn, M. Japink, P. W. van Horssen, C. Heunks, M. P. Collier, H. Poot, D. Beuker, and S. Dirksen. 2011. Effect studies offshore wind project Egmond aan Zee. Final report on fluxes, flight altitudes and behavior of flying birds. NoordzeeWind report nr OWEZ_R_231_T1_20111114_flux&flight. Bureau Waardenburg report nr 10-219. The Netherlands.

Kunz, T. H., E. B. Arnett, W. P. Erickson, A. R. Hoar, G. D. Johnson, R. P. Larkin, M. D. Strickland, R. W. Thresher, and M. D. Tuttle. 2007. Ecological impacts of wind energy development on bats: Questions, research needs, and hypotheses. Frontiers in Ecology and the Environment 5:315-324.

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

Lapena, P. B., K. M. Wijnberg, A. Stein, and S. J. M. H. Hulscher. 2013. Spatial variogram estimation from temporally aggregated seabird count data. Environmental and Ecological Statistics 20:353-375.

Larsen, J. K., and M. Guillemette. 2007. Effects of wind turbines on flight behaviour of wintering common eiders: Implications for habitat use and collision risk. Journal of Applied Ecology 44:516-522.

Leonhard, S. B., J. Pedersen, P. N. Grøn, H. Skov, J. Jansen, C. Topping, and I. K. Petersen. 2013. Wind farms affect Common Scoter and Red-throated Diver behaviour. In Danish Offshore Wind: Key Environmental Issues – A Follow-up. The Environment Group: The Danish Energy Agency, The Danish Nature Agency, DONG Energy and Vattenfall, pp. 70–93 (Chapter 5). http://orbit.dtu.dk/ws/files/55080896/Havvindm_llebog.pdf

Levrel H., Pioch S., and Spieler R. 2012. Compensatory mitigation in marine ecosystems: Which indicators for assessing the "no net loss" goal of ecosystem services and ecological functions? Marine Policy 36:1202-1210.

Lindeboom, H. J., H. J. Kouwenhoven, M. J. N. Bergman, S. Bouma, S. Brasseur, R. Daan, R. C. Fijn, D. d. Haan, S. Dirksen, R. v. Hal, R. H. R. Lambers, R. t. Hofstede, K. L. Krijgsveld, M. Leopold, and M. Scheidat. 2011. Short-term ecological effects of an offshore wind farm in the Dutch coastal zone; a compilation. Environmental Research Letters 6:035101

Linley, E. A. S., T. A. Wilding, K. Black, A. J. S. Hawkins, and S. Mangi. 2007. Review of the reef effects of offshore wind farm structures and their potential for enhancement and mitigation. PML Applications Ltd and the Scottish Association for Marine Science to the Department for Business, Enterprise and Regulatory Reform (BERR), Contract No: RFCA/005/0029P

Lopez, A., B. Roberts, D. Heimiller, N. Blair, and G. Porro. 2012. U.S. renewable energy technical potentials: A GIS-based analysis. National Renewable Energy Lab. NREL/TP-6A20-51946

Ma, Z., D. R. Becker, and M. A. Kilgore. 2012. Barriers to and opportunities for effective cumulative impact assessment within state-level environmental review frameworks in the United States. Journal of Environmental Planning and Management 55:961-978.

MacDonald, L. H. 2000. Evaluating and managing cumulative effects: Process and constraints. Environmental Management 26:299-316.

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

Madsen, P. T., M. Wahlberg, J. Tougaard, K. Lucke, and P. Tyack. 2006. Wind turbine underwater noise and marine mammals: Implications of current knowledge and data needs. Marine Ecology Progress Series 309:279-295.

Manwell, J. F., J. G. McGowan, and A. L. Rogers. 2009. Wind energy explained : theory, design and application. Wiley, Chichester, U.K.

Masden, E. A., and A. Cook. 2016. Avian collision risk models for wind energy impact assessments. Environmental Impact Assessment Review 56:43-49.

Masden, E. A., R. W. Furness, D. T. Haydon, A. D. Fox, and R. Bullman. 2010. Cumulative impact assessments and bird/wind farm interactions: Developing a conceptual framework. Environmental Impact Assessment Review 30:1-7.

Masden, E. A., D. T. Haydon, A. D. Fox, R. W. Furness, R. Bullman, and M. Desholm. 2009. Barriers to movement: impacts of wind farms on migrating birds. ICES Journal of Marine Science 66:746-753.

Masden, E. A., A. McCluskie, E. Owen, and R. H. W. Langston. 2015. Renewable energy developments in an uncertain world: The case of offshore wind and birds in the UK. Marine Policy Marine Policy 51:169-172.

Massachusetts Department of Energy Resources. 2017. Request for proposals for long-term contracts for offshore wind energy projects. https://macleanenergy.files.wordpress.com/2017/02/section-83c-request-for-proposals-for-long-term-contracts-for-offshore-wind-energy-projects-june-29-2017.pdf

McCann, J. 2012. Developing environmental protocols and modeling tools to support ocean renewable energy and stewardship. U.S. Dept. of the Interior, Bureau of Ocean Energy Management, Office of Renewable Energy Programs, Herndon, VA. OCS Study BOEM 2012-082

Michel, J. 2013. South Atlantic information resources: data search and literature synthesis. US Department of the Interior, Bureau of Ocean Energy Management, Gulf of Mexico OCS Region, New Orleans, LA. OCS Study BOEM 2013-01157

Michel, J., H. Dunagan, C. Boring, E. Healy, W. Evans, J. M. Dean, A. McGillis, and J. Hain. 2007. Worldwide synthesis and analysis of existing information regarding environmental effects of alternative energy uses on the outer continental shelf. Minerals Management Service (MMS), Herndon, VA. OCS MMS 2007-038. 254 pp

MMS. 2007. Programmatic Environmental Impact Statement for alternative energy development and production and alternate use of facilities on the Outer Continental Shelf: Final Environmental Impact Statement. https://http://www.boem.gov/Guide-To-EIS/

_____. 2009. Cape Wind EIS. https://http://www.boem.gov/Cape-Wind-FEIS/

Mowbray, T. B. 2002. Northern Gannet (Morus bassanus), The Birds of North America (P. G. Rodewald, Ed.). Ithaca: Cornell Lab of Ornithology; Retrieved from the Birds of North America: https://birdsna.org/Species-Account/bna/species/norgan.

Musial, W., and B. Ram. 2010. Large-Scale Offshore Wind Power in the United States: ASSESSMENT OF OPPORTUNITIES AND BARRIERS, The National Renewable Energy Laboratory (NREL), NREL/TP-500-40745.

Newton, I. 2013. Bird Populations. William Collins, London.

Norman, T. B., R. S. K. Buisson, and N. P. Askew. 2007. Report on the COWRIE workshop on the cumulative impact of offshore windfarms on birds. Report prepared by RPS for COWRIE. COWRIE CIBIRD-01-2007

Northeast Ocean Data Portal. 2018. Northeast Ocean Data. http://www.northeastoceandata.org/

Nur, N., J. Jahncke, M. P. Herzog, J. Howar, K. D. Hyrenbach, J. E. Zamon, D. G. Ainley, J. A. Wiens, K. Morgan, L. T. Ballance, and D. Stralberg. 2011. Where the wild things are: predicting hotspots of seabird aggregations in the California Current System. Ecological Applications 21:2241-2257.

NYSERDA. 2015. "Advancing the Environmentally Responsible Development of Offshore Wind Energy in New York State: A Regulatory Review and Stakeholder Perceptions," NYSERDA Report 15-16. Prepared by Wing Goodale and Kate Williams (Biodiversity Research Institute, Portland, ME). https://http://www.nyserda.ny.gov/publications

_____. 2016. NYSERDA Completes First Phases of World's Largest-Ever Digital Aerial Survey of Offshore Wildlife Along Long Island Coast. https://http://www.nyserda.ny.gov/About/Newsroom/2016-Announcements/2016-12-08-NYSERDA-Completes-First-Phases-of-Worlds-Largest-Digital-Aerial-Survey

O'Sullivan, D., and D. Unwin. 2014. Geographic information analysis. Second edition. John Wiley & Sons, Hoboken, New Jersey.

Offshore Wind Biz. 2018. The US East Coast states have committed to developing over 8GW of offshore wind capacity by 2030. https://http://www.offshorewind.biz/2018/02/05/us-east-coast-offshore-wind-commitments-top-8gw/

Parkins, J. R. 2011. Deliberative democracy, institution building, and the pragmatics of cumulative effects assessment. Ecology and Society 16.

Pelletier, S., T. Peterson, S. Boyden, K. Watrous, and J. Perkins. 2013a. Ongoing offshore Atlantic & Great Lakes acoustic bat research. US Department of Energy Offshore Wind Webinar. http://mhk.pnnl.gov/wiki/images/0/00/Pelletier_OSW_Webinar_4_24_13.pdf

Pelletier, S. K., K. S. Omland, K. S. Watrous, and T. S. Peterson. 2013b. Information synthesis on the potential for bat interactions with offshore wind facilities: Final Report. U.S. Dept of the Interior, Bureau of Ocean Energy Management, Headquarters, Herndon, VA. OCS Study BOEM 2013-01163. 119 pp. http://mhk.pnnl.gov/wiki/images/0/0b/BOEM_Bat_Wind_2013.pdf

Percival, S. 2010. Kentish Flats Offshore Wind Project: diver surveys 2009–10. Report commissioned by Vattenfall Wind Power. Ecology Consulting, Durham, England, United Kingdom. http://www.vattenfall.co.uk/en/file/Diver_follow-up_report_2010__PDF_1970_kB__16639636.pdf

Perrow, M. R., J. J. Gilroy, E. R. Skeate, and M. L. Tomlinson. 2011. Effects of the construction of Scroby Sands offshore wind farm on the prey base of Little tern (Sternula albifrons) at its most important UK colony. Marine Pollution Bulletin 62:1661-1670.

Petersen, I. K., T. K. Christensen, J. Kahlert, M. Desholm, and A. D. Fox. 2006. Final results of bird studies at the offshore wind farms at Nysted and Horns Rev, Denmark. National Environmental Research Institute Report, Rønde, Denmark: Commissioned by DONG energy and Vattenfall A/S

Petersen, I. K., and A. D. Fox. 2007. Changes in bird habitat utilisation around the Horns Rev 1 offshore wind project, with particular emphasis on Common Scoter. Report commissioned by Vattenfall A/S by National Environmental Research Institute, University of Aarhus, Denmark. http://www.vattenfall.se/sv/file/Horns-Rev-Habitat-Changes_11336653.pdf

Petersen, I. K., M. L. MacKenzie, E. Rexstad, M. S. Wisz, and A. D. Fox. 2011. Comparing pre- and post-construction distributions of Long-tailed Ducks Clangula hyemalis in and around the Nysted offshore wind farm, Denmark : A quasi-designed experiment accounting for imperfect detection, local surface features and autocorrelation. CREEM Technical Report , no. 2011-1 , University of St Andrews. http://hdl.handle.net/10023/2008

Pettersson, J. 2005. The impact of offshore wind farms on bird life in Southern Kalmar Sound Sweden final report based on studies 1999-2003. Lunds universitet. Ekologiska, institutionen. Department Animal Ecology, Lund University. Report 9163168782 9789163168789. http://www.wind-energie.de/fileadmin/dokumente/Themen_A-Z/Vogelschutz/Voegel_Offshore_Sweden.pdf

Piper, J. M. 2001. Barriers to implementation of cumulative effects assessment. Journal of Environmental Assessment Policy and Management 3:465-481.

Plonczkier, P., and I. C. Simms. 2012. Radar monitoring of migrating Pink-footed Geese: Behavioural responses to offshore wind farm development. Journal of Applied Ecology 49:1187-1194.

Poerink, B. J., S. Lagerveld, and H. Verdaat. 2013. Pilot study Bat activity in the dutch offshore wind farm OWEZ and PAWP. IMARES report number C026/13 / tFC report number 20120402.

Poot, M. J. M., van Horssen. P.W., M. P. Collier, R. Lensink, and S. Dirksen. 2011. Effect studies Offshore Wind Egmond aan Zee: Cumulative effects on seabirds. A modelling approach to estimate effects on population levels in seabirds. Bureau Waardenburg bv, commissioned by Noordzeewind, The Netherlands

R Core Team. 2015. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

Ram, B. 2011. Assessing integrated risks of offshore wind projects: Moving towards gigawatt-scale deployments. Wind Engineering 35:247-266.

Renewable UK. 2011. Consenting Lessons Learned. An offshore wind industry review of past concerns, lessons learned and future challenges.

_____. 2013. Cumulative Impact Assessment Guidelines: Guiding Principles For Cumulative Impacts Assessment In Offshore Wind Farms http://www.renewableuk.com/en/publications/index.cfm/cumulative-impact-assessment-guidelines.

Rodewald, P. E. 2015. The Birds of North America: https://birdsna.org. Cornell Laboratory of Ornithology, Ithaca, NY.

RStudio. 2017. Shiny. https://shiny.rstudio.com/

Salmon, M. 2003. Artificial night lighting and sea turtles. Biologist 50.

Schreiber, E. A., and J. Burger. 2001. Biology of marine birds. CRC Press, Boca Raton, FL.

Schultz, C. 2010. Challenges in connecting cumulative effects analysis to effective wildlife conservation planning. Bioscience 60:545-551.

Schultz, C. A. 2012. History of the cumulative effects analysis requirement under NEPA and its interpretation in U.S. Forest Service case law. Journal of Environmental Law and Litigation 27:125-190.

Schwartz, M. N., D. Heimiller, S. Haymes, and W. Musial. 2010. Assessment of offshore wind energy resources for the United States. NREL/TP-500-45889. https://http://www.nrel.gov/docs/fy10osti/45889.pdf

Siemens. 2016. Siemens 6.0 MW Offshore Wind Turbine. http://www.energy.siemens.com/us/pool/hq/power-generation/renewables/wind-power/6_MW_Brochure_Jan.2012.pdf

Silverman, E. D., D. T. Saalfeld, J. B. Leirness, and M. D. Koneff. 2013. Wintering sea duck distribution along the Atlantic Coast of the United States. Journal of Fish and Wildlife Management 4:178-198.

Smallwood, K. S. 2013. Comparing bird and bat fatality-rate estimates among North American wind-energy projects. Wildlife Society Bulletin:n/a.

Smith, M. D. 2006. Cumulative impact assessment under the National Environmental Policy Act: An analysis of recent case law. Environmental Practice 8:228-240.

Spiegel, C. S., A.M. Berlin, A.T. Gilbert, C.O. Gray, W.A. Montevecchi, I.J. Stenhouse, S.L. Ford, G.H. Olsen, J.L. Fiely, L. Savoy, M.W. Goodale, and C. M. Burke. 2017. Determining Fine- scale Use and Movement Patterns of Diving Bird Species in Federal Waters of the Mid- Atlantic United States Using Satellite Telemetry. Sterling (VA): U.S. Department of the Interior, Bureau of Ocean Energy Management . OCS Study BOEM 2017-069. .

Stelzenmüller, V., M. Coll, A. D. Mazaris, S. Giakoumi, S. Katsanevakis, M. E. Portman, R. Degen, P. Mackelworth, A. Gimpel, P. G. Albano, V. Almpanidou, J. Claudet, F. Essl, T. Evagelopoulos, J. J. Heymans, T. Genov, S. Kark, F. Micheli, M. G. Pennino, G. Rilov, B. Rumes, J. Steenbeek, and H. Ojaveer. 2018. A risk-based approach to cumulative effect assessments for marine management. Science of The Total Environment 612:1132-1140.

Stenhouse, I., C. Gray, A. Gilbert, and W. Montevecchi. 2015. Wintering movements and habitat use of Northern Gannets (Morus bassanus) in the mid-Atlantic U.S. In: 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 Williams KA, Connelly EE, Johnson SM, Stenhouse IJ (eds.) Award Number: DE-EE0005362. Report BRI 2015-11, Biodiversity Research Institute, Portland, Maine. 23 pp.

Stenhouse, I. J., W. A. Montevecchi, C. E. Gray, A. T. Gilbert, C. M. Burke, and A. M. Berlin. 2017. Occurrence and Migration of Northern Gannets Wintering in Offshore Waters of the Mid-Atlantic United States. in C. S. Spiegel, A.M. Berlin, A.T. Gilbert, C.O. Gray, W.A. Montevecchi, I.J. Stenhouse, S.L. Ford, G.H. Olsen, J.L. Fiely, L. Savoy, M.W. Goodale, andC. M. Burke, editors. Determining Fine- scale Use and Movement Patterns of Diving Bird Species in Federal Waters of the Mid- Atlantic United States Using Satellite Telemetry. Sterling (VA): U.S. Department of the Interior, Bureau of Ocean Energy Management . OCS Study BOEM 2017-069.

Teilmann, J., J. Tougaard, and J. Carstensen. 2012. Effects on harbour porpoises from Rodsand 2 Offshore Wind Farm. Scientific Report from DCE: Danish Centre for Environment and Energy. Number 42. Aahrus University. Department of Bioscience.http://www2.dmu.dk/pub/sr42.pdf

Thompson, P. M., D. Lusseau, T. Barton, D. Simmons, J. Rusin, and H. Bailey. 2010. Assessing the responses of coastal cetaceans to the construction of offshore wind turbines. Marine Pollution Bulletin 60:1200-1208.

Topping, C., and I. K. Petersen. 2011. Report on a Red-throated Diver agent-based model to assess the cumulative impact from offshore wind farms. Aarhus University, Department of Bioscience.

Tougaard, J., J. Carstensen, J. Teilmann, and N. I. Bech. 2005. Effects of the Nysted Offshore Wind Farm on harbour porpoises: Annual status report for the T-POD monitoring program. Technical Report to Energi E2 A/S. National Environmental Research Institute. Ministry of the Environment. http://mhk.pnnl.gov/wiki/images/a/a1/Effects_of_the_Nysted_Offshore_Wind_Farm_on_Harbour_Porpoises.pdf

UKDECC. 2011. UK Renewable Energy Roadmap. Department of Energy & Climate Change. https://http://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48128/2167-uk-renewable-energy-roadmap.pdf

USACE. 2012. Deepwater Wind Block Island Environmental Assessment. http://www.nae.usace.army.mil/Portals/74/docs/Topics/DeepwaterWind/EA17Sep2014.pdf

Vanermen, N., T. Onkelinx, W. Courtens, M. Van de walle, H. Verstraete, and E. W. M. Stienen. 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., , T. White, P., S.A. , and S. C. Perkins. 2016. Abundance and Distribution of Seabirds off Southeastern Massachusetts, 2011-2015. U.S. Department of the Interior, Bureau of Ocean Energy Management, Sterling, Virginia. OCS Study BOEM 2016-067. 82 pp.

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

Wade, H. M., E. A. Masden, A. C. Jackson, and R. W. Furness. 2016. Incorporating data uncertainty when estimating potential vulnerability of Scottish seabirds to marine renewable energy developments. Marine Policy 70:108-113.

Wakefield, E. D., T. W. Bodey, S. Bearhop, J. Blackburn, K. Colhoun, R. Davies, R. G. Dwyer, J. A. Green, D. Grémillet, A. L. Jackson, M. J. Jessopp, A. Kane, R. H. W. Langston, A. Lescroël, S. Murray, M. Le Nuz, S. C. Patrick, C. Péron, L. M. Soanes, S. Wanless, S. C. Votier, and K. C. Hamer. 2013. Space Partitioning Without Territoriality in Gannets. Science 341:68.

Waring, G. T., E. Josephson, K. Maze-Foley, and P. E. Rosel. 2009. US Atlantic and Gulf of Mexico marine mammal stock assessments 2009. U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Northeast Region, Northeast Fisheries Science Center. Woods Hole, Massachusetts. http://www.nefsc.noaa.gov/publications/tm/tm213/tm213.pdf

Williams, K., E. Connelly, S. Johnson, and I. Stenhouse. 2015. Wildlife Densities and Habitat Use Across Temporal and Spatial Scales on the Mid-Atlantic Outer Continental Shelf: Final Report to the Department of Energy EERE Wind & Water Power Technologies Office. Award Number: DE-EE0005362. Report BRI 2015-11, Biodiversity Research Institute, Portland, Maine. 715 pp.

Williams, K. A., DellaSala D, Fox A D, Goodale M W, Jodice P G R, Kinlan B, Langston R H W, Sinclair K, Souder H, Stenhouse I J, Adams E M, Arnett E, Brady D, leary J, DeSorbo C, Evers D, Halpin P, Kenney R, Meyer K, Paton P, Swingle M, von Oettingen S, Winiarski K, and Y. D. in prep. Development of wind energy for offshore regions of the Eastern United States: Known effects, data gaps, and policy recommendations for fish and wildlife. Unpublished manuscript.

Willmott, J. R., G. Forcey, and A. Kent. 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 U.S. Department of the Interior. Bureau of Ocean Energy Management, Office of Renewable Energy Programs. OCS Study BOEM 2013-207. 275 pp.

Willsteed, E. A., S. Jude, A. B. Gill, and S. N. R. Birchenough. 2017. Obligations and aspirations: A critical evaluation of offshore wind farm cumulative impact assessments. Renewable and Sustainable Energy Reviews 82: 2332-2345.

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

WWT. 2012. SOSS-04 Gannet Population Viability Analysis: Demographicdata, population model and outputs. The Crown Estate SOSS.