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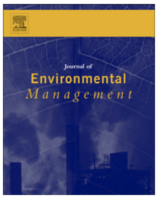

Research article

A Markov model for planning and permitting offshore wind energy: A case study of radio-tracked terns in the Gulf of Maine, USA

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ABSTRACT

Quantifying and managing the potential adverse wildlife impacts of offshore wind energy is critical for developing offshore wind energy in a sustainable and timely manner, but poses a significant challenge, particularly for small marine birds that are difficult to monitor. We developed a discrete-time Markov model of seabird movement around a colony site parameterized by automated radio telemetry data from common terns (*Sterna hirundo*) and Arctic terns (*S. paradisaea*), and derived impact functions that estimate the probability of collision fatality as a function of the distance and bearing of wind turbines from a colony. Our purpose was to develop and demonstrate a new, flexible tool that can be used for specific management and wind-energy planning applications when adequate data are available, rather than inform wind-energy development at this site. We demonstrate how the tool can be used 1) in marine spatial planning exercises to quantitatively identify setback distances under development scenarios given a risk threshold, 2) to examine the ecological and technical trade-offs of development alternatives to facilitate negotiation between objectives, and 3) in the U.S. National Environmental Policy Act (NEPA) process to estimate collision fatality under alternative scenarios. We discuss model limitations and data needs, and highlight opportunities for future model extension and development. We present a highly flexible tool for wind energy planning that can be easily extended to other central place foragers and data sources, and can be updated and improved as new monitoring data arises.

1. Introduction

Environmental concerns are one of the key barriers to public acceptance and permitting of offshore wind energy development (OWED) in the US (Firestone and Kempton, 2007; Goodale and Milman, 2016). The risk that wind farms can pose to birds is a main environmental issue (Drewitt and Langston, 2006; Fox et al., 2006; Langston, 2013; Schuster et al., 2015). Siting wind farms in a way that minimizes adverse effects to wildlife is imperative for developing and sustaining public approval and easing regulatory uncertainties (Firestone and Kempton, 2007; Firestone et al., 2009; Goodale and Milman, 2016), but remains an exceedingly challenging task. The difficulty of siting and permitting wind farms and understanding adverse environmental effects is heightened in offshore environments due to obstacles such as inadequate baseline data on wildlife, limited understanding of movement patterns and habitat use, and difficulty in collecting post-construction collision data (Goodale and Milman, 2016; Masden et al., 2015). Addressing the environmental uncertainties of OWED with empirical data and robust analytical tools is a critical step toward facilitating a sustainable and timely development of this technology (Langston, 2013; Marques et al., 2014).

As OWED proceeds in US waters, there is a need for spatial planning tools that can quantitatively balance ecological, technical, and social factors (Langston, 2013). Spatially-explicit optimization models are apt tools for modeling ecological, economic, and social tradeoffs of development scenarios, and have been used in terrestrial planning scenarios (Polasky et al., 2008; Eichorn and Dreschler, 2010). However, these methods require estimates of space use and spatially-explicit collision probabilities that can be difficult to acquire, especially for small marine birds.

A commonly used method for wind energy development is to

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develop an impact function - describing collision fatality as a function of the distance between a wind farm and a nesting site (Eichorn et al., 2012; Schaub, 2012). Although impact functions are commonly included in wind farm risk assessments (Carrete et al., 2012), to date they have been developed using only theory and expert opinion rather than empirical data (Schaub, 2012; Eichorn et al., 2012). In this paper, we develop a methodology for using cutting edge data to produce empirically-based impact functions.

For cases in which a population of birds is homogeneous in location and behavior, a Markov model can be used to model the movements of representative individual(s). These models can be used to develop impact functions in circumstances where tracking data are too sparse for more data-demanding agent-based methods (Eichorn et al., 2012). Markov models are a particularly apt choice for modeling bird movements because they are highly flexible and can be based on a large variety of data sources; they therefore can serve as a consistent and versatile tool for modeling movement data derived from rapidly evolving tracking technologies (Patterson et al., 2008). Markov models can also be run at many different physical and temporal scales, and in continuous time (e.g. Baker, 1989), giving great flexibility to modeling applications. Finally, Markov models can be easily extended to simulation exercises (e.g. Cowling et al., 1997), and therefore are a valuable tool for making predictions.

In this paper, we develop a new method for using automated VHF telemetry data to derive impact functions for central-place foraging marine birds, based on a simple Markov model. We apply the model to empirical data on the duration of foraging flights and colony attendance bouts of common terns (*Sterna hirundo*) and Arctic terns (*S. paradisaea*) in the Gulf of Maine. We demonstrate the model's utility for the development of impact functions, for identifying defensible set-back distances, for quantifying the tradeoffs between ecological risk and wind capacity in planning scenarios, and for estimating mean number of fatalities. Since the data we use in this application is limited, the results in this paper are not intended to specifically inform management at the study site in Maine. Rather, we demonstrate the development of a new, flexible tool that can be adapted to specific management problems when adequate data are available. To this end, we present results under simple scenarios to demonstrate easily understandable and intuitive qualitative insights, and discuss important issues in data collection and model extension for applying this tool successfully in an actual planning or management application.

2. Material and methods

2.1. Focal species

Common and Arctic terns are migratory water birds that nest colonially on islands and shorelines, and plunge dive and surface dip for prey. Both species are of conservation concern in the eastern US and are under active management (U.S. Fish and Wildlife Service, 2008; 2012a). Terns are expected to be at risk in the Atlantic Ocean during the breeding, staging and migratory periods (Burger et al., 2011). The degree to which wind energy development will impact terns in the US is still uncertain. Both species decreased in abundance at offshore pilot projects in Denmark and the Netherlands (Vanermen et al., 2015), and experienced high collision fatality rates (6.7 terns per turbine per year) at wind farms located <1 km from colony sites (Everaert and Stienen, 2007).

2.2. Field methods

In 2013 on Petit Manan Island in Steuben Maine, USA (44.3676° N, 67.8644° W), we captured adult terns on the nest using walk-in treadle traps and bow nets (Burger et al., 1995). We back-mounted 1.4 g Lotek Nano Tag coded VHF radio transmitters (Avian NanoTag NTQB-4-2, Lotek Wireless Inc., Newmarket, ON; 163 day expected tag life) with dissolvable sutures. The tags comprised <2% of mean body mass for all birds. Each transmitter emitted a uniquely coded signal at 166.380 MHz every 4–5 s, allowing us to track all individuals simultaneously. We tracked the terns with an array of automated telemetry receivers deployed at the colony site on a 41 m lighthouse, and at surrounding islands (Fig. 1). Each telemetry station had 2–4 nine-element Yagi antenna mounted atop a structure, and a sensorgnome receiver (www.sensorgnome.org) that continuously logged a GPS-synchronized time and signal strength for each tag burst. We excluded false positives by requiring at least three subsequent tag bursts of a given ID at multiples of the ID's unique burst interval.

We used presence and absence data at the colony receiver to generate empirical distributions of flight and attendance bout duration (i.e. discrete visits to the colony), each in 4 min time bins. We used data from 7 individuals of each species that exhibited consistent detections at night. We determined this by visually inspecting plots of signal strength over time during nocturnal hours when terns generally spend longer contiguous periods on the nest (Bluso-Demers et al., 2010). We only included detections before July 25 in the analysis to ensure we excluded dispersal activity at the end of the breeding season. We identified foraging trips by determining each instance in which a bird was not detected at the colony for >15 min and <11 h. This cutoff eliminated potential instances in which a bird could be at the colony but undetectable for a short period due to topography or body position, but very likely still captured most foraging events, based on maximum provisioning rates of roughly 2 feedings per hour in Gulf of Maine colonies (Rosell et al., 2000). We excluded absences >11 h from analyses as these events represented <2% of the data and may signify phenomena other than foraging events. We recorded 1519 foraging flights for Arctic terns and 994 for common terns. We summed the

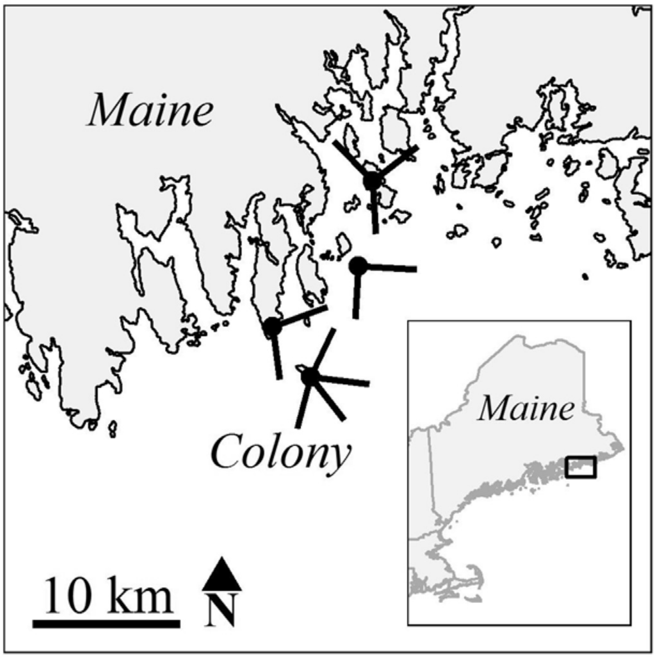

Fig. 1. Distribution of automated VHF telemetry receiving stations used to track radio-tagged common terns and Arctic terns tagged at the Petit Manan Island colony in Steuben Maine, USA during the 2013 breeding season. Lines show the orientation of antennas and extend to an approximate maximum detection range of 4 km.