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EVALUATING DIGITAL VHF TECHNOLOGY TO MONITOR SHOREBIRD AND SEABIRD USE OF OFFSHORE WIND ENERGY AREAS IN THE WESTERN NORTH ATLANTIC

A Dissertation Presented

by

PAMELA H. LORING

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ABSTRACT

EVALUATING DIGITAL VHF TECHNOLOGY TO MONITOR SHOREBIRD AND SEABIRD USE OF OFFSHORE WIND ENERGY AREAS IN THE WESTERN NORTH ATLANTIC

SEPTEMBER 2016

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Information on offshore movements of high priority bird species is needed for monitoring and managing adverse effects of offshore wind energy development in the western North Atlantic Ocean. This information is particularly important at night and during periods of inclement weather when risks of collision with offshore wind turbines may be elevated. For small-bodied avian taxa, technologies for monitoring movements of individually-marked birds are limited since satellite-based devices are still too heavy (> 5 g) for use on birds weighing < 150 g. In this dissertation, I evaluate the use of light-weight (1 to 1.5 g) digital VHF transmitters and a network of automated radio telemetry stations for tracking shorebirds and seabirds in offshore areas. In Chapter One, I compare digital VHF telemetry with satellite telemetry for tracking a shorebird, the American Oystercatcher (*Haematopus palliatus*), at nesting areas in coastal Massachusetts. In Chapter Two, I evaluate possible adverse effects and retention time of using a glue and suture method for attaching digital VHF transmitters to the inter-scapular region of Common Terns

(*Sterna hirundo*), a small-bodied seabird. In Chapter Three, I analyze data on the movements of digital VHF-tagged Common Terns and Arctic terns (*Sterna paradisaea*) from four colonies throughout the western North Atlantic Ocean to assess the utility of this technology for tracking birds at regional scales. In Chapter Four, I examine movements of digital VHF-tagged Common Terns from two colonies in southern New England shelf region of the U.S. Atlantic relative to Wind Energy Areas in state and federal waters. The aim of this chapter is to evaluate the use digital VHF telemetry for tracking terns across offshore Wind Energy Areas and to relate offshore movement events to temporal (time of day, calendar date), atmospheric (wind speed, precipitation rate, visibility) and demographic (sex, nesting colony) covariates associated with assessments of collision risk. Through these studies, I evaluate the safety and effectiveness of using digital VHF transmitter technology on non-Endangered Species Act listed shorebird and seabirds with the aim of informing future studies on two species of high conservation concern, the federally threatened Piping Plover (*Charadrius melodus*) and the federally endangered Roseate Tern (*Sterna dougallii*).

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COMPARING SATELLITE AND DIGITAL RADIO TELEMETRY TO ESTIMATE SPACE AND HABITAT USE OF AMERICAN OYSTERCATCHERS (*HAEMATOPUS PALLIATUS*) IN MASSACHUSETTS

Abstract

The use of digital VHF telemetry is expanding as a relatively light weight alternative to satellite-based technologies for tracking bird movements, though few studies have compared how they perform. During 2013, satellite telemetry and digital VHF telemetry were compared for estimating the length of stay, home ranges, and habitat characteristics of American Oystercatchers (*Haematopus palliatus*) on their breeding grounds in coastal Massachusetts, USA. American Oystercatchers ($n = 5$) were captured at their nest sites and tagged with both a 9.5 g solar-powered satellite transmitter, and a 1 g digitally coded VHF transmitter, and tracked using the Argos satellite system, an array of eight automated radio telemetry stations, and periodic land-based and aerial telemetry surveys. Estimates of mean minimum length of stay in the study area were slightly longer for satellite telemetry at 118 ± 12 days vs. digital VHF telemetry at 108 ± 11 days. Size estimates of mean (± SE) fixed kernel 95% utilization distributions were similar for satellite telemetry (22.53 ± 16.87 km^2) and VHF telemetry (27.27 ± 21.58 km^2), as were size estimates of 50% core-use areas (4.14 ± 2.99 km^2 for satellite telemetry and 4.80 ± 4.05 km^2 for VHF telemetry). Both satellite and VHF telemetry found tagged individuals most frequently occurring on coarse-grained sand beaches (mean proportion: 0.58 to 0.77), and salt to brackish marshes (mean proportion: 0.06 - 0.29). Despite a small sample size, digital VHF telemetry, when combined with automated radio telemetry stations and recurrent telemetry surveys, performed similarly to satellite telemetry for

estimating timing and home range size of shorebirds on their breeding grounds, although spatial distributions of home ranges varied between the two techniques.

Introduction

Advances in tracking technologies are expanding opportunities to collect new information on the movements and space use of shorebirds with important applications to conservation and management efforts (Brown *et al.* 2001; O'Connell *et al.* 2011). Various types of tracking technologies are used to monitor the movements of shorebirds (Warnock and Takekawa 2003; Schwemmer and Garthe 2011; Burger *et al.* 2012), each offering a unique set of tradeoffs in spatial and temporal resolution of location estimates, data storage and acquisition, cost per unit, and weight. Satellite-based Global Positioning System (GPS) technologies offer high spatial accuracy (< 30 m) and frequent sampling rates (one location per sec.; Tomkiewicz *et al*. 2010). However, the lightest available GPS units (currently 1 g) acquire limited numbers of locations (< 100 stored in the unit), requiring recovery of the device (M. van den Tillaart, pers. commun.). Other satellite-based technologies include Platform Transmitter Terminals (PTTs), which estimate locations using the Doppler effect, can obtain multiple locations per day with an optimal accuracy ranging from 250 to >1,500 m, and relay data in near-real time to an online server (Argos 2015). However, the smallest available PTTs are still relatively heavy (2 to 5 g) for use on small-bodied shorebird species since tags should be restricted to < 3 to 5% of body mass (Fair *et al*. 2010) and are available on a limited production run basis only (C. Bykowsky, pers. comm.). Further, at thousands of dollars per unit, the high cost of satellite-based tags may preclude robust sample sizes (Hebblewhite and Haydon 2010). Other types of tracking technologies used on shorebirds include light-level geolocators that are light-weight (< 1 g), but are limited to estimating two locations per day and routinely subject to errors of > 200 km, so are of limited use for studies requiring locations with high spatial and temporal resolution (Bridge *et al*. 2011). As with GPS units, geolocators also require that individuals are re-trapped to retrieve the data.

For small-bodied species (< 100 g), radio telemetry remains one of the sole options for collecting frequent, high-accuracy (optimally < 10 m) location data over extended durations (Ponchon *et al*. 2013). Radio transmitters are light-weight (≥ 0.25 g) devices with high pulse-rates (tens to hundreds of signals per minute) and relatively long operating life (> 4 months for 1-g units), that are tracked using specialized antennas and receiving systems (Kenward 1987). Automated radio telemetry stations, consisting of one or more antennas elevated on a mast and connected to a data-logging radio receiver, allow researchers to track animals continuously within target geographic areas (Cochran *et al*. 1965; Larkin *et al*. 1996). Automated radio telemetry has been used to examine shorebird foraging ecology and movements during the nesting period (Sherfy *et al*. 2012.), duration and movements during staging (Verkuil *et al*. 2010), home ranges and local movements on wintering grounds (Leyrer *et al*. 2006), and long-distance movements along migratory corridors (Green *et al*. 2002).

With traditional radio telemetry, each transmitter operates on a unique frequency and receiving systems monitor a single transmitter at a time, resulting in a trade-off between sample size and sampling frequency (Kenward 1987). Recent advances in the development of light-weight, digitally-coded VHF transmitters now make it possible to continuously track the movements of hundreds of individuals on a single frequency (Mills *et al*. 2011; Taylor *et al*. 2011; Woodworth *et al*. 2014). With some limitations, digital VHF telemetry can thus offer a lightweight alternative to satellite-based tracking technologies for monitoring movements of small-bodied species at regional scales.

In this study, we compared digital VHF telemetry and satellite telemetry for estimating length of stay, home range size and distribution, and habitat characteristics of a coastal-nesting shorebird, the American Oystercatcher (*Haematopus palliatus*), on breeding grounds within coastal Massachusetts, USA.

Methods

We conducted fieldwork in eastern Nantucket Sound, Massachusetts, USA (Fig. 1.1). We captured and tagged American Oystercatchers on Monomoy National Wildlife Refuge (NWR; 41° 36’ 31.53” N, 69° 59’ 12.86” W), a 30 km^2 barrier beach and island complex, and on Coskata-Coatue Wildlife Refuge on Nantucket Island, Massachusetts (41°19′26.23” N 70°03′49.22” W), a 10 km^2 barrier beach system. Monomoy NWR and adjacent South Beach in Chatham, Massachusetts, support 30 to 35 breeding pairs of American Oystercatchers annually and over 200 individuals during the fall staging period (Schulte *et al*. 2007). Coaskata-Coatue Wildlife Refuge on Nantucket has a high density of nesting sites for American Oystercatchers in the Northeast, supporting up to 40 nesting pairs annually and flocks of 15 to 20 individuals during the fall staging period (Schulte *et al*. 2007).

Capture and Transmitter Attachment

From 16 May to 5 June 2013, we used decoys, playback calls, and whoosh nets to capture nesting adult American Oystercatchers during the incubation period. We banded each American Oystercatcher with an incoloy U.S. Geological Survey band below the tarso-metatarsal joint and duplicate engraved color Darvic bands with a unique alphanumeric combination above each tarso-metatarsal joint. We used a modified version of the figure-8 leg loop harness (Sanzenbacher *et al*. 2000) to attach a combination of a 9.5 g (38 x 17 x 12 mm) solar-powered PTT (Microwave Telemetry, Inc.) and a 1.0 g (11 x 8 x 7 mm) digital VHF transmitter ('Avian NanoTag'; Lotek Wireless, Inc.) to a total of five American Oystercatchers, two from Monomoy NWR and three from Nantucket. We modified the Sanzanbacher design by using Teflon ribbon (4 mm width) as harness ligature, and by gluing a 40 x 20 x 2 mm square of Neoprene fabric to the base of the satellite transmitter to provide padding at the attachment site. The combined weight of the PTT, VHF transmitter, and attachment materials did not exceed 3% of the body mass of each tagged individual. Since there was no overlap in the operating frequencies or harmonics of the PTT (401.650 MHz) and the digital VHF transmitter (166.380 MHz), we assumed that electrical interference between the two devices was not a factor.

Satellite Telemetry

PTTs were programmed to transmit locations to Argos satellites on a 10 hr on, 24 hr off, duty cycle for an expected operating life of approximately two years. Locations had an optimal accuracy of 250 m (Argos Accuracy Classification "L3"; Argos 2015) and were relayed to an online server. We used the Douglas-Argos program (Douglas *et al*. 2012) in SAS (SAS Institute 2008) to download and process Argos data transmitted by the PTTs, and retained all locations with estimated accuracy classifications < 500 m (Argos Accuracy Classification "L2") for subsequent analysis.

Digital VHF Telemetry

Digital VHF transmitters were programmed to transmit signals on 166.380 MHz every 5 - 6 seconds, for a total expected operational life of 163 days. Signals from VHF transmitters were received by a network of six automated radio telemetry towers erected at coastal and island sites in eastern Nantucket Sound, Massachusetts (Fig. 1.1). Each tower consisted of an array of six Yagi antennas end-mounted in a radial configuration atop a 9.2 m mast. Each antenna was separated by 60° with a horizontal plane beam-width of 35°. The antennas were connected to a solar-powered, automated receiving unit (SRX 600; Lotek Wireless, Inc.) that scanned for signals with each antenna for 6.5 seconds in succession, 24 hrs per day. We also operated a receiving station consisting of a SRX-600 receiver equipped with a single omnidirectional (200 W) antenna on a passenger ferry that followed a north-south route across Nantucket Sound two to six times per day. All receiving units were programmed to automatically log several types of data from each antenna, including: transmitter ID number, time stamp (synchronized among all receivers in network using GPS clocks), antenna (defined by receiving station and bearing), and signal strength (non-linear scale: 0 to 255). We tested detection ranges of the radio telemetry stations to ground-level targets by placing a test transmitter at known distances and orientations from the receiving antennas**.** From these tests, we determined that the maximum range of the automated radio telemetry towers with Yagi antennas was approximately 1 km to targets at ground level. The range of the omni-directional antenna on the ferry was < 0.5 km to targets at ground level.

In addition to tracking American Oystercatchers using automated radio telemetry techniques, we also conducted land-based and aerial telemetry surveys to relocate individuals that may have moved outside of the range of our automated radio telemetry array. From June through September 2013, we used land-based VHF telemetry techniques to relocate tagged individuals at nesting, feeding, and roosting sites up to five days per week. During these surveys, we used a hand-held, 3-element Yagi antenna and a SRX-600 receiver to scan for VHF transmitters. We followed individuals on foot and used a hand-held compass to record the bearing of maximum signal strength of the VHF transmitter. When individuals were in view, we estimated their locations using bearings of maximum signal strength and distance. When possible we determined their position using bi-angulation or triangulation techniques from multiple bearing and distance estimates.

From July through September, 19 aerial VHF telemetry surveys were conducted to search for tagged American Oystercatchers along 1,540 km of transects throughout Nantucket Sound and adjacent coastal waters. Transects were flown in a fixed-wing aircraft at an altitude of 229 m (750 ft) and an air speed of approximately 100 knots. The aircraft was equipped with a pair of 4-element, Yagi antennas, mounted at a 45° angle to each strut. Each antenna connected to a SRX-600 receiver via a switchbox that was used to toggle between antennas so that signals could be isolated on one side of the airplane to localize individuals.

We used a filtering algorithm in the statistical program R (R Development Core Team 2015) to remove false detections from the raw VHF telemetry data collected by the automated radio telemetry stations, and during land and boat-based telemetry surveys, based on the following parameters: minimum of three consecutive bursts required to comprise a run, a maximum of 20 consecutive missed bursts allowed within each run, and a maximum deviation of four milliseconds from a tag's unique burst interval between its consecutive bursts (J. Brzustowski, pers. commun.). For aerial telemetry data, we used the same criteria as above but allowed a minimum of two consecutive bursts to comprise a run because the relatively high speed (100 knots) of the aircraft resulted in missed detections of test beacons using the three consecutive burst criteria (P. Loring, unpubl. data).

Data Analyses

We conducted all statistical analyses using the program R (R Development Core Team 2015). We tested for differences between PTTs and VHF transmitters in total number of detections, number of unique days detected, and estimated length of stay in study area using non-parametric Wilcoxon signed-rank tests, since the data were non-normally distributed. To examine home ranges, we randomly selected datasets consisting of 25 locations per individual and transmitter to generate kernel density estimates (Worton 1989). For each dataset, we determined the sample size by visually delineating asymptotes of area-observation curves (Kernohan *et al*. 2001), and randomly sampled locations that were separated by a minimum of 12-hrs to reduce serial autocorrelation (Swihart and Slade 1997). We generated home ranges as kernel density estimates (0.95 utilization distributions and 0.50 core use areas) with the software Geospatial Modeling Environment (Beyer 2011), using a Gaussian kernel and cross-validation bandwidth estimator, which outperforms other estimators when estimating kernel density estimates from sample sizes < 50 (Horne and Garton 2006), and selected a grid size of 250-m to correspond with optimal locational accuracy of the PTTs. We used Wilcoxon signed-rank tests to examine differences between VHF and PTT data in the total area of both 0.95 utilization distributions and 0.50 core-use areas estimated for each bird. We examined static interaction of kernel density estimates (0.95 and 0.50, respectively) by quantifying the proportion of overlap among kernel density estimates generated from VHF and PTT data for each double-tagged bird (Kernohan *et al*. 2001).

We used Environmental Sensitivity Index (ESI) data (National Oceanic and Atmospheric Administration 2004) to compare the proportion of shoreline habitat types within 0.95 utilization distributions and 0.50 core-use areas generated by PTT versus VHF transmitters. ESI habitat types were categorized as coarse-grained sand beaches, fine-grained sand beaches, exposed rocky shores, riprap structures, sheltered human-made structures, salt to brackish marshes, and exposed tidal flats.

Results

Location data were collected from two of the American Oystercatchers until 15 to 19 August, 2013, when the tags were lost as confirmed by band resighting. Locations were collected from two additional individuals later into the season (9 September and 25 October 2013), though PTTs never transmitted locations outside of the study area, indicating transmitter loss or malfunction prior to fall migration. The remaining bird retained its PTT through migration, departing from the study area on 29 October 2013 to wintering areas in the southeastern United States, where it transmitted location data through 4 January 2014.

The mean (± SE) number of locations with estimated accuracy $\leq$ 500 m recorded per tagged individual was 317 (± 42) for PTTs and 375 (± 169) for VHF transmitters, with no significant difference among transmitter type (Wilcoxon Signed Rank Test $V = 8$, $P = 1$; Table 1.1). A higher mean (± SE) proportion of PTT locations per individual were obtained within the < 250 m accuracy class (0.61 ± 0.01) than the 250 to 500 m accuracy class (0.39 ± 0.01; Table 1.1). For VHF transmitters, the mean (± SE) proportion of locations recorded per bird was similar between those detected by automated radio telemetry stations (0.50 ± 0.20) and by manual telemetry surveys (0.50 ± 0.20; Table 1). However, the mean (± SE) number of days that each bird was detected was higher (Wilcoxon Signed Rank Test $V = 0$, $P = 0.062$) for PTTs (61 ± 5 days) than VHF transmitters (30 ± 10 days), indicating that PTT locations were more evenly sampled in time than VHF locations (Table 1.2). The PTT data also indicated a slightly longer mean length of stay in the study area (118 ± 12 days) than did the VHF data (108 days ± 11; Wilcoxon Signed Rank Test V = 0, P = 0.063; Table 1.2).

Three American Oystercatchers provided enough data for comparisons of utilization distributions between their PTT and VHF locations (Figs. 1.2 – 1.4). For these three individuals, estimates of mean (± SE) fixed kernel 95% utilization distribution and 50% core-use areas estimated from PTT locations did not significantly differ (Wilcoxon Signed-Rank Test $V = 5$, $P = 0.5$ for 95% UD and V = 3, $P = 1$ for 50% CU) from estimates of mean fixed kernel 95% home range and 50% core use areas estimated from VHF locations (Table 1.3). Mean (± SE) percent spatial overlap of kernel density estimates from satellite telemetry and digital VHF telemetry was 67% (± 6%) for 95% utilization distributions and 32% (± 11%) for 50% core use areas.

The mean (± SE) proportion of shoreline habitat types in the 95% utilization distributions was similar between satellite telemetry estimates and VHF telemetry estimates, and was predominantly coarse-grained sand beaches (0.58 ± 0.22 and 0.58 ± 0.21) and salt to brackish marshes (0.29 ± 0.20 and 0.19 ± 0.12), with lesser mean proportions (≤ 0.15) of riprap structures, exposed rocky shorelines, sheltered human-made structures, fine-grained sand beaches, and exposed tidal flats (Fig. 1.5A). Similar to the 95% utilization distributions, mean (± SE) proportion of habitat types within 50% core use areas for both satellite and VHF telemetry estimates was predominantly coarse-grained sand beaches (0.63 ± 0.20 and 0.77 ± 0.18, respectively), and salt to brackish marshes (0.24 ± 0.13 and 0.06 ± 0.03, respectively), with lesser proportions (≤ 0.05) of the other shoreline habitat types (Fig. 1.5B).

Discussion

Our study found that digital VHF telemetry generally performed similarly to satellite telemetry for quantifying timing and space-use of American Oystercatchers on their breeding grounds, although the scope of inference from our results is limited due to small sample sizes and tag loss. Estimates of length of stay and home range size should be considered a minimum since the majority of tagged individuals in our study lost their back-pack units prior to departing from the study area. However, metrics obtained from PTTs could still be directly compared to those obtained from VHF transmitters because individual American Oystercatchers dropped their PTT and VHF transmitters simultaneously.

Studies on Black Oystercatcher (*Haematopus bachmani*) have also reported poor retention of dorsal-mounted transmitters attached with similar leg-loop harnesses (e.g., Johnson *et al*. 2010). Double-layered teflon ribbon harnesses may help improve retention, however to our knowledge this has not been widely field tested. Other methods of attaching transmitters to shorebirds including coelemic implants and epoxy to the leg band (Warnock and Takekawa 2003), may also increase retention time. However, injuries (Nisbet *et al*. 2011) and high mortality rates (Johnson *et al*. 2010) have been associated with these techniques.

In our study, three of five VHF tags and all five PTTs provided enough data to estimate home ranges. Due to the small sample size and high variability, our results should be interpreted cautiously (Kernohan *et al*. 2001). However, the home range sizes of American Oystercatchers in our study are consistent with other studies reporting individual-based movements of *Haematopus* oystercatchers on breeding grounds, and documented movements between nesting and foraging areas that ranged from < 1 km (Ens *et al*. 1992; Virzi and Lockwood 2010; Schwemmer and Garthe 2011) to over 5 km (Schwemmer and Garthe 2011). Within home ranges, American Oystercatchers in our study primarily used coarse-grained sand and marsh habitats, a finding similar to several other studies (Nol and Humphrey 2012). Aebischer et al. (1993) suggest a minimum sample size of 6 individuals were needed to compare habitat use among techniques, therefore we did not have enough data to statistically compare habitat use between VHF and PTT locations.

Estimates of timing, home range size, and habitat proportion were generally similar between VHF and PTT data. However, because the VHF locations were more clumped in time and space than PTTs, the PTTs were detected on twice as many unique days relative to VHF transmitters. The extent of spatial overlap among home range estimates from PTTs and VHF locations was also variable. These differences in the spatial and temporal resolution between VHF and PTT data likely resulted from the way locations were acquired using each tracking technology. The VHF transmitters were programmed to emit signals every five to six seconds, but needed to be within range of an automated radio telemetry station, or detected during manual telemetry surveys, to be relocated. The PTTs, in contrast, transmitted signals every 90 to 200 sec. during a 10-hr transmission period, which occurred every 24 hrs, and needed only to be within range of visibility of polar-orbiting satellites to acquire a location. The clear advantage of satellite-based tracking technology over VHF technology is that it permits systematic sampling anywhere on the globe, so it is an especially suitable tool for studying the long-distance movements of wide-ranging species (Hebblewhite and Haydon 2010). However, the spatial and temporal resolution of PTT data is relatively coarse, and PTTs require prolonged off periods necessary for conserving battery power. In contrast, VHF locations can achieve optimal accuracy of < 10 m, and can be monitored nearly continuously through targeted geographic areas using automated radio telemetry stations as long as tagged individuals are within range of a receiver (Bridge *et al*. 2011).

To maximize the quality of location estimates from automated radio telemetry stations, it is important to consider the height, spacing, and positioning of antennas, and the life histories of target species. Accuracy of position estimates is improved when antenna beams from multiple stations detect animals simultaneously (White and Garrott 1990), so the home range size of target species and detection range of the telemetry system should be considered when siting automated radio telemetry stations on the landscape. Maximizing detection range also depends largely on maximizing antenna height (Cochran 1980), and since VHF waves emitted by transmitters travel within line-of-sight, factors such as topography, vegetation, and electronic noise can block, reflect, or attenuate the signal (Kenward 1987).

Conducting regular telemetry surveys, by foot, boat, or plane is an effective way to supplement locations collected by the automated radio telemetry towers, and relocate individuals that may have moved outside the range of automated radio telemetry towers.

Land-based telemetry surveys can be used to search for tags within targeted areas, and facilitate direct observations of marked individuals that can be combined with behavioral or *in situ* habitat sampling. By comparison, boat-based and aerial telemetry surveys permit systematic searches over larger geographic areas. While conventional telemetry surveys are useful for searching for individuals that may have moved outside of the detection range of automated radio telemetry stations, these surveys can incur considerable effort, personnel, and travel costs. The cost of the tracking VHF transmitters is scaled according to the number of VHF transmitters deployed on the shared frequency, and may be partially offset by coordinating efforts with complimentary studies, cost comparisons of tracking VHF transmitters and PTTs are not straightforward. Ground work is useful for supplementing VHF stations but may not be necessary depending on the objectives and design of the telemetry study. Conventional telemetry surveys are most effective for studies where tagged individuals do not range widely, such as tracking American Oystercatchers on their breeding grounds. Remote tracking of satellite-tagged individuals is thus more suitable for studies covering a wider geographic extent, such as migration.

Despite the considerable resources required to track VHF transmitters over long-distances, efforts are underway in the western Hemisphere to coordinate digital VHF tracking projects and receiving stations on a shared frequency (e.g., the Motus Wildlife Tracking System), allowing for thousands of tagged animals to be detected on an expanding network of receiving stations throughout North and South America. Thus, with strategic deployment and coordination of receiving equipment, digital VHF telemetry can now be used to track land-scape scale movements of birds with relatively high spatial and temporal resolution, something that was recently only possible with satellite-based technologies. However, satellite-based technologies remain the sole option for global, high-resolution wildlife tracking throughout the annual cycle.

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Literature Cited

Aebischer, N. J., P. A. Robertson and R. E. Kenward. 1993. Compositional analysis of habitat use from animal radio-tracking data. Ecology 74: 1313-1325.

American Oystercatcher Working Group, E. Nol and R. C. Humphrey. 2012. No. 082 in The Birds of North America Online (A. Poole, Ed.). Cornell Lab of Ornithology, Ithaca, New York. http://bna.birds.cornell.edu/bna/species/082, accessed 3 June 2015.

Argos. 2015. Argos user's manual. Collecte Localisation Satellites/Argos, Toulouse, France. http://www.argos-system.org, accessed 30 June 2015.

Beyer, H.L. 2011. Geospatial modelling environment software v. 0.7.2.1. Spatial Ecology, LLC, Toronto, Canada. http://www.spatialecology.com/gme, accessed 10 June 2015.

Bridge, E. S., K. Thorup, M. S. Bowlin, P. B. Chilson, R. H. Diehl, R. W. Fléron, P. Hartl, R. Kays, J. F. Kelly and W. D. Robinson. 2011. Technology on the move: recent and forthcoming innovations for tracking migratory birds. BioScience 61: 689-698.

Brown, S., C. Hickey, B. Harrington and R. Gill, Eds. 2001. The U. S. Shorebird conservation plan, 2nd ed. Manomet Center for Conservation Sciences, Manomet, Massachusetts.

Burger, J., L. J. Niles, R. R. Porter, A. D. Dey, S. Koch and C. Gordon. 2012. Migration and over-wintering of Red Knots (*Calidris canutus rufa*) along the Atlantic Coast of the United States. Condor 114: 302-313.

Cochran, W. W. 1980. Wildlife telemetry. Pages 507-520 *in* Wildlife Management Techniques (S. P. Schemnitz, Ed.), 4th ed. The Wildlife Society, Inc., Washington, D.C.

Cochran, W. W., D. W. Warner, J. R. Tester and V. B. Kuechle. 1965. Automatic radio-tracking system for monitoring animal movements. BioScience 15: 98-100.

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.

Ens, B. J., M. Kersten, A. Brenninkmeijer and J. B. Hulscher. 1992. Territory quality, parental effort and reproductive success of oystercatchers (*Haematopus ostralegus*). Journal of Animal Ecology 61: 703-715.

Fair, J. M., E. Paul, J. Jones, A. B. Clark, C. Davie and G. Kaiser. 2010. Guidelines to the Use of Wild Birds in Research. Third edition. Ornithological Council, Washington, DC. www.nmnh.si.edu/BIRDNET/guide, accessed 21 July 2015.

Green, M., T. Piersma, J. Jukema, P. De Goeij, B. Spaans and J. Van Gils. 2002. Radio-telemetry observations of the first 650 km of the migration of Bar-tailed Godwits (*Limosa lapponica)* from the Wadden Sea to the Russian Arctic. Ardea 90: 71-80.

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 of London B: Biological Sciences 365: 2303-2312.

Horne, J. S. and E. O. Garton. 2006. Likelihood cross-validation versus least squares cross-validation for choosing the smoothing parameter in kernel home-range analysis. Journal of Wildlife Management 70: 641-648.

Johnson, M., P. Clarkson, M. I. Goldstein, S. M. Haig, R. B. Lanctot, D. F. Tessler and D. Zwiefelhofer. 2010. Seasonal movements, winter range use, and migratory connectivity of the Black Oystercatcher. Condor 112: 731-743.

Kenward, R. 1987. Wildlife radio tagging. Academic Press, San Diego, California.

Kernohan, B. J., R. A. Gitzen and J. J. Millspaugh. 2001. Analysis of animal space use and movements. Pages 125-166 *in* Radio tracking and animal populations (J.J. Millspaugh and J.M. Marzluff, eds). Academic Press, San Diego, California.

Larkin, R. P., A. Raim and R. H. Diehl. 1996. Performance of a non-rotating direction-finder for automatic radio tracking. Journal of Field Ornithology 67: 59-71.

Leyrer, J., B. Spaans, M. Camara and T. Piersma. 2006. Small home ranges and high site fidelity in Red Knots (*Calidris c. canutus*) wintering on the Banc d’Arguin, Mauritania. Journal of Ornithology 147: 376-384.

Mills, A. M., B. G. Thurber, S. A. Mackenzie and P. D. Taylor. 2011. Passerines use nocturnal flights for landscape-scale movements during migration stopover. Condor 113: 597-607.

National Oceanic and Atmospheric Administration. 2004. Sensitivity of Coastal Environments and Wildlife to Spilled Oil: Massachusetts. Unpublished report, National Ocean Service, Office of Response and Restoration, Hazardous Materials Response Division, Seattle, Washington and the Coastal Services Center, Charleston, South Carolina. http://response.restoration.noaa.gov/maps-and-spatial-data/download-esi-maps-and-gis-data.html, accessed 15 June, 2015.

Nisbet, I. C. T., C. S. Mostello, R. R. Veit, J. W. Fox and V. Afanasyev. 2011. Migrations and winter quarters of five Common Terns tracked using geolocators. Waterbirds 34: 32-39.

O'Connell, A., C. S. Spiegel and S. M. Johnston. 2011. Compendium of Avian Occurrence Information for the Continental Shelf Waters along the Atlantic Coast of the United States, Final Report (Database Section - Shorebirds). Unpublished report, U.S. Department of the Interior, Fish and Wildlife Service, Hadley, Massachusetts.

Ponchon, A., D. Gremillet, B. Doligez, T. Chambert, T. Tveraa, J. González-Solís and T. Boulinier. 2013. Tracking prospecting movements involved in breeding habitat selection: insights, pitfalls and perspectives. Methods in Ecology and Evolution 4: 143-150.

R Development Core Team. 2015. R: a language and environment for statistical computing v. 3.0.2. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/, accessed 17 May 2015.

Sanzenbacher, P., S. M. Haig and L. W. Oring. 2000. Application of a modified harness design for attachment of radio transmitters to shorebirds. Wader Study Group Bulletin 91: 16-20.

SAS Institute, Inc. 2008. SAS statistical software v. 9.2. SAS Institute, Inc., Cary, North Carolina.

Schwemmer, P. and S. Garthe. 2011. Spatial and temporal patterns of habitat use by Eurasian Oystercatchers (*Haematopus ostralegus*) in the eastern Wadden Sea revealed using GPS data loggers. Marine Biology 158: 541-550.

Sherfy, M. H., M. J. Anteau, T. L. Shaffer, M. A. Sovada and J. H. Stucker. 2012. Foraging ecology of least terns and piping plovers nesting on central Platte River sandpits and sandbars. Open-File Report 2012-1059, U.S. Department of the Interior, U.S. Geological Survey, Reston, Virginia.

Swihart, R. K. and N. A. Slade. 1997. On testing for independence of animal movements. Journal of Agricultural, Biological, and Environmental Statistics 2: 48-63.

Taylor, P. D., S. A. Mackenzie, B. G. Thurber, A. M. Calvert, A. M. Mills, L. P. McGuire and C. G. Guglielmo. 2011. Landscape movements of migratory birds and bats reveal an expanded scale of stopover. PLOS ONE 6:e27054.

Tomkiewicz, S. M., M. R. Fuller, J. G. Kie and K. K. Bates. 2010. Global positioning system and associated technologies in animal behaviour and ecological research. Philosophical Transactions of the Royal Society of London B: Biological Sciences 365: 2163-2176.

Verkuil, Y. I., J. J. Wijmenga, J. C. E. W. Hooijmeijer and T. Piersma. 2010. Spring migration of Ruffs *Philomachus pugnax* in Fryslân: estimates of staging duration using resighting data. Ardea 98: 21-33.

Virzi, T. and J. L. Lockwood. 2010. Conservation of American Oystercatchers in New Jersey. Unpublished report. Unpublished report, Rutgers, New Brunswick, New Jersey.

Warnock, N. and J. Y. Takekawa. 2003. Use of radio telemetry in studies of shorebirds: past contributions and future directions. Wader Study Group Bulliten. 100: 138-150.

White, G. and R. Garrott. 1990. Analysis of wildlife radio-tracking data. Academic Press, San Diego, California.

Woodworth, B. K., C. M. Francis and P. D. Taylor. 2014. Inland flights of young Red-eyed Vireos *Vireo olivaceus* in relation to survival and habitat in a coastal stopover landscape. Journal of Avian Biology 45: 387-395.

Worton, B. J. 1989. Kernel methods for estimating the utilization distribution in home-range studies. Ecology 70: 164-168.

Table 1.1. Identification number (ID) and frequency count (*n*) of locations of American Oystercatchers estimated by satellite Platform Transmitter Terminals (PTT) and VHF radio transmitters on breeding grounds in coastal Massachusetts in 2013. Proportions are shown for PTT locations by estimated accuracy intervals (LC 3: < 250 m and LC 2: 250 to < 500 m), and for VHF locations by tracking method: automated radio telemetry tower (Tower), receiving station on passenger ferry (Ferry), land-based radio telemetry survey (Land), and aerial radio telemetry survey (Aerial).

			Proportion of locations by type					
	Locations (n)		PTT		VHF			
ID	PTT	VHF	LC3	LC2	Tower	Ferry	Land	Aerial
68	240	48	0.65	0.35	0.00	0.00	0.85	0.15
69	326	950	0.59	0.41	0.13	0.70	0.14	0.03
70	208	297	0.58	0.42	0.45	0.46	0.08	0.01
71	386	53	0.63	0.37	0.00	0.00	0.00	1.00
72	427	529	0.62	0.38	0.75	0.00	0.00	0.25

Table 1.2. Identification number (ID), capture site (Coskata-Coatue Wildlife Refuge, Nantucket [Nantucket] and Monomoy National Wildlife Refuge [Monomoy]), capture date, number of unique days tracked (unique days), estimated length of stay in study area, and last date in study area for American Oystercatchers (*n*=5) fitted with satellite Platform Transmitter Terminals (PTTs) and VHF transmitters on breeding grounds in coastal Massachusetts in 2013.

			Unique days		Length of stay		Last date in study area	
ID	Capture site	Capture date	PTT	VHF	PTT	VHF	PTT	VHF
68	Nantucket	05/16/13	52	9	90	83	08/14/13	08/07/13
69	Nantucket	05/17/13	62	47	115	111	09/09/13	09/05/13
70	Nantucket	05/16/13	46	28	95	90	08/19/13	08/14/13
71	Monomoy	6/5/2013	71	10	142	112	10/25/13	09/25/13
72	Monomoy	6/5/2013	73	57	146	145	10/29/13	10/28/13

Table 1.3. Total area (km^2) by transmitter type and percent (%) overlap between transmitter type of individual core-use areas (50% isopleth) and utilization distributions (95% isopleth) for American Oystercatchers (*n* = 3) fitted with satellite Platform Transmitter Terminals (PTTs) and VHF transmitters on breeding grounds in coastal Massachusetts in 2013.

	Area (km^2)							
	50%		95%		Overlap (km^2)		Overlap (%)	
ID	PTT	VHF	PTT	VHF	50%	95%	50%	95%
69	10.11	12.89	56.27	70.29	6.85	52.01	53	74
70	1.02	0.46	5.46	2.79	0.12	1.99	25	71
72	1.30	1.05	5.87	8.71	0.18	4.85	17	56

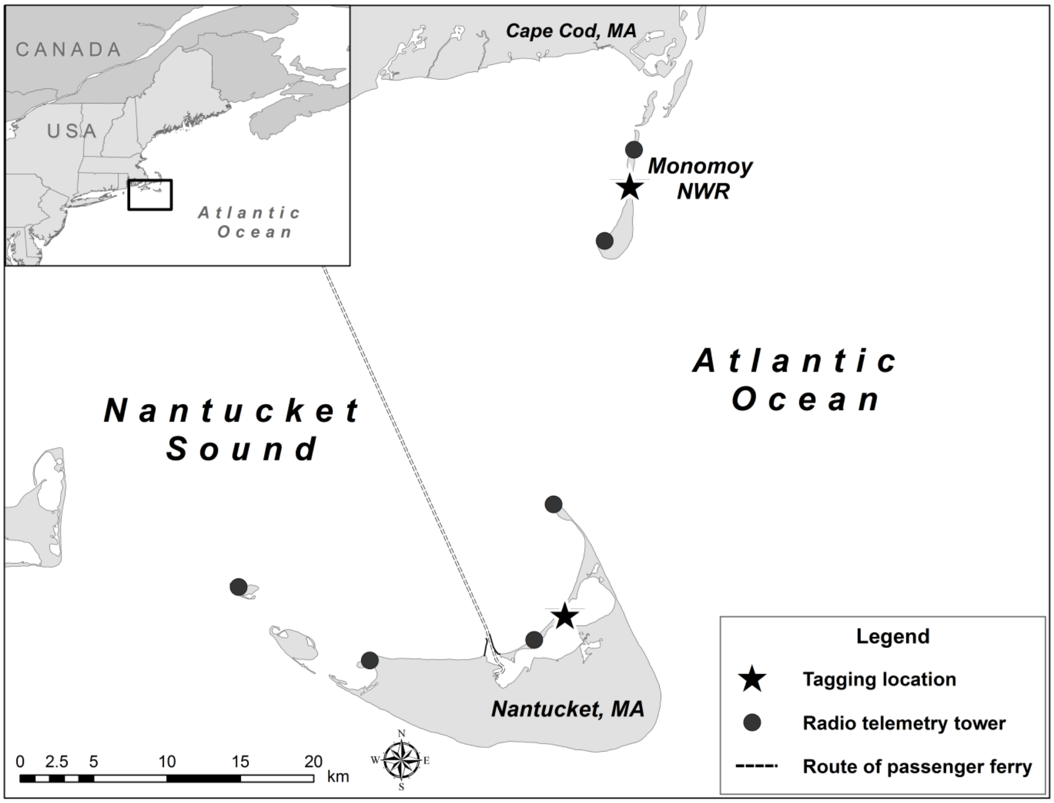
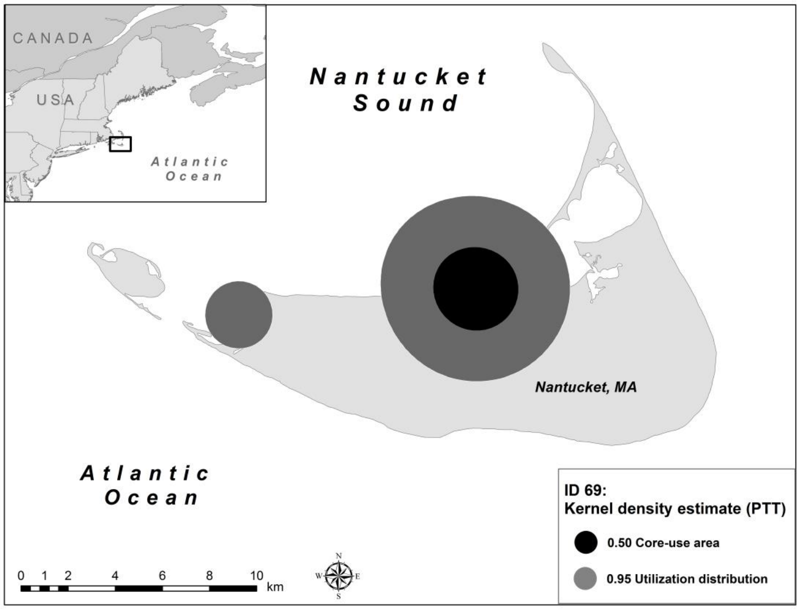


Figure 1.1. Map of 2013 study area in coastal Massachusetts, USA, showing tagging locations (black stars) of American Oystercatchers (*n*=5) at breeding sites on Monomoy National Wildlife Refuge (NWR) and Coskata-Coatue Wildlife Refuge (Nantucket), locations of six land-based automated radio telemetry towers (black circles), and the route (dashed line) of an automated radio telemetry receiver on a passenger ferry in Nantucket Sound.

A.



B.

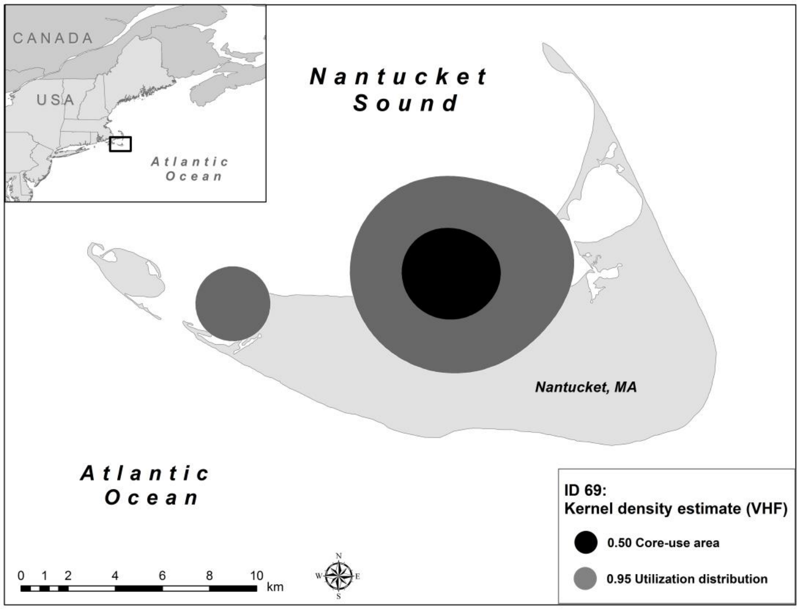


Figure 1.2. Kernel density estimate (KDE) of the core-use areas (dark grey, 50% isopleth) and utilization distribution (light grey, 95% isopleth) of a double-tagged American Oystercatcher (ID number 69), estimated by locations from a satellite Platform Transmitter Terminal (PTT; 3A, top) and a VHF radio transmitter (3B, bottom) on breeding grounds in coastal Massachusetts during 2013.

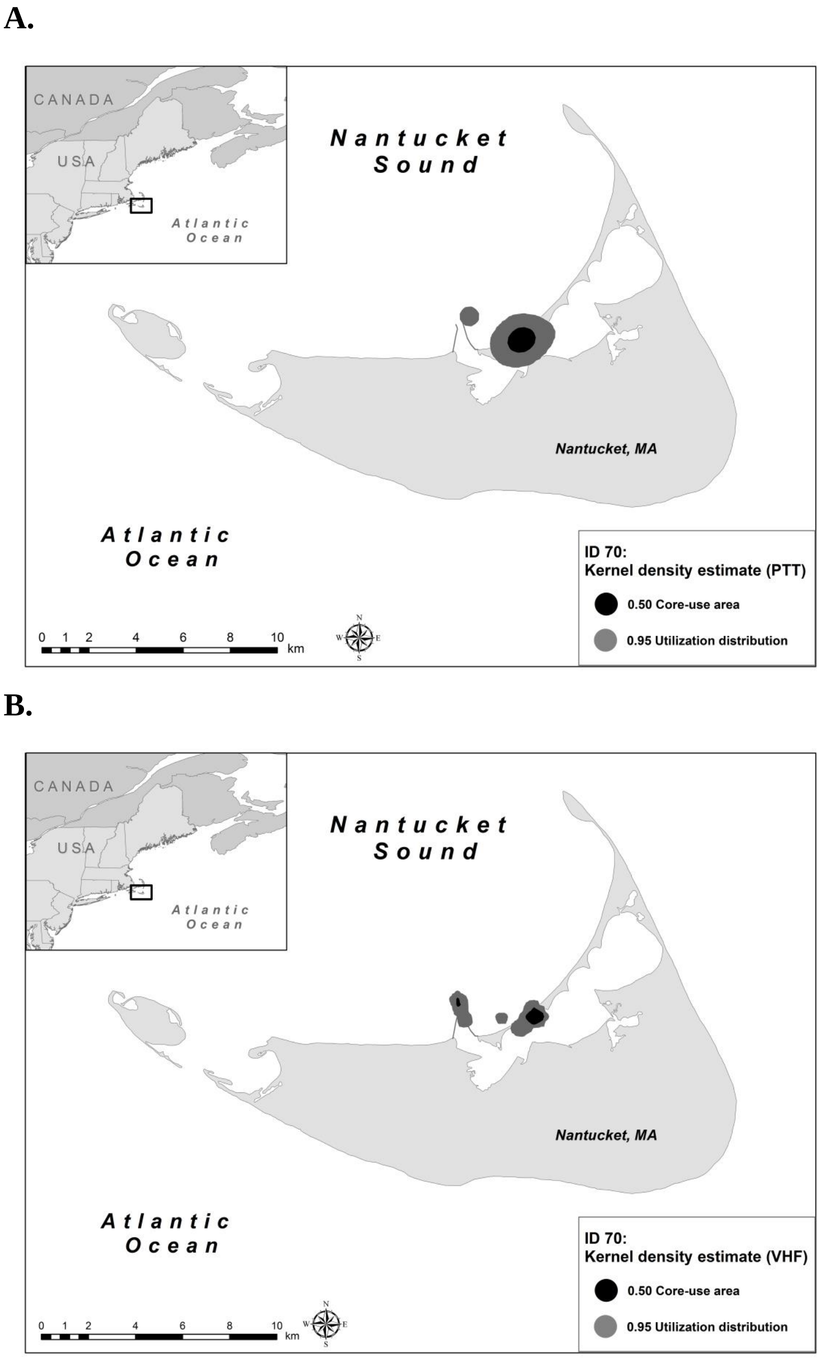


Figure 1.3. Kernel density estimate (KDE) of the core-use areas (dark grey, 50% isopleth) and utilization distribution (light grey, 95% isopleth) of a double-tagged American Oystercatcher (ID number 70), estimated by locations from a satellite Platform Transmitter Terminal (PTT; 3A) and a VHF radio transmitter (3B) on breeding grounds in coastal Massachusetts during 2013.

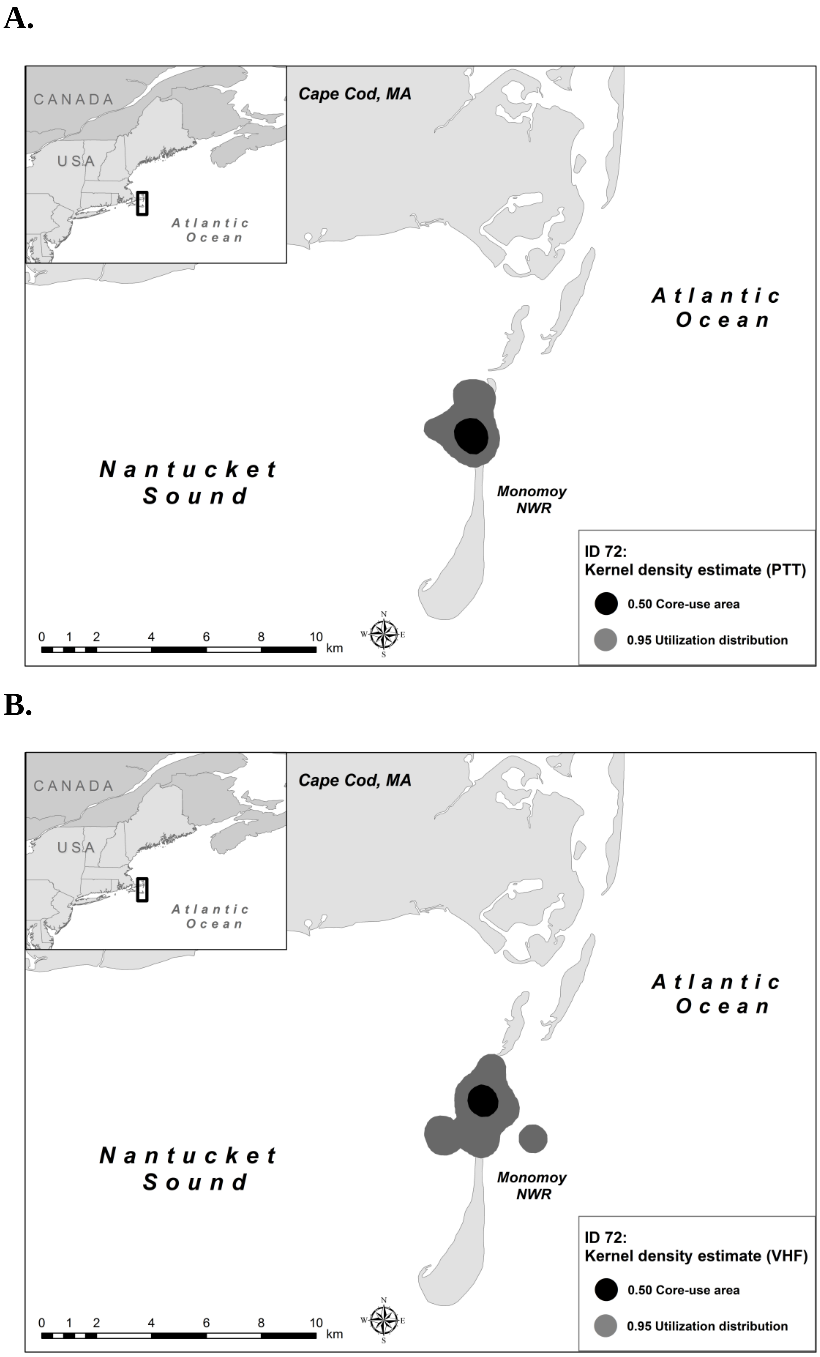


Figure 1.4. Kernel density estimate (KDE) of the core-use areas (dark grey, 50% isopleth) and utilization distribution (light grey, 95% isopleth) of a double-tagged American Oystercatcher (ID number 72), estimated by locations from a satellite Platform Transmitter Terminal (PTT; 3A) and a VHF radio transmitter (3B) on breeding grounds in coastal Massachusetts during 2013.

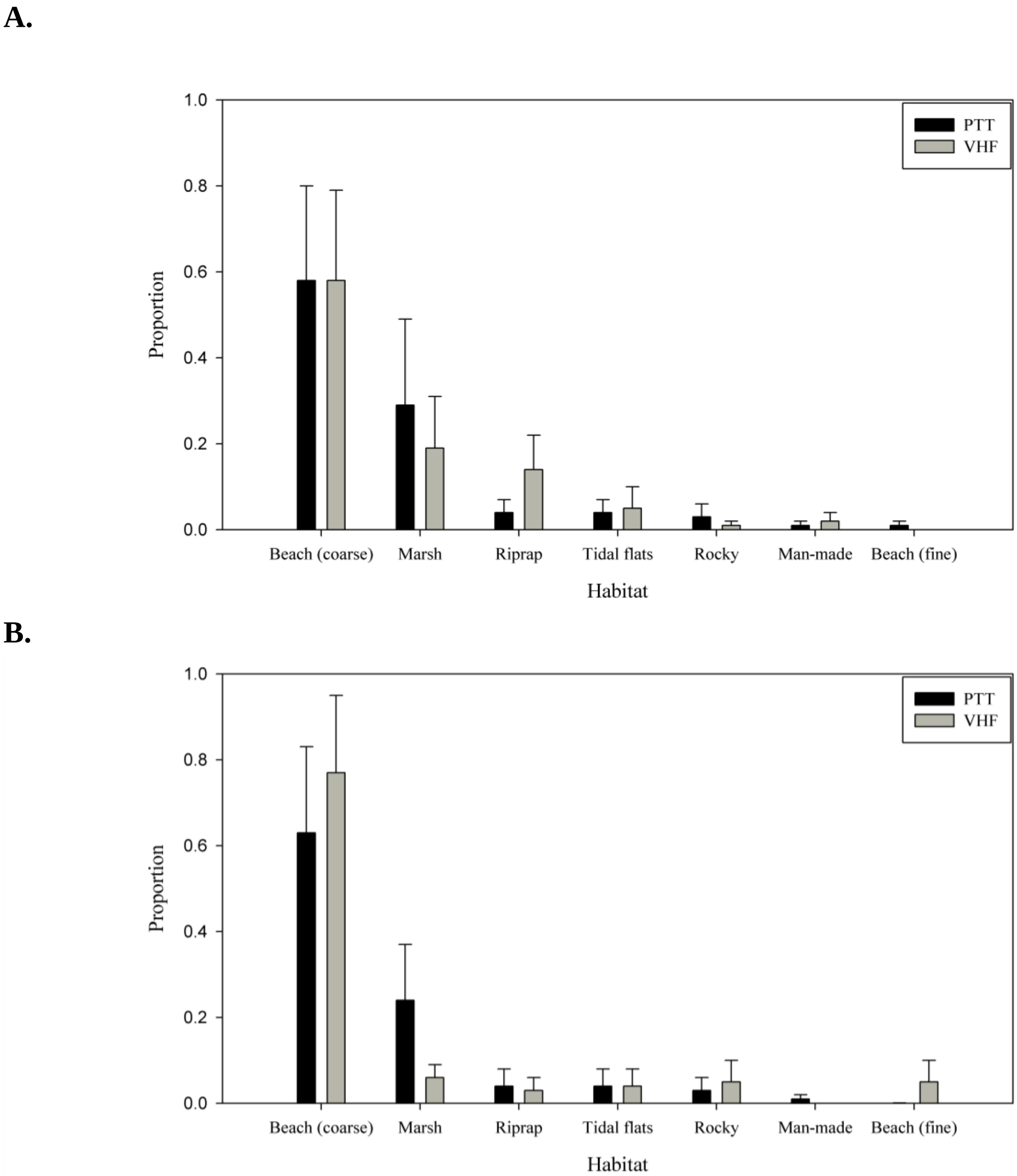


Figure 1.5. Mean (± SE) proportion of shoreline habitat type comprising the core-use areas (50% isopleth; 6A) and utilization distributions (95% isopleth; 6B) estimated by locations from satellite Platform Transmitter Terminals (PTT, black) and VHF radio transmitters (grey) fitted to American Oystercatchers (n = 3) on breeding grounds in coastal Massachusetts in 2013.

CHAPTER 2

ASSESSING THE EFFECTS OF DIGITAL VHF TRANSMITTERS ON NESTING COMMON TERNS

Abstract

Recent advances in digital VHF radio transmitters and automated telemetry stations now allow biologists to quantify fine-scale movements of seabirds. However, before widespread use of this new technology is permitted, particularly on threatened or endangered species, it is important to monitor transmitter retention times and potential adverse impacts on the behavior of similar species. Digital VHF radio tags (1.5 g, <2% of body mass) were attached to one member of 50 pairs of adult Common Terns (*Sterna hirundo*) nesting within a colony of 7,500 Common Terns at Monomoy NWR, MA. Tags were attached to the interscapular region using cyanoacrylate adhesive and subcutaneous sutures. An array of eight automated radio telemetry stations within 30 km of the colony was used to quantify tag retention through post-fledging dispersal. Productivity of tagged and non-tagged (control) pairs was estimated by following chicks through fledging in 20 productivity plots within the colony. Two tags stopped transmitting immediately, but most adult terns (81%, *n* = 48) retained their tags until their chicks had fledged. Mean (± SE) retention time was 48 days (± 2 days, range 22 to 90 days), with females slightly more likely to retain their tag until their brood fledged than males. Only one tagged pair was unsuccessful in fledging at least one chick, and fledging success did not differ between the tagged and control groups. Using cyanoacrylate adhesive and sub-cutaneous sutures is a useful technique for attaching lightweight transmitters to Common Terns for

studies lasting from one to three months because this technique did not appear to affect nesting productivity, and retention rates were high.

Introduction

Recent advances in tracking technologies provide invaluable and otherwise unattainable information about avian movement ecology, particularity for wide-ranging taxa such as seabirds (Burger and Shaffer 2008). Despite the benefits of information gained by telemetry studies, there are inherent risks associated with tracking devices (White and Garrott 1990, Murray and Fuller 2000, Wilson and McMahon 2006, Barron et al. 2010). Researchers have legal and ethical responsibilities to assess and minimize adverse effects to tagged individuals, particularly when working with threatened or endangered populations (Fair et al. 2010). Further, minimizing risks to tagged individuals is critical for studies designed to draw inferences to the broader non-tagged populations, as adverse effects on health, behavior, or movements of tagged individuals may bias results (Murray and Fuller 2000).

One approach for reducing adverse effects of transmitters is to minimize their size and limit the combined mass of the transmitter and attachment materials to under 3 to 5% of the mass of tagged individuals (White and Garrott 1990, Murray and Fuller 2000, Kenward 2001, Fair et al. 2010), although attachments below this threshold may still have disproportionate impacts on energy expenditure of some species (Vandenabeele et al. 2011). Where and how the transmitter is attached can also affect study success, as it can influence tag retention, bird welfare, and study outcomes (Barron et al. 2010, Vandelabeele et al. 2014). For short- and moderate-term studies (lasting a few weeks to a few months), a variety of temporary attachment materials have been used including adhesive (Johnson et al. 1991) and tape (Söhle et al. 2000), which allow the tracking device to fall off the tagged individual after its battery expires (Hawkins 2004). These temporary attachment methods are generally thought to have less impact than long-term or permanent alternatives (e.g. mounted to leg-bands, surgical implants; Barron et al. 2010).

Selecting an appropriate attachment method for seabirds can be challenging because they are wide ranging, occupy marine environments, and employ foraging strategies that may stress tag attachment (Burger and Shaffer 2008). For terns of the genus *Sterna*, attaching devices is particularly difficult due to their relatively small body mass (generally <150 g), and high-impact foraging strategies (i.e., plunge diving from about 3-4 m above the water surface; Duffy 1986). Therefore, the tag and attachment methodology needs to be lightweight yet robust. Several techniques have been used to attach tracking devices to terns, including band-mounts, tail-mounts, and back-mounts (Klaassen et al. 1992, Morris and Burness 1992, Sirdevan and Quinn 1997, Perrow et al. 2006, Mostello et al. 2014). Techniques for long-term attachment, such as gluing geolocators to leg bands, have been successful for attaching tracking devices to terns throughout the annual cycle, although some negative effects have been reported, including leg injuries, reduced body mass, and reduced inter-annual return rates (Nisbet et al. 2011, Mostello et al. 2014). Short-term attachments that are designed to fall off, such as glue or Tesa tape (Beiersdorf AG, Hamburg, Germany), tend to be associated with very short retention times, such as <10 days for tail mounts (Perrow et al. 2006) and <12 days for transmitters glued to the back (Massey et al. 1988).

Retention time of back-mounted transmitters can be extended by using a combination of adhesive and sub-cutaneous sutures (Warnock and Takekawa 2003). Some biologists have successfully used adhesive, in combination with sutures, to attach transmitters to Red-winged Blackbirds (*Agelaius phoeniceus*; (Martin and Bider 1978)), ducks (*Anas* spp.; (Wheeler 1991)), Sage Grouse (*Centrocercus urophasianus*; [Burkepile et al. 2002]), Great Shearwaters (*Puffinus gravis*; L. Welch, pers. comm.), and Forster's Terns (*Sterna forsteri*; (Ackerman et al. 2009)). Thus, this technique appears to be a promising attachment method for studies lasting from one to five months, and may represent a safer alternative relative to other more permanent attachment techniques (Wheeler 1991).

To our knowledge, no one has previously assessed the retention time or potential adverse effects of the adhesive and suture technique to attach transmitters on a plunge-diving tern. Using adhesive and sub-cutaneous sutures, we dorsally-mounted Very High Frequency (VHF) radio-transmitters on adult Common Terns (*Sterna hirundo*), a relatively abundant species that breeds throughout North America (Nisbet 2002). Our specific objectives were to: 1) determine if transmitters attached with cyanoacrylate adhesive and sub-cutaneous sutures to the inter-scapular region of nesting adult Common Terns affected the fledging success of their chicks; 2) quantify retention time of transmitters attached to terns using adhesive and sutures; and 3) compare transmitter retention between male versus female adult Common Terns through the post-fledging period.

Methods

Study area

We conducted fieldwork on South Monomoy Island (41° 36’ 31.53” N, 69° 59’ 12.86” W), within Monomoy National Wildlife Refuge (NWR), a 30 km^2 barrier beach and island complex located off of the coast of Cape Cod, Massachusetts, USA (Fig. 1). South Monomoy Island is approximately 9 km from north to south, and up to 2 km wide. The island supports, one of the largest Common Tern colonies on the Atlantic Coast, with over 7,500 nesting pairs in 2013 (USFWS, unpublished data).

Tag deployments

During the mid-incubation through early chick-rearing period, we captured 100 adult Common Terns, each from a different nest, in 20 productivity plots that were randomly-located throughout the Monomoy tern colony. Of the 100 terns that we captured, 50 terns were fitted with a digitally-coded VHF transmitter (tagged group) and 50 terns were assigned as controls with no VHF transmitter (control group). Productivity plots were designed to estimate fledging rates of Common Tern chicks by retaining chicks near nests until they were nearly capable of sustained flight. Each plot was a hexagon constructed from 15.25 m of 0.3 m tall, 6-mm mesh hardware cloth. We tagged an average of 2.4 (± 0.2 SE, range = 1 to 5) terns per plot from 4 to 25 June 2013 using walk-in treadle traps. We individually marked terns on their tarsometatarsus with an incoloy U.S. Geological Survey band on one leg and a wrap-around black plastic field readable band inscribed in white with a unique 3-digit alphanumeric code on the opposite leg. We also collected three to five contour feathers from each bird to determine gender by molecular analysis (Avian Biotech, Gainesville, FL).

We attached a digital 1.5 g VHF transmitter ('Avian NanoTag'; Lotek Wireless, Inc., Newmarket, Ontario, Canada) to individuals within the tagged group. Digital coding within each transmitter's pulse allowed up to 521 individuals to be uniquely identified on a single VHF frequency by receiving units. We programmed transmitters to transmit signals on 166.380 MHz every five to six seconds, for a total expected operational life of approximately 160 days. Each transmitter body measured 11 mm x 8 mm x 7 mm, and had custom fitted tubes (inner diameter 1 mm) at the anterior and posterior ends for attachment materials, and a 15-cm whip antenna. Total weight of each transmitter and attachment materials was < 2% of the body mass of the birds in our study. We attached transmitters to the dorsal inter-scapular region using cyanoacrylate adhesive and two sutures (Prolene: 45-cm length, 4.0, BB taper point needle, catalog # 8581H) that we inserted subcutaneously and secured to the end-tubes of the transmitter. We captured, processed, banded, and released birds from the control group using the same procedures as tagged birds. Total handling time, from capture to release, ranged between 20 to 40 min per individual for both tagged and control individuals.

Nest monitoring

From nest initiation through fledging, all chicks within productivity plots were monitored every one to three days by U.S. Fish and Wildlife Service biological staff at Monomoy NWR. All chicks were banded within three days of their hatch date with an incoloy U.S. Geological Survey Band. We determined hatch order for each chick within a brood based on size and plumage characteristics, where 'A', 'B', and 'C' was used to identify the first hatched, second hatched, and third hatched chick, respectively. We classified all chicks that survived to 23 days old as successfully fledging (Nisbet 2002). For nests with chicks that did not survive to 23 days, we recorded the nest failure date as the date when the last egg or chick was lost.

Tracking

We tracked the movements of tagged terns using a network of automated radio telemetry stations (hereafter network) established throughout the eastern Nantucket Sound region of Massachusetts (Fig. 2.1). The network included six automated radio telemetry towers, each consisting of an array of six 9-element (11.1 dBd) Yagi antennas end-mounted in a radial configuration atop a 9.2 m mast. The antennas were connected to a solar-powered, automated receiving unit (SRX-600, Lotek Wireless, Ontario, Canada) that scanned for signals with each antenna for 6.5 seconds in succession, around the clock.

The network also included a receiving station, consisting of a SRX-600 receiver equipped with a single omnidirectional (200 W) antenna, located on a passenger ferry that followed a north-south route across Nantucket Sound two to six times per day (Fig. 1). In addition, we operated a receiving station consisting of a SRX-600 receiver equipped with a single omnidirectional (200 W) antenna mounted on a 1.2 m mast that was adjacent to the tern nesting colony and configured to monitor nest attendance. We programmed all receiving units to automatically log the following data from each antenna: transmitter ID number, time stamp (synchronized among all receivers in the array using GPS clocks), antenna (defined by receiving station and bearing), and signal strength (non-linear scale: 0 to 255).

Tag retention

We were unable to calculate the complete duration of tag retention for each bird beyond the post-fledgling period when adults disperse beyond the detection range of our network to staging or wintering grounds (Nisbet 2002). Therefore, we estimated the minimum retention duration as the number of days between the date of tag attachment and date of last detection by our network. We classified transmitters as dropped if we detected a consistent, continuous signal from a single antenna over a period of several days, indicating that the transmitter was stationary. When we did not have direct evidence of a dropped transmitter from our network, we assumed that an individual had dropped their transmitter if they were last detected by our network prior to the estimated fledging date of their chick (for successful nests) or the date of nest failure (for unsuccessful nests). Previous research on Common Terns has determined that both members of the pair remain in the nesting colony until their chicks fledge (Nisbet 2002). Therefore, we assumed that individuals retained their transmitters and successfully dispersed from the nesting colony if their last detection from our network occurred after the estimated fledging date of their chicks.

Data Analyses

We tested for gender-based differences in transmitter retention rates through the fledging period using Pearson's Chi-squared test with Yates' continuity correction. To compare minimum retention time (in days) between genders, we used a Mann-Whitney *U* test since our data violated the assumption of equal variance (rejected, $P < 0.05$). To examine the effects of transmitters on reproductive success, we used a generalized linear mixed model with a logit link and binomial error distribution (lme4 package; R Development Core Team 2015), with the individual fledge success of each chick as the binary response variable (1 = survived to fledge, 0 = did not survive); hatch order, tag presence, and their interactions as fixed effects, and plot ID as a random effect. We evaluated the significance of fixed effects in the model using Wald z-statistics, to assess whether transmitter presence, hatch order, and their interactions had a significant influence on fledge success of chicks from tagged versus non-tagged nests (Bolker et al. 2009). We present mean ± SE unless stated otherwise.

Results

Tag retention

Two transmitters malfunctioned immediately after deployment (i.e., did not transmit any data after tag date), and were removed from subsequent analyses. We captured most tagged birds during incubation (12.8 d ± 0.9 d before hatching, *n* = 38), whereas others were captured while brooding chicks (2 d ± 0.4 d after hatching, *n* = 10). Of the 48 tagged individuals, we determined gender for 47 individuals: 24 females and 23 males. Nine tagged individuals (7 males and 2 females) were not detected by our automated array up to the estimated fledging date of their chicks, therefore we assumed these tags fell off prematurely. We tracked individuals that dropped their tags for an average of 30.1 d ± 0.6 d before we lost their signals. Apparent detachment of tags occurred an average of 7.7 d ± 0.7 d before estimated fledge date. The remainder of the tagged individuals (81%; *n* = 39) were detected by the network through the fledge date of their chicks.

There was a tendency for females (92% retention, *n* = 24) to be more likely to retain their tags until their chicks' fledged than males (70% retention *n* = 23; χ-squared = 2.4, df = 1, *P* = 0.07, Fig. 2.2). For all birds, mean retention time was 48.1 d ± 2.2 d (range 22 d to 90 d, *n* = 48), and for individuals that retained their tags to the post-fledging period the mean retention time was 52.3 d (± 2.2 d, *n* = 39). There was no difference between genders in retention times for individuals that retained their tags until after their chick(s) fledged (Mann-Whitney U-Test 170.5, *P* = 0.65; Fig. 2.3). For adults tracked during the interval beginning with fledging of their chicks, and ending with their own departure from the study area, there was no difference between males and females in minimum retention times (Mann-Whitney U-Test 181.5, *P* = 0.89; Fig. 2.3).

Tag effects

Of the 48 broods associated with our tagged birds, only one brood did not have at least one chick fledge. There was no evidence of a difference in the fledge success of chicks from nests from tagged nests (1.68 ± 0.09 chicks fledged per brood) versus non-tagged control nests (1.63 ± 0.11 chicks fledged per brood) and no significant interactions between tag presence and hatch order (Table 2.1). Across both tagged and non-tagged control nests, probability of fledge was highest for A chicks and decreased with hatch order (Fig. 2.4).

Discussion

Retention

Using the glue and suture technique, the majority (81%) of individuals in our study retained their transmitters until they departed from the nesting colony. This estimate is conservative because we assumed that birds that were not detected through the fledge or fail date of their nests dropped their transmitters, but the tags could have malfunctioned, as occurred with two tags shortly after deployment. We did not recover any dropped tags near our network of land-based telemetry stations, indicating that transmitters may have fallen off while the birds were away from the colony. We found slightly lower tag retention of males relative to females, which may result from male Common Terns spending more time foraging during the breeding period than females (Wiggins and

Morris 1987). Thus, transmitters on males may have been subjected to increased levels of stress and impact associated with plunge diving compared to females who spent more time during the chick-rearing period within the nesting colony.

Retention time of transmitters in our study was similar to estimates reported by Ackerman et al. (2009), who used sutures to back-mount VHF transmitters to fledgling Forster's Terns and tracked their movements for up to 44 days. Conversely, studies using different types of temporary attachment methods on terns, such as attaching transmitters to the central rectrices (Black 2006), or back-mounting transmitters with adhesive and/or tape (Perrow et al. 2006), reported considerably lower retention times (i.e., less than two weeks), indicating that these other attachment techniques are more suitable for short-term deployments. Therefore, researchers requiring transmitter retention for one to three months, such as during the breeding period, should consider using glue in combination with sutures as it appears to be a more reliable method of tag attachment.

Influence of tags on productivity

During the breeding period, radio transmitters can reduce foraging efficiency and chick provisioning rates, leading to reduced chick growth and productivity (Whidden et al. 2007). A reduction in chick provisioning may have had disproportionate influence on younger chicks, as typically the older, larger chicks often outcompete younger and smaller chicks for prey items that adults bring back to the nest (Nisbet 2002). Although we did document an inverse relationship between fledge success and hatch order across all nests in the study, we did not detect any differences among fledge success of chicks between tagged and control nests.

Several studies also examined effects of different types of back-mounted transmitters on terns during the breeding period (Massey et al. 1988, Hill and Talent 1990, Becker et al. 1993, Perrow et al. 2006). Although an early study on Least Terns (*Sternula antillarum*) reported abnormal behavior of four birds with radio-tags glued to the inter-scapular region, the behavior was temporary and did not affect nest success or chick provisioning (Massey et al. 1988). In a subsequent study of Least Terns, transmitters weighing 6 to 7% of body weight, and glued over the bird's center of gravity did not affect behavior, nest survival, nest predation, or nest desertion (Hill and Talent 1990). Additionally, transmitters glued to the back of Least Tern chicks did not influence their growth rate or movement, despite being 5 to 8% of a chick's weight (Whittier and Leslie 2005**.** Perrow et al. (2006) found no apparent adverse effects of back-mounted transmitters on the behavior and nesting success of Little Terns (*Sternula albifrons*) and suggested that the back-mounting attachment technique was "a relatively benign procedure". During the breeding period, Common Terns carrying relatively heavy transmitters (8 g) glued to the skin between their wings, displayed similar behavior, food intake, energy expenditure, and body mass relative to controls (Klaassen et al. 1992, Becker et al. 1993)**.**

The glue and suture technique we used for this study appears to be a suitable technique for attaching transmitters to terns for medium-duration studies, such as during the breeding period, in regards to both transmitter retention and bird welfare. However, because we were not able to track terns after they departed from our study area, the retention times reported herein should be considered minimum estimates. Additional coordinated automated telemetry stations are currently being established throughout the western Hemisphere (www.motus-wts.org), making it possible to track tagged birds over longer distances and thus will enable improved estimates of transmitter retention on Common Terns and other species after they depart from the breeding grounds.

Although we did not observe adverse effects on the reproductive metrics that we examined, we suggest that researchers employing the glue and suture attachment technique in future studies examine additional effects that are specific to their study period. For studies during the breeding period, additional metrics could include foraging efficiency, physiological stress, chick growth and survival, and colony attendance (Burger and Shaffer 2008, Barron et al. 2010). For studies spanning the annual cycle, additional research on the effects of transmitters on energetics and return rates of tagged individuals may be warranted (Vandenabeele et al. 2011).

Acknowledgements

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Literature Cited

Ackerman, J. T., J. D. Bluso-Demers and J. Y. Takekawa. 2009. Postfledging Forster's Tern movements, habitat selection, and colony attendance in San Francisco Bay. Condor 111:100-110.

Barron, D. G., J. D. Brawn and P. J. Weatherhead. 2010. Meta-analysis of transmitter effects on avian behaviour and ecology. Methods in Ecology and Evolution 1:180-187.

Becker, P. H., D. Frank and S. R. Sudmann. 1993. Temporal and spatial pattern of Common Tern (*Sterna hirundo*) foraging in the Wadden Sea. Oecologia 93:389-393.

Black, A.L. 2006. Foraging area characteristics of Arctic Terns (*Sterna paradisaea*) and Common Terns (*Sterna hirundo*) breeding on Machias Seal Island. Ph.D. dissertation. University of New Brunswick, Canada.

Bolker, B. M., M. E. Brooks, C. J. Clark, S. W. Geange, J. R. Poulsen, M. H. H. Stevens and J.-S. S. White. 2009. Generalized linear mixed models: a practical guide for ecology and evolution. Trends in Ecology and Evolution 24:127-135.

Burger, A. E. and S. A. Shaffer. 2008. Perspectives in ornithology Application of tracking and data-logging technology in research and conservation of seabirds. Auk 125:253-264.

Burkepile, N. A., J. W. Connelly, D. W. Stanley and K. P. Reese. 2002. Attachment of radiotransmitters to one-day-old Sage Grouse chicks. Wildlife Society Bulletin 30:93-96.

Duffy, D. C. 1986. Foraging at patches: interactions between Common and Roseate Terns. Ornis Scandinavia 7:47-52.

Fair, J. M., E. Paul, J. Jones, A. B. Clark, C. Davie and G. Kaiser. 2010. Guidelines to the use of wild birds in research. Ornithological Council. <www.nmnh.si.edu/BIRDNET/guide>. Accessed 21 July 2015.

Hawkins, P. 2004. Bio-logging and animal welfare: practical refinements. Memoirs of National Institute of Polar Research, Special Issue 58:58-68.

Hill, L. A. and L. G. Talent. 1990. Effects of capture, handling, banding, and radio-marking on breeding Least Terns and Snowy Plovers. Journal of Field Ornithology 61:310-319.

Johnson, G. D., J. L. Pebworth and H. O. Krueger. 1991. Retention of transmitters attached to passerines ssing a glue-on technique. Journal of Field Ornithology 62:486-491.

Kenward, R. 2001. A manual for wildlife radio tagging. Academic Press, London.

Klaassen, M., P. H. Becker and M. Wagener. 1992. Transmitter loads do not affect the daily energy expenditure of nesting Common Terns. Journal of Field Ornithololgy 63:181-185.

Martin, M. L. and J. R. Bider. 1978. A transmitter attachment for blackbirds. Journal of Wildlife Management 42:683-685.

Massey, B. W., K. Keane and C. Boardman. 1988. Adverse effects of radio transmitters on the behavior of nesting Least Terns. Condor 90:945-947.

Morris, R. D. and G. P. Burness. 1992. A new procedure for transmitter attachment: effects on brood attendance and chick feeding rates by male Common Terns. Condor 94:239-243.

Mostello, C. S., I. C. Nisbet, S. A. Oswald and J. W. Fox. 2014. Non-breeding season movements of six North American Roseate Terns *Sterna dougallii* tracked with geolocators. Seabirds 27:1-21.

Mulcahy, D. M. and D. Esler. 1999. Surgical and immediate postrelease mortality of Harlequin Ducks (*Histrionicus histrionicus*) implanted with abdominal radio transmitters with percutaneous antennae. Journal of Zoo and Wildlife Medicine 30:397-401.

Murray, D. L. and M. R. Fuller. 2000. A critical review of the effects of marking on the biology of vertebrates. Pages 15-64 *in* Research techniques in animal ecology: controversies and consequences (L. Boitani, andT. K. Fuller, Eds.). Columbia University Press, New York..

Nisbet, I. C. T. 2002. Common Tern (*Sterna hirundo*). No 618 *in* The Birds of North America Online (A. Poole, Ed.). Cornell Lab of Ornithology, Ithaca, New York. http://bna.birds.cornell.edu/bna/species/618doi:10.2173/bna.618, accessed 15 May 2016.

Nisbet, I. C. T., C. S. Mostello, R. R. Veit, J. W. Fox, and V. Afanasyev. 2011. Migrations and winter quarters of five Common Terns tracked using geolocators. Waterbirds 34:32-39.

R Development Core Team. 2015. R: a language and environment for statistical computing v. 3.0.2. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/, accessed 17 Dec 2015.

Pennycuick, C. J., P. L. F. Fast, N. Ballerstädt, and N. Rattenborg. 2011. The effect of an external transmitter on the drag coefficient of a bird's body, and hence on migration range, and energy reserves after migration. Journal of Ornithology 153:633-644.

Perrow, M. R., E. R. Skeate, P. Lines, D. Brown, and M. L. Tomlinson. 2006. Radio telemetry as a tool for impact assessment of wind farms: the case of Little Terns *Sterna albifrons* at Scroby Sands, Norfolk, UK. Ibis 148:57-75.

Sirdevan, J. E., and J. S. Quinn. 1997. Foraging patterns of Caspian Terns (*Sterna caspia*) determined using radio-telemetry. Colonial Waterbirds 20:429-435.

Söhle, I. S., H. Moller, D. Fletcher, and C. J. R. Robertson. 2000. Telemetry reduces colony attendance by Sooty Shearwaters (*Puffinus griseus*). New Zealand Journal of Zoology 27:357-365.

Vandenabeele, S. P., E. Grundy, M. I. Friswell, A. Grogan, S. C. Votier, and R. P. Wilson. 2014. Excess baggage for birds: Inappropriate placement of tags on gannets changes flight patterns. PLoS ONE 9:e92657.

Vandenabeele, S. P., E. L. Shepard, A. Grogan, and R. P. Wilson. 2011. When three per cent may not be three per cent; device-equipped seabirds experience variable flight constraints. Marine Biology 159:1-14.

Wanless, S., M. P. Harris, and J. A. Morris. 1988. The effect of radio transmitters on the behavior of Common Murres and Razorbills during chick rearing. Condor 90:816-823.

Warnock, N., and J. Y. Takekawa. 2003. Use of radio telemetry in studies of shorebirds: past contributions and future directions. Wader Study Group Bulletin 100:138-150.

Weimerskirch, H., M. L. Corre, F. Marsac, C. Barbraud, O. Tostain, and O. Chastel. 2006. Postbreeding movements of frigatebirds tracked with satellite telemetry. Condor 108:220-225.

Wheeler, W. E. 1991. Suture and glue attachment of radio transmitters on ducks. Journal of Field Ornithology 62:271-278.

Whidden, S. E., C. T. Williams, A. R. Breton, and C. L. Buck. 2007. Effects of transmitters on the reproductive success of Tufted Puffins. Journal of Field Ornithology 78:206-212.

White, G. and R. Garrott. 1990. Analysis of wildlife radio-tracking data. Academic Press, San Diego, California.

Whittier, J. B., and D. M. Leslie. 2005. Efficacy of using radio transmitters to monitor Least Tern chicks. Wilson Bulletin 117:85-91.

Wiggins, D.A. and R.D. Morris. 1987. Parental care of the Common Tern *Sterna hirundo*. Ibis 129: 533-540.

Wilson, R. P., and C. R. McMahon. 2006. Measuring devices on wild animals: what constitutes acceptable practice? Frontiers in Ecology and the Environment 4:147-154.

Wilson, R. P., and M.-P. T. Wilson. 1989. A peck activity record for birds fitted with devices. Journal of Field Ornithology 60:104-108.

Table 2.1. Parameter estimates of a Generalized Linear Mixed Model of the effects of VHF transmitters on fledge success of nesting Common Terns, where fledge success is a binomial response variable, and fixed effects are: Group (where 'Tagged' indicates that nesting pair had one VHF tagged adult and 'Control' indicates that both adults in nesting pair were not VHF-tagged); Hatch Order (where A, B, and C indicate the first hatched, second hatched, and third hatched chicks, respectively) and their interactions. The 'Tagged' Group and 'A' chick are the reference classes.

	Estimate	SE	z-value	p-value
(Intercept)	3.31	0.75	4.42	< 0.001
Control Group	-1.02	0.87	-1.18	0.238
B Chick	-2.22	0.81	-2.76	0.006
C Chick	-5.80	1.10	-5.28	< 0.001
Control Group:B Chick	1.27	1.01	1.25	0.210
Control Group:C Chick	2.04	1.34	1.52	0.129

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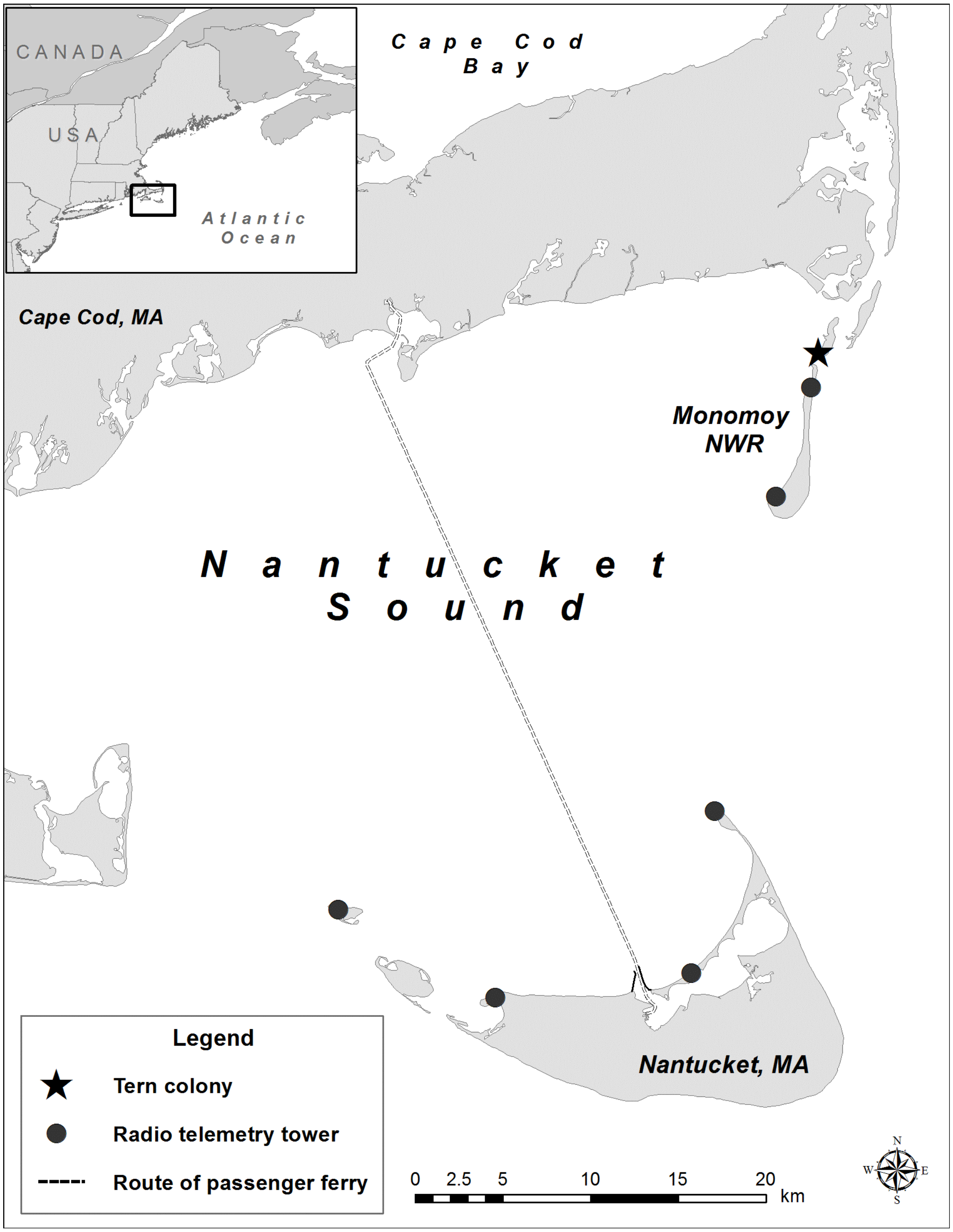

Figure 2.1. Study area in Nantucket Sound, Massachusetts, USA where Common Terns were monitored at a colony on Monomoy National Wildlife Refuge in 2013 (NWR; black star), seven land-based Automated Radio Telemetry Stations (ARTS; black circles), and the route of a passenger ferry with an ARTS (dashed line).

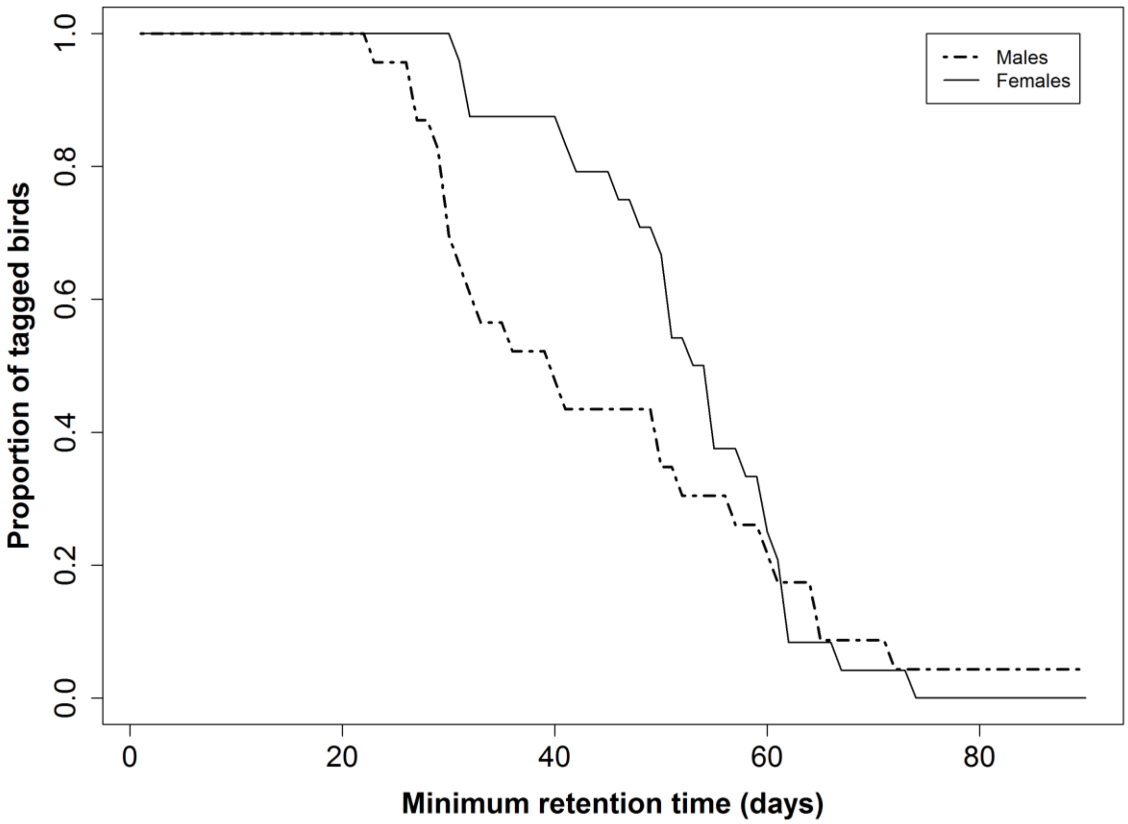

Figure 2.2. Cumulative distributions of minimum retention time (days) of VHF transmitters attached to adult male (*n* = 23) and female (*n* = 24) Common Terns tracked at Monomoy NWR in 2013.

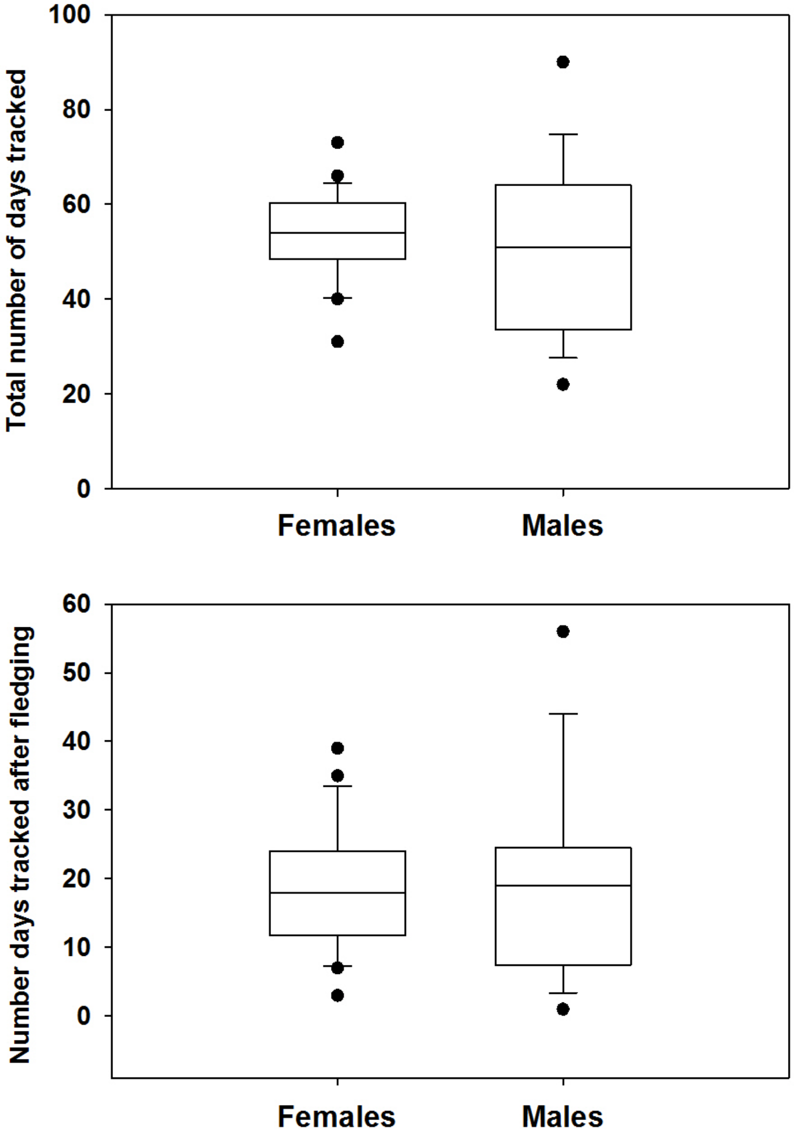

Figure 2.3. Gender differences in minimum retention time (in days) of VHF-transmitters back-mounted on adult Common Terns and tracked by a network of automated radio telemetry stations after initial capture (upper panel), and after their chicks had fledged (lower panel). Horizontal lines of the boxes represent 25th, 50th and 75th percentiles, whiskers represent 5th and the 95th percentiles, and points represent outliers.

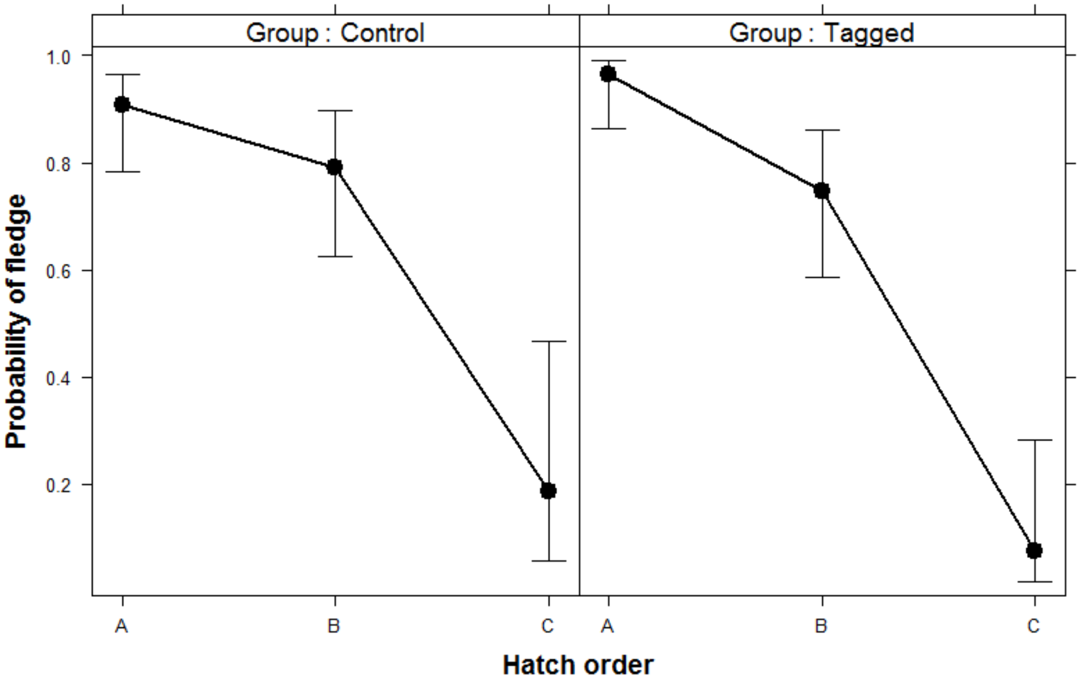

Figure 2.4. Probability that a Common Tern chick fledged as a function of hatch order in broods where one adult had a VHF-transmitter (Group: Tagged, *n* = 50) and neither adult had a transmitter (Group: Control, *n* = 50), where 'A', 'B', and 'C' identifies the first hatched, second hatched, and third hatched chick, respectively.

CHAPTER 3

POST-BREEDING DISPERSAL AND STAGING OF COMMON AND ARCTIC TERNS THROUGHOUT THE WESTERN NORTH ATLANTIC

Abstract

In the western North Atlantic, Common (*Sterna hirundo*) and Arctic (*S. paradisaea*) terns are sympatric at breeding colonies but show divergent migration strategies to coastal areas of South America and pelagic regions of the Antarctic, respectively. During 2013, we studied post-breeding movements of adult Common (*n* = 130) and Arctic (*n* = 52) terns from four breeding colonies in the eastern USA and Canada using digital VHF transmitters and an array of 62 automated radio telemetry towers. Common Terns were detected during the post-breeding period by coastal towers upwards of 850 km south of their original nesting sites. Our array detected post-breeding movements of Arctic Terns from the Petit Manan Island colony in the Gulf of Maine as they traveled eastward past Nova Scotia, Canada. Nantucket Sound, Massachusetts, USA was identified as an important staging area for Common Terns from all colonies, whereby 26% (*n* = 53) of tagged Common Terns from colonies in the Gulf of Maine and Canada were detected for up to three weeks. Common Terns were detected in Nantucket Sound within two to ten days after their last detection at Gulf of Maine and Canadian colonies suggesting rapid post-breeding dispersal. Post-breeding dispersal of Arctic Terns was poorly documented with the array of receivers suggesting that this species uses offshore areas after departing their colonies prior to long-distance migrations. Arrival times of both species at staging areas occurred at night and during early morning hours and departures followed at dawn. We conclude that digital VHF telemetry is a useful method for monitoring regional

movements of Common Terns, but additional offshore receiving stations are needed to effectively monitor movements of Arctic Terns away from their nesting colonies.

Introduction

During the post-breeding period, seabirds use various dispersal and staging strategies to build energy reserves for migration (Huettmann and Diamond 2000, Klaassen et al. 2011, Montevecchi et al. 2012). High-quality staging areas provide sufficient space for roosting aggregations, abundant prey, and minimal disturbance by humans and predators (Warnock 2010). Species that disperse along the coast may use persistent staging areas with reliable roosting and foraging habitats (Trull et al. 1999), whereas species that roost and feed offshore may use dynamic staging areas in response to patchy prey distributions (Suryan et al. 2006, Guilford et al. 2009, Hedd et al. 2012). Advances in tracking technologies are increasing our understanding of the connectivity between nesting populations and staging areas of seabirds (Mosbech et al. 2012, Gilg et al. 2013, van der Winden et al. 2014). However, detailed information on post-breeding dispersal and staging movements is lacking for many species of seabirds, such as the small-bodied terns, due to limitations of the spatial and temporal resolution of lightweight tracking devices (Bridge et al. 2011). In this study, we used digital Very High Frequency (VHF) radio transmitters and an array of coordinated automated radio telemetry stations ('telemetry array') to track the post-breeding movements of small-bodied seabirds at a regional scale.

In the western North Atlantic, from southern Labrador, Canada (52° N) to Cape Cod, Massachusetts, USA (41° N), the breeding ranges of Common (*Sterna hirundo*) and Arctic (*S. paradisaea*) terns overlap and the two species nest sympatrically on nearshore and offshore islands (Gaston et al. 2009, Kress et al. 1983). Common and Arctic terns target similar species of prey fish and invertebrates (Rock et al. 2007). However, differences in the proportions of prey types consumed by each species, and differences in habitat use, where Common Terns generally feed inshore and Arctic Terns tend to feed more offshore, suggests some degree of resource partitioning (Braune and Gaskin 1982, Hall et al. 2000, Hatch 2002). The wintering ranges of these populations are geographically separated, with Common Terns wintering along the coasts of Central and South America (Hays et al. 1997, Nisbet et al. 2011*a*), and Arctic Terns wintering along the Antarctic pack ice (Hatch 2002).

Little is known about the fall migratory routes of terns that breed in the western North Atlantic; although recent studies using archival light-level loggers (geolocators) have revealed that Common Terns migrate directly south across western North Atlantic (Nisbet et al. 2011*a*), and Arctic Terns depart east across the north Atlantic (L. Welch, unpublished data). Prior to migration, mixed flocks of terns (primarily Common and Roseate (*S. dougallii*) terns) stage at sites along the U.S. Atlantic coast from Maine through New Jersey (Shealer and Kress 1994, Nisbet 2002), with large flocks of over >10,000 terns reported on Cape Cod, Massachusetts (Trull et al. 1999). However, there are few quantitative data regarding the post-breeding movements of terns nesting in the western North Atlantic.

In 2013, we conducted a regional study of the post-breeding movements of Common and Arctic terns from four nesting colonies using digital VHF transmitters and telemetry array that extended from Nova Scotia, Canada to Cape Cod, MA, USA. The specific objectives of our study were to quantify: 1) length of stay at nesting colonies, 2) timing and length of stay at staging sites, 3) timing of departure from the study area, and 4) diel variation in staging and departure movements.

Methods

Study area

During 2013, we conducted telemetry studies at four breeding colonies ranging from north-eastern Nova Scotia, Canada to Cape Cod, MA, USA (Fig. 3.1). Petit Manan Island (44°21' N, 67°52' W) is a 6.5-ha island located approximately 4 km off the coast of Maine, USA and supports a mixed colony of about 1,370 pairs of Common and Arctic terns (Gulf of Maine Working Seabird Group (GOMSWG) 2013). Country Island (45°06' N, 61°32' W), is a 19-ha island located approximately 5 km off the east coast of Nova Scotia, Canada and contains a mixed colony of about 1,300 pairs of Common and Arctic terns (GOMSWG 2013). Sable Island (43°55' N, 60°00' W) is a crescent-shaped, 3,400-ha island located approximately 180 km offshore from mainland Nova Scotia, Canada. Approximately 4,200 pairs of Common and Arctic terns nested on Sable Island during recent surveys in 2013 (Ronconi et al. *in press*). Monomoy National Wildlife Refuge (NWR; 41°37' N, 69°59' W) is a 2,800-ha barrier beach and island complex located in the eastern Nantucket Sound region of Massachusetts, USA, approximately 400 to 800 km south of the northern tern colonies included in this analysis. Located within Monomoy NWR and < 5 km from the mainland coast of Cape Cod, South Monomoy Island supports one of the largest Common Tern colonies on the Atlantic coast, with over 7,500 nesting pairs in 2013 (GOMSWG 2013). Small numbers (< 18 pairs) of Arctic Terns historically nested on the islands of Monomoy NWR, but have not since 1990 (USFWS, *unpublished data*).

Automated radio telemetry

In 2013, a telemetry array (www.motus-wts.org) was established at the four colony study sites and an additional 62 coastal and island sites spanning nearly 1,000 km of coastline from north-eastern Nova Scotia to Cape Cod (Fig. 3.1). Each telemetry station was equipped with automated data-logging VHF receivers (SRX-600, Lotek Wireless Newmarket, ON or SensorGnome http://www.sensorgnome.org) connected to antennas using RG58 coaxial cable. Antennas included single-pole omni-directional, or an array of two to six directional (Yagi) antennas (five or nine element) mounted on lighthouses, 10-m telescoping tripod poles, or other structures. Receivers were plugged into external AC power sources, or powered by solar panel arrays (one or two 55 or 65 W panels) connected to a battery bank (one to five 12VDC sealed lead acid batteries). Receivers monitored and recorded VHF signals from all tagged birds within detection range (typically < 20 km) continuously from time of tagging at each site through to October (all sites) or December (Sable Island, Country Island, and some coastal sites).

Tagging

From early June to mid-July 2013, we used walk-in traps and bow nets to capture terns at their nest sites during the late incubation period through approximately 3 days following hatch. Across the four study sites, we deployed a total of 182 transmitters on 130 adult Common Terns and 52 adult Arctic Terns (Tables 3.1 and 3.2). All terns were tagged using digitally-coded VHF transmitters (Avian NanoTag series; Lotek Wireless, Newmarket, ON) that allowed over 500 individual identification codes to be monitored simultaneously on a single frequency (166.380 MHz). Depending on the site, transmitters weighed between 1.2 to 1.5 g and were programmed with burst rate intervals that varied between 4.8 to 10.5 seconds, resulting in an expected tag life that ranged from 124 to 240 days. At each site, transmitters were attached to the inter-scapular region using cyanoacrylate adhesive and held in place with sub-cutaneous sutures that were secured to the transmitter through custom fit end-tubes (inner diameter 1 mm).

We assessed transmitter retention by searching for dropped transmitters within the tern colony, and by examining signals recorded by automated radio telemetry stations, where continuous detections by a single antenna over multiple days indicated a stationary tag. Individuals with dropped transmitters were excluded from subsequent analyses. However, we were unable to account for birds with dropped transmitters that were not recovered by field crews or that were dropped beyond detection range of the automated radio telemetry array.

Data Processing

All analyses were conducted in R version 3.0.2 (R Development Core Team 2016). We processed raw detection data using a burst rate filter in the R package 'sensorgnome' (Brzustowski 2015), that retained data as valid when at least three consecutive detections were separated by the transmitters' burst rate interval.

Length of Stay

Length of stay at the nesting colonies was calculated as the number of days between estimated hatch date and departure date from colony; however, we excluded nine nests from Petit Manan Island that failed prior to hatch (three Common Tern nests and six Arctic Tern nests). Length of stay at staging sites was calculated as the difference in days between the time of first detection at the staging site and the time of final detection at the staging site. Length of stay in the study area was calculated as the difference in days between the time of tagging and the time of last detection by the telemetry array.

After verifying normality and homoscedasticity of the data, we fit a series of general linear models to compare the length of stay by species and colony. For the first model, the dependent variable was length of stay in the colony and the independent variables were species (Arctic or Common Tern), nesting colony (Petit Manan Island, Country Island, or Sable Island), and an interaction term between species and nesting colony. For the second model, the dependent variable was length of stay in the study area and the independent variables were species (Arctic or Common Tern), nesting colony (Petit Manan Island, Country Island, or Sable Island), and an interaction term between species and nesting colony. We used post-hoc Tukey tests (R package 'multcomp', Hothorn 2016) to determine which colonies were significantly different ($p < 0.05$) for all comparisons.

We fit two additional general linear models using data from just the Common Terns in our study. For these models, we compared length of stay in the nesting colony and length of stay in the study area between Common Terns from the colonies in the Gulf of Maine and Canada (pooled) versus Common Terns from the South Monomoy Island colony in Nantucket Sound.

Dispersal and staging

We examined the probability of dispersal to Nantucket Sound by Common Terns among the three colony sites in the Gulf of Maine and Canada using logistic regression, where the dependent variable was binary (where 1 = individuals that staged in Nantucket Sound and 0 = individuals that did not), and the independent variables were nesting colony (Petit Manan Island, Country Island, or Sable Island) and length of stay in the nesting colony (in days). We used a likelihood ratio test to assess the effects of colony site and length of stay in the nesting colony (Hosmer and Lemeshow 2001).

Next, we present summary statistics of the distance and duration of staging movements detected by the array. We calculated the distance of staging movements as the Euclidian distance traveled between the nesting colony and staging sites. We estimated travel time as the number of days between the last detection at the colony and the first detection at staging sites in the Nantucket Sound region (specifically Monomoy NWR, and Great Point, Coatue Point, and Eel Point, on Nantucket Island, and Muskeget Island). We calculated length of stay at staging sites as the total amount of time (in days) between the first and last detection recorded by automated radio telemetry station(s) at each site. For all birds, we assumed that the timing of their final observations coincided with departure from the study area. However, estimates of length of stay and departure dates at the nesting colonies and staging sites should be considered minimum estimates due to the possibility of additional, unobserved dropped tags.

Diel variation in movements

To examine diel variation in movements, we used circular statistics (R package 'Circular', Agostinelli and Lund 2013) to calculate mean departure times (on a 24-hour clock) and mean resultant length of timing of key movements (ρ, a measure of dispersion of a sample of directional measurements). Specifically, we examined: 1) arrival times of Common Terns at staging sites; 2) timing of detections of post-breeding movements of Arctic Terns; and 3) departure times from the study area for both species. We used a Watson's goodness of fit test to determine if circular data met the assumptions of a von

Mises distribution (circular normal). The data on timing of arrival to staging areas and timing of post-breeding movements of Arctic Terns from Petit Manan Island detected passing through Nova Scotia did not meet the assumptions for the von Mises distribution, so we used the non-parametric Rao spacing test of non-uniformity to determine if these times were spaced uniformly throughout a 24-hour period (Batschelet 1981, Zar 1999). The data on departure times from the study area met the assumptions of the von Mises distribution, so we used the parametric Rayleigh test of uniformity to determine whether the distribution of departure times was uniform throughout a 24-hour period. We then conducted a circular Analysis of Variance (R package 'Circular', Agostinelli and Lund 2013) to assess variation in departure times between species (Zar 1999).

Results

Tag retention

Of 182 deployed transmitters, 13 transmitters (7%) were dropped before individuals departed their nesting colony (2 of which were redeployed). This resulted in a total of 171 tags (120 Common Terns and 51 Arctic Terns) that were included in the final analyses (Table 3.1).

Length of stay

Length of stay at the colony site differed significantly between Arctic and Common terns ($F_{1,87} = 6.312$, $p = 0.014$) but not among colonies ($F_{2,87} = 1.439$, $p = 0.334$; Fig. 3.2). Overall, mean (± SE) length of stay at the colony was about 8 days longer for Arctic Terns (29 days ± 2 days, range -5 to 48 days) than Common Terns (21 days ± 2 days, range -5 to 71 days). For Common Terns, length of stay in the colony was significantly longer (T_{117} = 5.992, p <0.001) for birds from the South Monomoy Island colony in Nantucket Sound compared to birds from the colonies in the Gulf of Maine and Canada.

For Common and Arctic terns from colonies in the Gulf of Maine and Canada, mean departure date from the study area was 22 July (range 19 Jun to 7 Sep) and did not differ significantly among colonies ($F_{2,96}$ = 0.261, p = 0.771) or species ($F_{1,96}$ = 1.133, p = 0.290; Table 3.2). Common Terns from Nantucket Sound departed from the study area significantly later (t_{117} = 5.91, p < 0.001) relative to Common Terns from colonies in the Gulf of Maine and Canada (Table 3.2).

Dispersal of Common Terns

Overall, 26% of Common Terns from the three colonies in the Gulf of Maine and Canada were detected in Nantucket Sound during dispersal (Fig. 3.3). We found no significant differences in the probability of dispersal to Nantucket Sound among nesting colonies (Likelihood Ratio Test: χ^2 = 60.26, n = 52, p = 0.854), although there was a significant, positive relationship between length of stay at the nesting colony and probability of staging in Nantucket Sound (Likelihood Ratio Test: χ^2 = 38.341, n = 52, p < 0.001). The mean (± SE) minimum (Euclidian) distance traveled by Common Terns (n = 14) from their nesting colonies to Nantucket Sound was 705 km (± 62 km; range 352 to 891 km). The mean (± SE) trip duration was 4.58 days (± 0.65 days; range 1.77 to 10.0 days; Table 3.3).

Common Terns from colonies in the Gulf of Maine and Canada arrived in Nantucket Sound between 26 July and 6 Sep, and departed from Nantucket Sound between 7 Aug and 7 Sep (Table 3.4). Mean (± SE) length of stay of Common Terns (n = 14) in Nantucket Sound was 5.24 days (± 1.58 days; range < 1 to 23.28 days; Table 3.4). All of the terns staging in the Nantucket Sound area were detected at Monomoy NWR., with some birds remaining for up to three weeks (Table 3.5). With the exception of one tern from Country Island, Common Terns that dispersed to Nantucket Sound were not detected again by northern sites within our network of telemetry towers, indicating they likely departed southward from the region to continue migration. The one Country Island tern staged in Nantucket Sound for 2.75 days, and then flew approximately 160 km north to the Isle of Shoals in the Gulf of Maine where it was detected for approximately three hours before departing from the study area.

Dispersal of Arctic Terns

Dispersal movements of Arctic Tern were largely undetected by the telemetry array. Arctic Terns from Sable Island and Country Island were not detected beyond 100 km of their nesting colonies. We detected 27% (*n* = 15) of the Arctic Terns from Petit Manan Island at sites along the eastern coast of Nova Scotia during post-breeding period, between 25 July and 17 Aug (Fig 3.4). Three of the four Arctic Terns detected in Nova Scotia were observed for < 5 minutes as they passed within range of receiving stations. The remaining bird departed the breeding colony and was detected along the coast of Nova Scotia for three days. It then traveled back to the breeding colony, where it remained for approximately one day. This bird then traveled back through Nova Scotia where it was detected for less than five minutes as it passed by within range of a telemetry station. The mean (± SE) minimum (Euclidian) distance traveled by Arctic Terns (*n* = 4) from the Petit Manan Island colony to sites in Nova Scotia was 682 km (± 266 km; range 377 to 1,478 km) and the mean (± SE) trip duration was 10.02 days (± 3.74 days; range 1.00 to 17.90 days; Table 3.3). Mean (± SE) length of stay of Arctic

Terns (*n* = 4) from the Petit Manan Island colony at sites in coastal Nova Scotia was 0.78 days (± 0.77 days; range < 0.01 to 3.11 days; Table 4).

Timing of movements

For Common and Arctic Terns that were detected away from their colony sites during the post-breeding period (*n* = 14 Common Terns and *n* = 4 Arctic Terns, respectively), Common Terns arrived at staging areas between 15:00 hrs and 05:00 hrs, peaking within two hours of sunset (Fig. 3.5A), and Arctic Terns were detected passing by the coast of Nova Scotia at night, between 22:00 hrs and 04:00 hrs (Fig. 3.5B). Across all terns in the study (*n* = 182), timing of departure from the study area occurred just before sunrise, with a unimodal distribution that had a mean departure time of 04:49 hrs ($\rho = 0.175$; Fig. 3.6). Departure times were not uniformly distributed throughout the day (R=0.1753, $p = 0.005$), and did not vary between species (Circular Analysis of Variance Likelihood Ratio Test: $\chi^2 = 0.001$, $n = 182$, $p = 0.972$).

Discussion

Using an automated international telemetry array and VHF tracking technology, this study offered new insights into the migratory behavior of two seabird species from breeding sites in the western North Atlantic. We documented connectivity among nesting sites in the Gulf of Maine and Canada for Common Terns and a staging site in Massachusetts, USA. In contrast, the lack of detections of Arctic Terns by the array suggests this species predominately migrates offshore. From a behavioral perspective, our data show that both tern species initiate post-breeding movements principally at night, typically within two hours prior to sunrise.

Our results showed wide variation in length of stay of terns at the colony site relative to their hatch dates. Among Common and Arctic terns, timing of fledging typically varied between 21 to 29 days after eggs hatch and successful breeders disperse away from their colony sites between 10 to 20 days after chicks fledge (Nisbet 1976, Hatch 2002), whereas failed breeders may depart from the colony within days following nest loss (P. Loring, *unpublished data*). However, due to incomplete productivity data across our study sites, we were unable to relate departure date to reproductive success of individual birds in this analysis. Alternatively, differences in length of stay among colonies may also be influenced by variation of prey availability (Safina and Burger 1989), which we were unable to quantify in this study. It is also likely that some apparent departure prior to estimated fledge dates was due to tag loss or malfunction. We removed known dropped transmitters (7% of deployments) from analyses, but it is possible that additional birds dropped their transmitters beyond range of the telemetry array prior to colony departure, and thus were not accounted for as dropped. Therefore, estimates of length of stay at the colony site and proportions of terns that staged in the Nantucket Sound region should be considered a minimum.

During the post-breeding period (July and August), Common and Roseate terns from nesting colonies throughout the western North Atlantic may disperse hundreds of kilometers to staging areas throughout the region (Austin 1953, Shealer and Kress 1994, Trull et al. 1999). We found that, from late July to early September, 26% (n = 53) of our tagged Common Terns from northern colonies dispersed up to 800 km to staging areas in Nantucket Sound, and that their mean travel time (< 1 week) was shorter relative to the dispersal of Roseate Terns across similar distances reported by other studies (mean travel time > 3 weeks (Shealer and Kress 1994).

Nesting terns remained significantly longer at the South Monomoy Island colony, and all of the Common Terns from northern colony sites that staged in the Nantucket Sound region were detected at Monomoy NWR. Some birds remained on Monomoy NWR for up to three weeks. During the post-breeding period, Monomoy NWR is known as an important staging area for terns, due to its remote location with relatively low levels of human disturbance, large area of sand flats available for roosting, and proximity to foraging areas that includes extensive shoals (Trull et al. 1999). During the post-breeding period, the majority of staging terns in the Cape Cod and Nantucket Sound region used Monomoy NWR and an adjacent barrier beach as nocturnal roosting areas (Trull et al. 1999). We found that a minimum of 25% of our tagged birds from Gulf of Maine and Canadian tern colonies dispersed to Monomoy NWR during the post-breeding period, further highlighting the importance of Monomoy NWR for post-breeding terns within the western North Atlantic Ocean.

Common Terns that staged in Nantucket Sound departed from the region between mid-August and early September, which is consistent with past studies (Veit and Petersen 1993, Trull et al. 1999). Using geolocators, Nisbet et al. (2011*b*) found that the mean fall migration date of female Common Terns from the southern New England area was in mid-August, while the mean date for males was in early September. Most terns that staged in Nantucket Sound appeared to depart from the study area from that region, with the exception of one individual that was detected flying from Nantucket Sound to the Gulf of Maine prior to departure. Northern movements of terns from the southern New

England region to sites in Gulf of Maine during the post-breeding period was documented for Common Terns (Austin 1953) and Roseate Terns (Shealer and Kress 1994).

With the exception of eastward movements of Arctic Terns from the Petit Manan Island colony that were detected passing through sites in Nova Scotia, we were unable to assess the post-breeding dispersal of Arctic Terns with our telemetry array. This suggests that Arctic Terns use offshore routes after departing their colonies. This was not entirely unexpected, as prior research to document Arctic Tern migration using geolocators have demonstrated that Arctic Terns from colonies in the Gulf of Maine traveled north-northeast after nesting, then migrated east across the Atlantic Ocean (L. Welch, *unpublished data*). Geolocator studies of Arctic Terns tagged from colonies in Greenland and Iceland revealed that, during post-breeding dispersal, individuals traveled to a pelagic stopover region in the eastern Newfoundland Basin and western slope of mid-North Atlantic Ridge (41 to 53° N and 27 to 41° W) where they spent an average of three weeks prior to migrating southeast towards the coast of Africa (Egevang et al. 2010).

Departure movements of both species were initiated primarily at night during this study. There is little empirical evidence of the precise timing of tern movements within the literature, but observational and radar data indicate that terns initiate migratory movement at dusk and fly at migratory altitudes (1,000 to 3,000 m) during night (Alerstam 1985, Veit and Petersen 1993). We found that, for both Common and Arctic terns, departure times from the study area peaked just before dawn (04:00 to 05:00 hrs). It is possible that these departure times coincided with morning foraging flights, as peak foraging activity is known to occur largely during morning hours (Burger and Gochfeld

1991, Galbraith et al. 1999). More complete coverage of automated radio telemetry stations throughout their post-breeding range is needed to more precisely quantify timing of migratory movements using digital VHF technology.

Conclusions

Common and Arctic terns from colonies in the western North Atlantic exhibit divergent strategies for dispersal. Nantucket Sound appears to be an important pre-migratory staging area for Common Terns from breeding colonies in the western North Atlantic. More information is needed on post-breeding movements of Arctic Terns to identify important offshore staging areas, although geolocator technology has provided evidence of offshore staging and stopover areas at relatively coarse temporal and spatial scales (Egevang et al. 2010, Duffy et al. 2013, McKnight et al. 2013). Additional automated radio telemetry stations, in both coastal and offshore areas, would be useful for more accurately tracking the post-breeding movements of Common and Arctic terns in our study area.

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Literature Cited

Agostinelli, C. and U. Lund. 2013. Circular: circular statistics. [online] URL: http://CRAN.R-project.org/package=circular. R package version 0.4–7.

Alerstam, T. 1985. Strategies of migratory flight, illustrated by arctic and common terns, Sterna paradisaea and Sterna hirundo. - In: Rankin, M. A. (ed.). Migration: Mechanisms and Adaptive Significance. Contr. Mar. Sci. Suppl. 27: 580-603.

Austin, O. L. 1953. The migration of the Common Tern (*Sterna hirundo*) in the Western Hemisphere. *Bird-Banding* 24:39-55.

Batschelet, E. 1981. Circular Statistics in Biology. Academic Press, New York, NY, 371 pp.

Braune, B. M., and D. E. Gaskin. 1982. Feeding ecology of nonbreeding populations of larids off Deer Island, New Brunswick. *Auk* 99:67-76.

Bridge, E. S., K. Thorup, M. S. Bowlin, P. B. Chilson, R. H. Diehl, R. W. Fléron, P. Hartl, R. Kays, J. F. Kelly, and W. D. Robinson. 2011. Technology on the move: recent and forthcoming innovations for tracking migratory birds. *BioScience* 61:689-698.

Brzustowski, J. 2015. SensorGnome. [online] URL: http://public.sensorgnome.org/Sensorgnome_Package.

Burger, J., and M. Gochfeld. 1991. The Common Tern: Its Breeding Biology and Social Behavior. Columbia University Press, New York, New York, USA, 413 pp.

Duffy, D. C., A. McKnight, and D. B. Irons. 2013. Trans-Andean passage of migrating Arctic Terns over Patagonia. *Marine Ornithology* 41:155-159.

Egevang, C., I. J. Stenhouse, R. A. Phillips, A. Petersen, J. W. Fox, and J. R. D. Silk. 2010. Tracking of Arctic Terns (*Sterna paradisaea)* reveals longest animal migration. *Proceedings of the National Academy of Sciences* 107:2078-2081.

Galbraith, H., J. J. Hatch, I. C. T. Nisbet, and T. H. Kunz. 1999. Age-specific reproductive efficiency among breeding Common Terns *Sterna hirundo*: measurement of energy expenditure using doubly-labelled water. *Journal of Avian Biology* 30:85-96.

Gaston, A. J., D. F. Bertram, A. W. Boyne, J. W. Chardine, G. Davoren, A. W. Diamond, A. Hedd, W. A. Montevecchi, J. M. Hipfner, M. J. F. Lemon, M. L. Mallory, J. F. Rail, and G. J. Robertson. 2009. Changes in Canadian seabird populations and ecology since 1970 in relation to changes in oceanography and food webs. *Environmental Reviews* 17:267-286.

Gilg, O., B. Moe, S. A. Hanssen, N. M. Schmidt, B. Sittler, J. Hansen, J. Reneerkens, B. Sabard, O. Chastel, J. Moreau, R. A. Phillips, T. Oudman, E. M. Biersma, A. A. Fenstad, J. Lang, and L. Bollache. 2013. Trans-equatorial migration routes, staging sites and wintering areas of a high-arctic avian predator: the Long-tailed Skua (*Stercorarius longicaudus*). *PloS ONE* 8:e64614.

Guilford, T., J. Meade, J. Willis, R. A. Phillips, D. Boyle, S. Roberts, M. Collett, R. Freeman, and C. M. Perrins. 2009. Migration and stopover in a small pelagic seabird, the Manx shearwater (*Puffinus puffinus)*: insights from machine learning. *Proceedings of the Royal Society of London B: Biological Sciences*:rspb-2008.

Gulf of Maine Seabird Working Group (GOMSWG). 2013. 2013 Gulf of Maine Seabird Working Group Census Results. [online] URL: http://gomswg.org/pdf_files/GOMSWG%20Census%20Data%202013.pdf

Hall, C. S., S. W. Kress, and C. R. Griffin. 2000. Composition, spatial and temporal variation of Common and Arctic Tern chick diets in the Gulf of Maine. *Waterbirds* 23:430-439.

Hatch, J. J. 2002. Arctic Tern (*Sterna paradisaea*), *The Birds of North America Online* (A. Poole, Ed.). Ithaca: Cornell Lab of Ornithology. [online] URL: http://bna.birds.cornell.edu.bnaproxy.birds.cornell.edu/bna/species/707doi:10.2173/bna.707.

Hays, H., J. DiCostanzo, G. Cormons, P. T. Z. Antas, and J. L. X. do Nascimento. 1997. Recoveries of Roseate and Common Terns in South America. *Journal of Field Ornithology* 68:79-90.

Hedd, A., W. A. Montevecchi, H. Otley, R. A. Phillips, and D. A. Fifield. 2012. Trans-equatorial migration and habitat use by Sooty Shearwaters (*Puffinus griseus)* from the South Atlantic during the nonbreeding season. *Marine Ecology Progress Series* 449:277-290.

Hosmer, D. W., and S. Lemeshow. 2000. Applied Logistic Regression. Second edition. John Wiley and Sons, New York, New York, USA.

Hothorn, T., F. Bretz, and P. Westfall. 2015. Multcomp. [online] URL: https://cran.r-project.org/web/packages/multcomp/index.html. R package version 1.4–4.

Huettmann, F., and A. W. Diamond. 2000. Seabird migration in the Canadian northwest Atlantic Ocean: moulting locations and movement patterns of immature birds. *Canadian Journal of Zoology* 78:624-647.

Klaassen, R. H. G., B. J. Ens, J. Shamoun-Baranes, K.-M. Exo, and F. Bairlein. 2011. Migration strategy of a flight generalist, the Lesser Black-backed Gull (*Larus fuscus). Behavioral Ecology* 23:58-68.

Kress, S. W., E. H. Weinstein, C. T. N. Ian, G. W. Shugart, W. C. Scharf, H. Blokpoel, G. A. Smith, K. Karwowski, G. R. Maxwell, G. Chapdelaine, W. A. Montevecchi, A. R. Lock, C. F. Smith, E. Miller, J. A. Spendelow, M. Gochfeld, J. Burger, and R. M. Erwin. 1983. The status of tern populations in northeastern United States and adjacent Canada. *Colonial Waterbirds* 6:84-106.

McKnight, A., A. J. Allyn, and D.B. Irons. 2013. Stepping stone pattern in Pacific Arctic Tern migration reveals the importance of upwelling areas. *Marine Ecology Progress Series* 491:253-264.

Montevecchi, W. A., A. Hedd, L. McFarlane Tranquilla, D. A. Fifield, C. M. Burke, P. M. Regular, G. K. Davoren, S. Garthe, G. J. Robertson, and R. A. Phillips. 2012. Tracking seabirds to identify ecologically important and high risk marine areas in the western North Atlantic. *Biological Conservation* 156:62-71.

Mosbech, A., K. L. Johansen, N. I. Bech, P. Lyngs, A. M. Harding, C. Egevang, R. A. Phillips, and J. Fort. 2012. Inter-breeding movements of little auks (*Alle alle)* reveal a key post-breeding staging area in the Greenland Sea. *Polar Biology* 35:305-311.

Nisbet, I. C. T. 1976. Early stages in postfledging dispersal of Common Terns. *Bird-Banding* 47:163-164.

Nisbet, I. C. T. 2002. Common Tern (*Sterna hirundo*), *The Birds of North America Online* (A. Poole, Ed.). Ithaca: Cornell Lab of Ornithology. [online] URL: http://bna.birds.cornell.edu/bna/species/618doi:10.2173/bna.618.

Nisbet, I. C. T., C. S. Mostello, R. R. Veit, J. W. Fox, and V. Afanasyev. 2011*a*. Migrations and winter quarters of five Common Terns tracked using geolocators. *Waterbirds* 34:32-39.

Nisbet, I. C. T., P. Szczys, C. S. Mostello, and J. W. Fox. 2011*b*. Female common terns (*Sterna hirundo)* start autumn migration earlier than males. *Seabird* 24:103-106.

R Core Team. 2015. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. [online] URL: http://www.R-project.org/

Rock, J.C., M.L. Leonard, and A.W. Boyne. 2007. Do co-nesting Arctic and Common Terns partition foraging habitat and chick diets? *Waterbirds* 30:579-587.

Ronconi, R. A., J. R. Stephens, Z. J. Crysler, I. L. Pollet, D. T. Fife, A. G. Horn, P. D. Taylor 2016. Distribution, abundance and trends of gulls and terns breeding on Sable Island, Nova Scotia, Canada. *Waterbirds* 39:44-56.

Safina, C., and J. Burger. 1989. Inter-annual variation in prey availability for Common Terns at different stages in their reproductive cycle. *Colonial Waterbirds* 12:37-42.

Shealer, D. A., and S. W. Kress. 1994. Post-breeding movements and prey selection of Roseate Terns at Stratton Island, Maine. *Journal of Field Ornithology* 65:349-362.

Suryan, R. M., F. Sato, G. R. Balogh, K. D. Hyrenbach, P. R. Sievert, and K. Ozaki. 2006. Foraging destinations and marine habitat use of short-tailed albatrosses: a multi-scale approach using first-passage time analysis. *Deep Sea Research Part II: Topical Studies in Oceanography* 53:370-386.

Trull, P., S. Hecker, M. J. Watson, and I. C. T. Nisbet. 1999. Staging of Roseate Terns (*Sterna dougallii)* in the post-breeding period around Cape Cod, Massachusetts, USA. *Atlantic Seabirds* 1:145-158.

van der Winden, J., R. C. Fijn, P. W. v. Horssen, D. Gerritsen-Davidse, and T. Piersma. 2014. Idiosyncratic migrations of Black Terns (*Chlidonias niger*): Diversity in routes and stopovers. *Waterbirds* 37:162-174.

Veit, R. R., and W. R. Petersen. 1993. *Birds of Massachusetts*. Massachusetts Audubon Society, Lincoln, MA, USA.

Warnock, N. 2010. Stopping vs. staging: the difference between a hop and a jump. *Journal of Avian Biology* 41:621-626.

Zar, J. H. 1999. Biostatistical Analysis. Fourth edition. Prentice Hall, Upper Saddle River, New Jersey, USA.

Table 3.1. Number of Common and Arctic terns fitted with digital VHF transmitters at four colonies in the western North Atlantic in 2013. Tagged (*n*) indicates the starting sample size, and Final (*n*) indicates the sample size retained for subsequent analyses after removing (and in some instances redeploying) transmitters that were dropped.

	Tagged (*n*)		Final (*n*)	
Colony	Common	Arctic	Common	Arctic
Petit Manan Is.	14	16	14	15
Country Is.	15	15	11	16
Sable Is.	29	21	28	20
Monomoy Is.	72	0	67	0
Total	130	52	120	51

Table 3.2. Median (range) dates of transmitter deployment, estimated hatch, and final detection in our study area of Common (n = 120) and Arctic terns (n = 51) marked with digital VHF transmitters at four nesting colonies in the western North Atlantic in 2013.

	Deployment		Hatch		Final detection	
Colony	Common	Arctic	Common	Arctic	Common	Arctic
Petit Manan Is.	6/13 (6/13-6/21)	6/13 (6/13-6/20)	6/26 (6/22-6/30)	6/24 (6/20-7/20)	7/23 (6/28-8/19)	7/23 (6/27-8/17)
Country Is.	6/15 (6/14-7/4)	6/15 (6/14-7/14)	6/26 (6/23-7/20)	6/24 (6/20-7/20)	7/9 (6/23-8/18)	7/30 (6/28-8/14)
Sable Is.	6/10 (6/9-6/13)	6/10 (6/9-6/11)	6/24†	6/24†	7/20 (6/20-9/7)	7/30 (6/19-8/10)
Monomoy Is	6/20 (6/4-7/6)	---	6/21 (6/15-7/15)	---	8/5 (7/4-9/15)	---

† On Sable Island, individual nests were not monitored so assumed mean hatch date of 6/24

Table 3.3. Mean (± SE and range) distance traveled by Common (*n* = 53) and Arctic terns (*n* = 51) to post-breeding dispersal sites and duration (in days) of post-breeding dispersal movements (assuming Euclidian distances) from three nesting colonies in the western North Atlantic during 2013.

	Minimum Distance Traveled (km)		Trip Duration (days)	
Colony	Common	Arctic	Common	Arctic
Petit Manan Is.	356 (± 3; 352-361)	681 (± 265.7; 377-1478)	3.5 (± 0.9; 1.8-5.8)	7.5 (± 2.9; 1.0-17.9)
Country Is.	556 (± 199; 160-786)	---	2.4 (± 0.4; 1.5-2.8)	---
Sable Is.	867 (± 5; 851-891)	---	5.5 (± 0.9, 2.6 - 10.0)	---

Table 3.4. Common (*n* = 14) and Arctic Tern (*n* = 4) arrival and departure dates (median and range) and length of stay (mean ± SE and range) at post-breeding dispersal sites from three nesting colonies in the western North Atlantic in 2013.

	Arrival date		Departure date		Length of stay (days)	
	Common	Arctic	Common	Arctic	Common	Arctic
Petit Manan Is.	8/4 (7/26 - 8/6)	8/1 (7/25 - 8/17)	8/12 (8/7 - 8/19)	8/3 (7/30 - 8/17)	10.20 (± 4.41; 4.04-23.28)	0.78 (±0.77; <0.01 - 3.11)
Country Is.	8/10 (8/6 - 8/13)	---	8/16 (8/14 - 8/18)	---	6.36 (± 1.43; 4.92-7.79)	---
Sable Is.	8/11 (7/26 - 9/6)	---	8/12 (7/27 - 9/7)	---	2.47 (± 0.90; 0.01 - 7.68)	---

Table 3.5. Number of Common Terns detected (n) and their length of stay (mean ± SE and range, in days) in Nantucket Sound, MA from three nesting colonies in the western North Atlantic during the post-breeding dispersal period in 2013.

Colony	*n*	Length of stay	SE	Min	Max
Petit Manan Island	4	9.29	4.20	4.02	21.83
Country Island	2	3.91	3.18	0.73	7.09
Sable Island	8	1.82	0.94	0.00	7.68

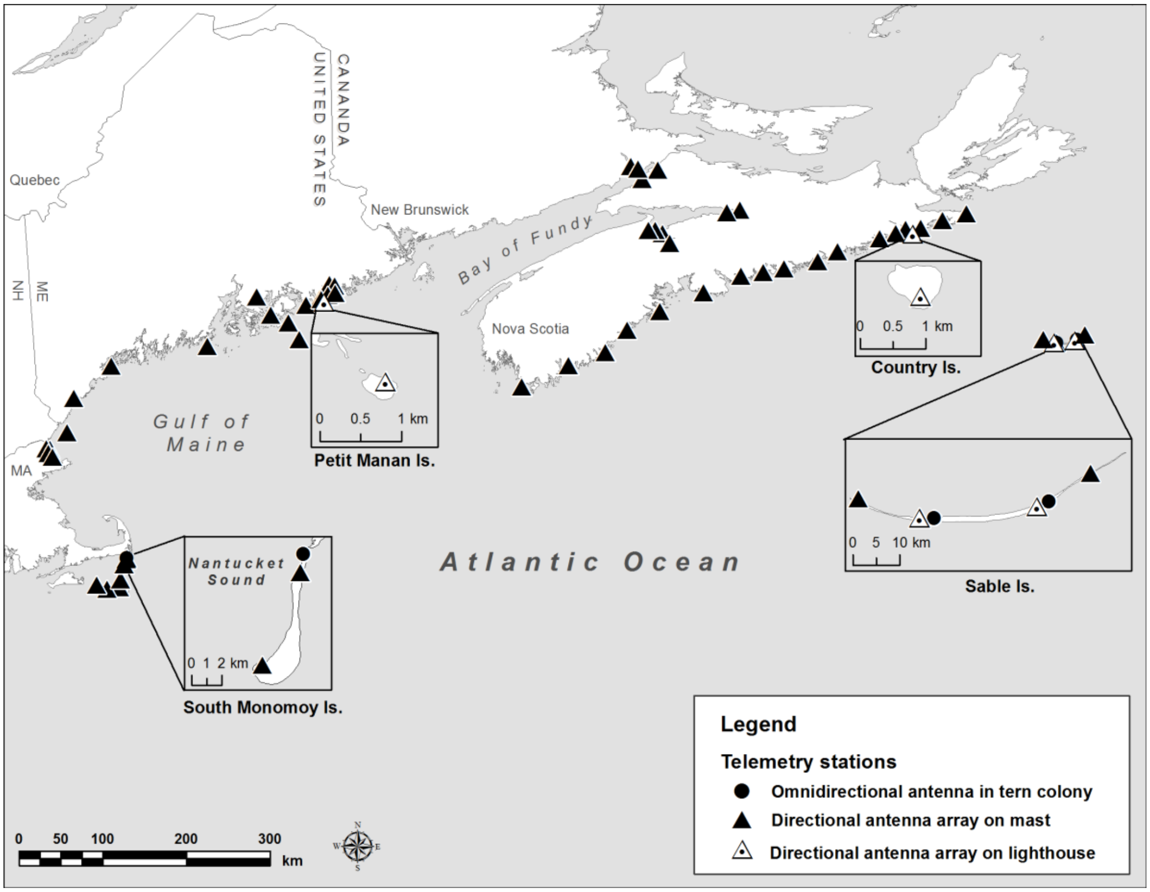

Figure 3.1. Map of 2013 study area in the western North Atlantic showing the locations of four tern breeding colonies (insets) and 62 automated radio telemetry stations, each consisting of directional antenna arrays mounted on masts or lighthouses (solid and open triangles, respectively) or omnidirectional antennas positioned in tern colonies (solid points).

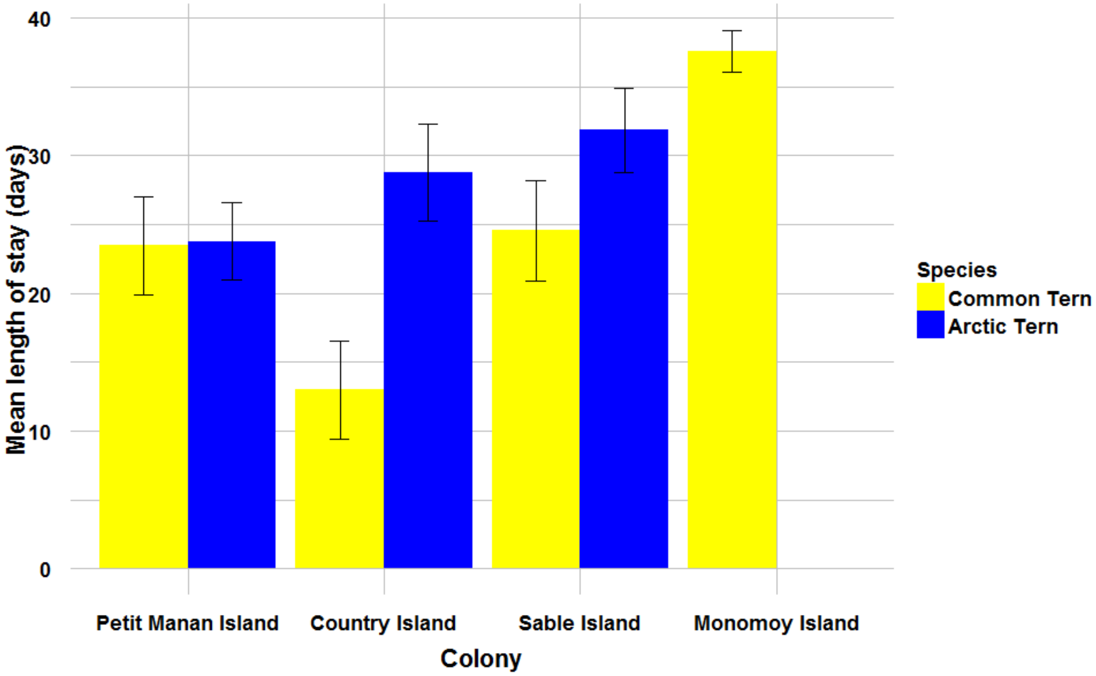

Figure 3.2. Mean (± SE) length of stay (in days), relative to estimated hatch dates, within the nesting colony of Common Terns (yellow) and Arctic Terns (blue) during the breeding period.

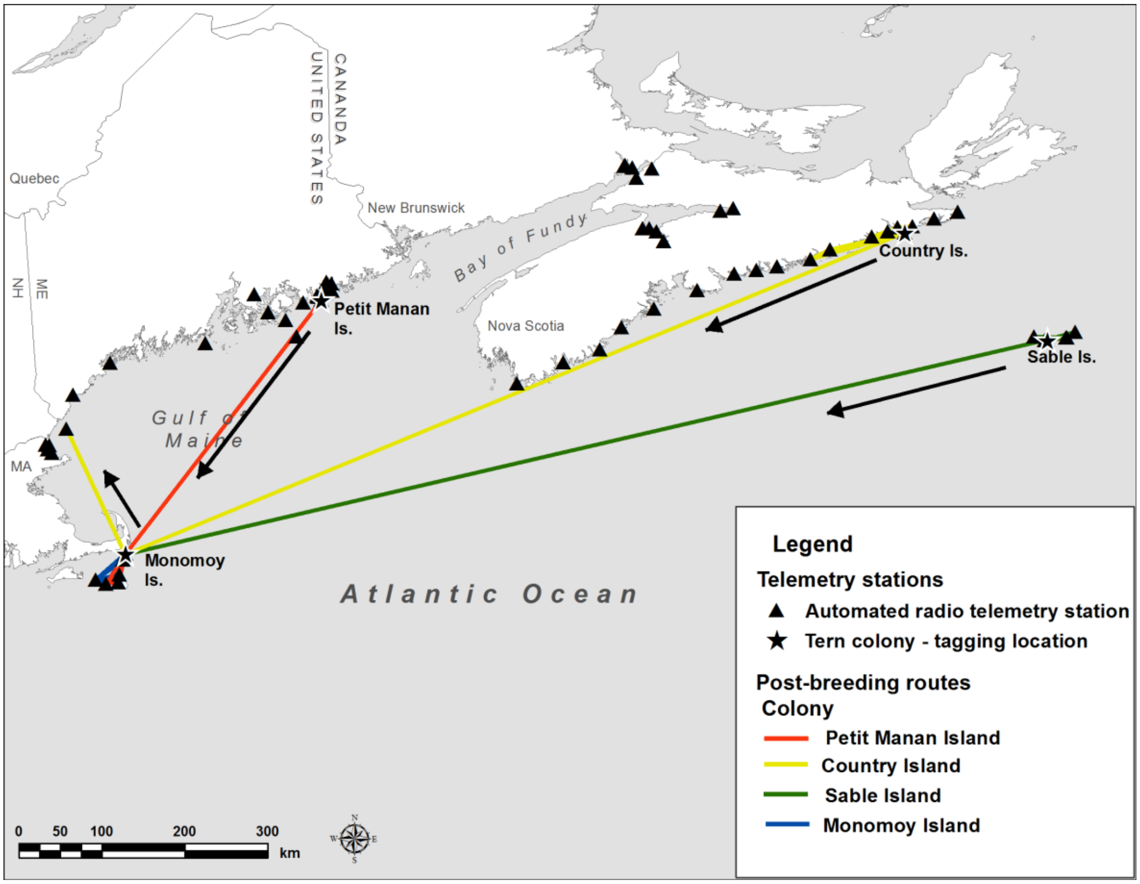

Figure 3.3. Euclidian post-breeding movements of tagged Common Terns (*n* = 120) from four nesting colonies in the northwest Atlantic (Petit Manan Island, Maine, USA [red]; Country Island, Nova Scotia, Canada [yellow]; Sable Island, Nova Scotia, Canada [green]; and South Monomoy Island, Massachusetts, USA [blue]) tracked by 62 automated radio telemetry stations during the 2013 post-breeding dispersal period. Black arrows show generalized direction of travel.

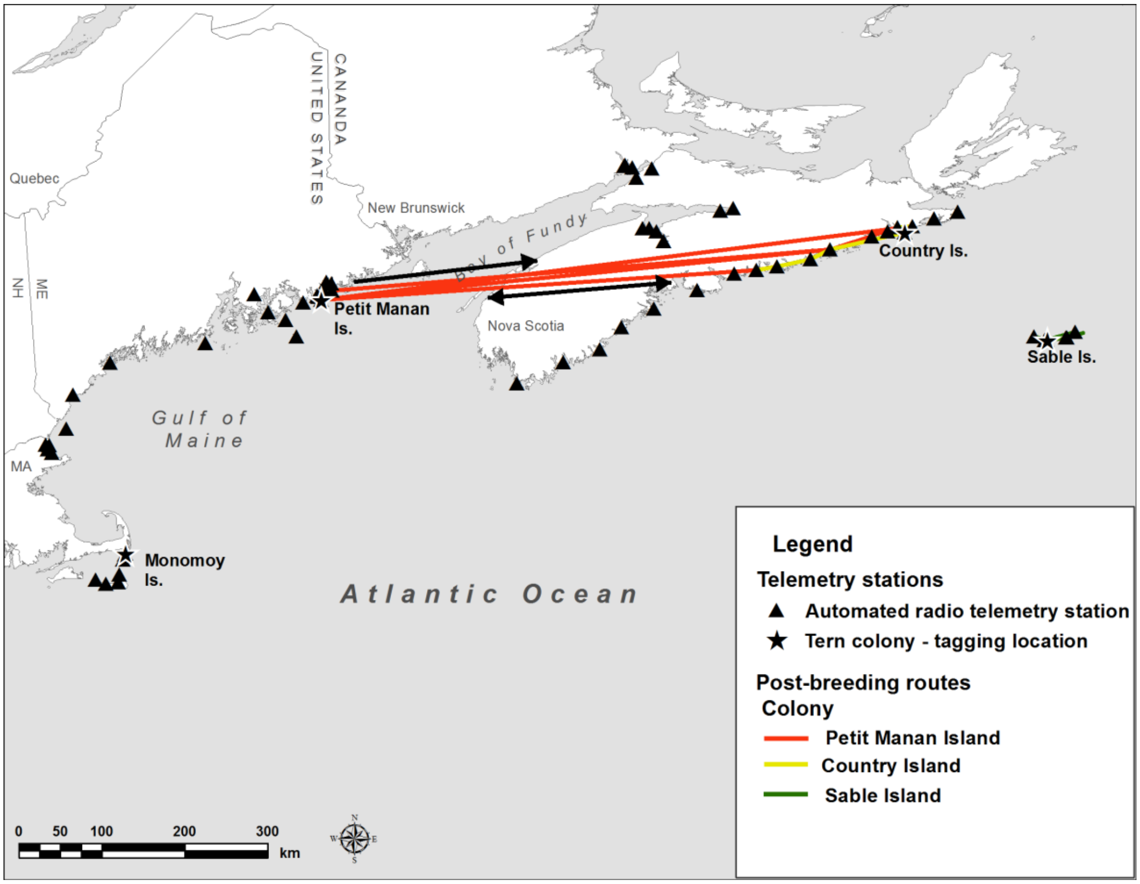

Figure 3.4. Euclidian post-breeding movements of tagged Arctic Terns (*n* = 52) from three nesting colonies in the northwest Atlantic (Petit Manan Island, Maine, USA [red]; Country Island, Nova Scotia, Canada [yellow]; and Sable Island, Nova Scotia, Canada [green]) tracked by 62 automated radio telemetry stations during 2013. Black arrows show generalized direction of travel.

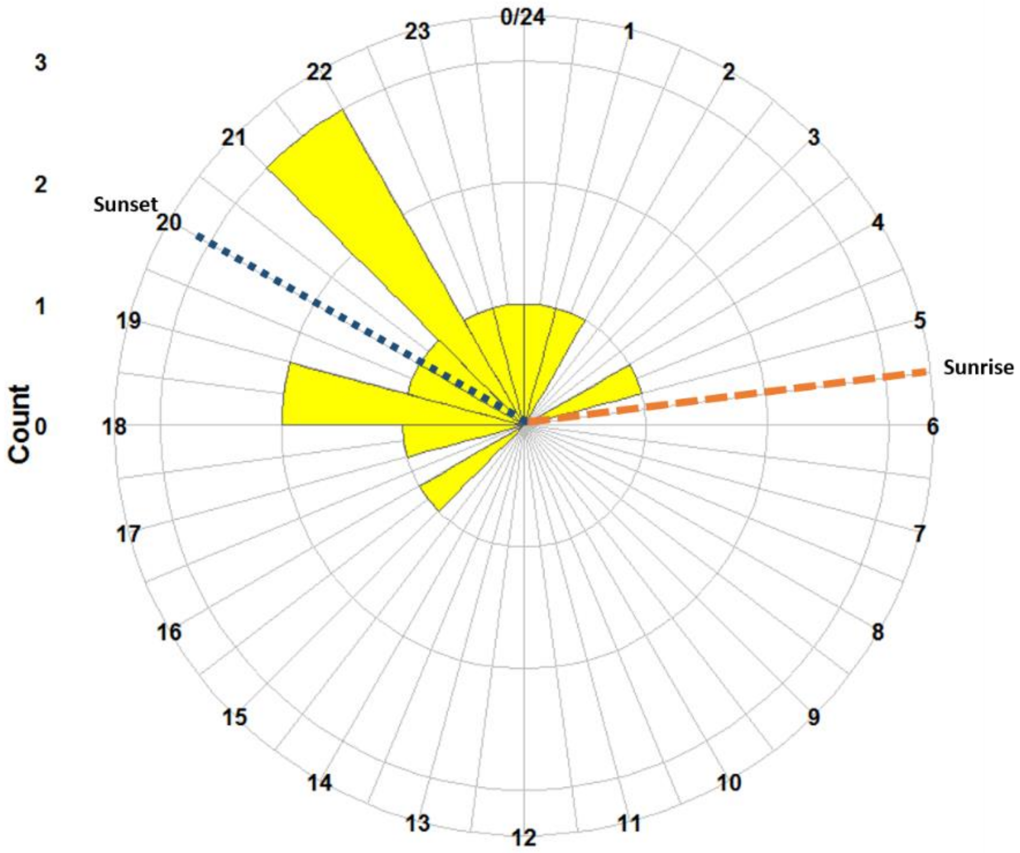

Figure 3.5. Diel variation (hrs, in local time) in arrival times of Common Terns (*n* = 14) from three nesting colonies in the northwest Atlantic (Petit Manan Island, Maine, USA; Country Island, Nova Scotia, Canada; and Sable Island, Nova Scotia, Canada) at staging areas in Nantucket Sound, Massachusetts, USA during 2013. Dashed lines show local times of sunrise (orange) and sunset (blue).

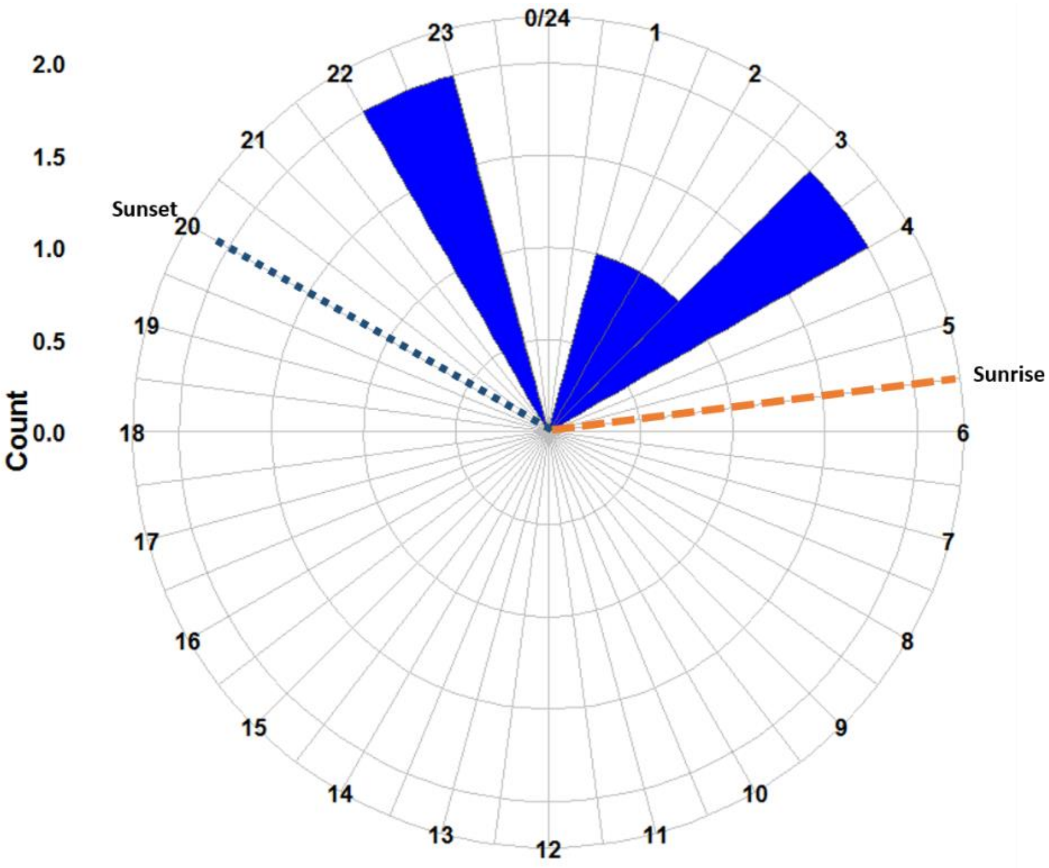

Figure 3.6. Diel variation (hrs, in local time) in passage times of Arctic Terns (*n* = 4) from Petit Manan Island, Maine, USA passing through sites in Nova Scotia, Canada during the post-breeding period in 2013. Dashed lines show local times of sunrise (orange) and sunset (blue).

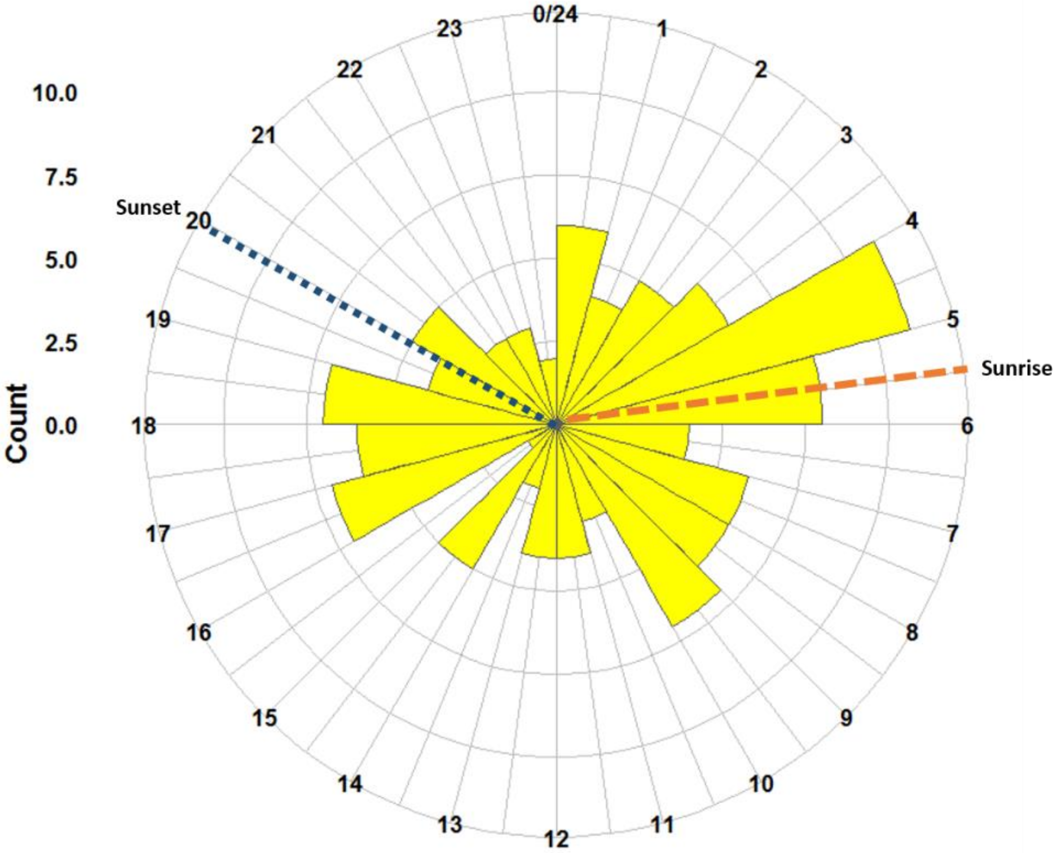

Figure 3.7. Diel variation (hrs, local time) of post-breeding departure times of Common Terns (6A; *n* = 120) from western North Atlantic study area during 2013. Dashed lines show local times of sunrise (orange) and sunset (blue).

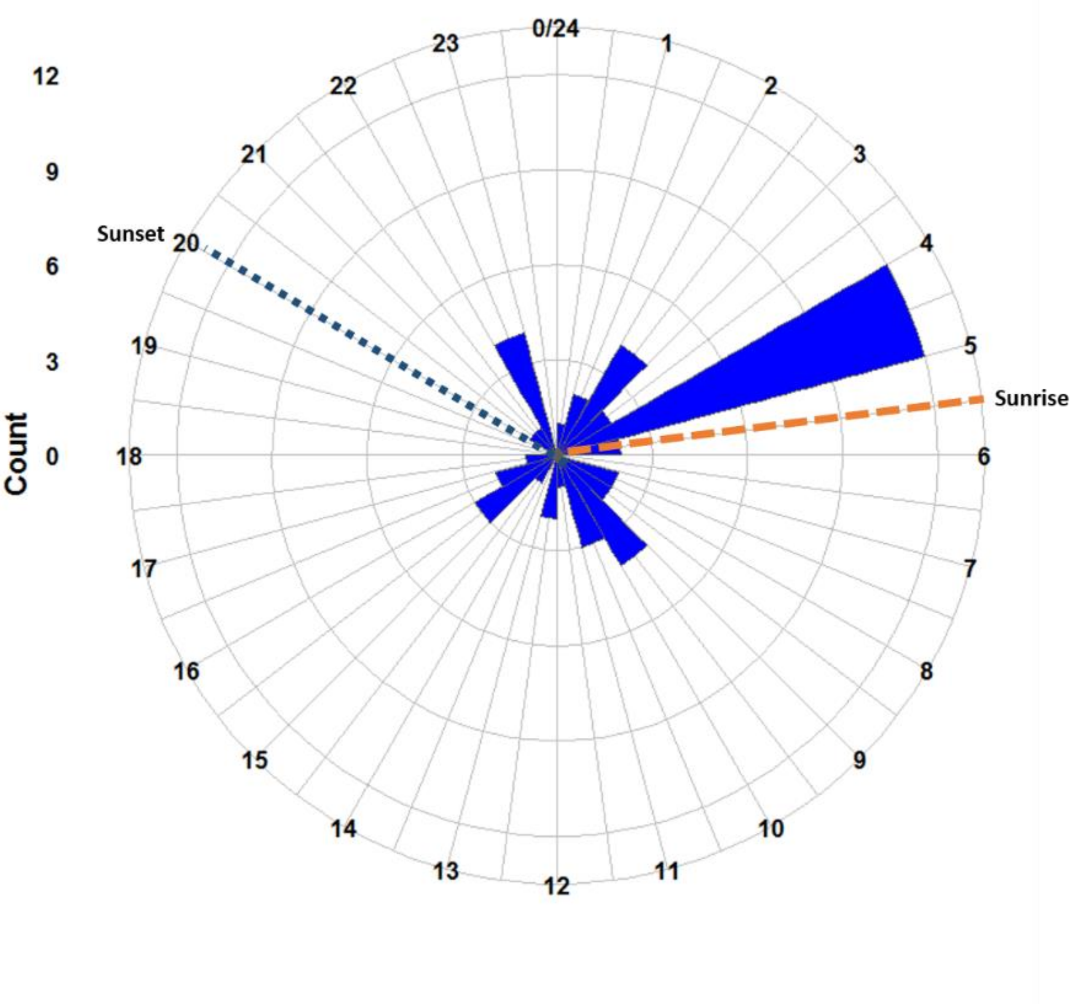

Figure 3.8. Diel variation (hrs, local time) of post-breeding departure times of Arctic Terns (6B; *n* = 52) from western North Atlantic study area during 2013. Dashed lines show local times of sunrise (orange) and sunset (blue).

CHAPTER 4

ATMOSPHERIC, TEMPORAL, AND DEMOGRAPHIC FACTORS INFLUENCE EXPOSURE OF COMMON TERNS TO OFFSHORE WIND ENERGY AREAS IN THE U.S. ATLANTIC

Abstract

Individual-based tracking studies are critical for assessing potential effects of offshore wind energy facilities on bird populations. This is particularly true when inclement weather limits visibility and leads to elevated collision risks with offshore wind turbines. In 2014, we attached digital VHF transmitters to 116 adult Common Terns (*Sterna hirundo*) from two major nesting colonies in the U.S. Atlantic: South Monomoy Island, MA and Great Gull Island, NY. We tracked their regional movements using a network of automated towers erected at strategically-placed coastal and offshore sites from Cape Cod, MA, to Long Island, NY, and used a Brownian Bridge Moment Model to estimate flights across Wind Energy Areas (WEAs) in state and federal waters. We used an extended Cox Proportional Hazard Analysis to model the rate of WEA crossing events to various atmospheric and demographic covariates. We documented a total of 94 WEA crossing events that occurred across all hours of the day and night. Adult females from Great Gull Island were more likely to cross WEAs relative to males from South Monomoy Island. WEA crossing events that occurred early on in the study period, within days following chick hatch, were associated with higher wind speeds and lower visibility relative to events that occurred later in the study period, during post-breeding dispersal. Our study addresses a long-standing information gap on the movements of

terns at night and during inclement weather, and demonstrates the utility of digital VHF telemetry for conducting similar studies on the taxonomically similar but Federally endangered Roseate Tern (*Sterna dougallii*).

Introduction

Renewable energy initiatives, such as the U.S. Department of Energy's effort to achieve 54 gigawatts of offshore wind generating capacity by 2030, have spurred plans for development of offshore wind energy facilities off the U.S. Atlantic Coast (Beaudry-Losique et al. 2011). To date, the Bureau of Ocean Energy Management (BOEM) has issued eleven commercial wind energy leases within the Atlantic Outer Continental Shelf (AOCS), totaling over 1.1 million acres (4,781 km^2) of Federal waters ($\geq$ 5.5 km offshore), and is in the planning stages for leasing additional offshore areas along the AOCS (Bureau of Ocean Energy Management 2016). Several Atlantic coast states are developing plans to site additional wind energy facilities within their jurisdictional waters ($\leq$ 5.5 km from the coast), and the first offshore wind facility in the U.S. is currently under construction off the coast of Rhode Island (Baranowski et al. 2016).

With this expansion in renewable energy development offshore comes a need for more detailed information on the occurrence of birds in the AOCS, so that possible adverse effects to avian populations can be monitored and managed (Goodale and Milman 2016). Research at existing facilities in western Europe has shown that offshore wind facilities may subject birds to various adverse effects, including: acting as barriers to movement (e.g. between foraging and roosting sites, along migration routes); destruction, modification, or displacement of habitat; and causing direct mortality from collisions with infrastructure or pressure vortices (Exo et al. 2003, Fox et al. 2006).

Risks of collisions with offshore wind turbines are elevated during periods of night and low visibility (Dirksen et al. 1998), and inclement weather conditions, such as fog, precipitation, or high wind speeds (Exo et al. 2003). Thus, information on timing, distribution, movements of birds offshore, particularly at night and during adverse weather conditions, is needed for siting offshore wind facilities in areas with relatively low levels of avian use, and for monitoring interactions between birds and wind energy facilities that have already been sited using the best available science (Johnson 2014).

Previous work within the AOCS assessed the timing, distribution, and movements of birds using ship-based, aerial, and telemetry surveys (Perkins et al. 2003, Sadoti et al. 2005, Winiarski et al. 2014, Goyert et al. 2016). Ship-based and aerial survey methods provide static counts of the spatial distribution and abundance of birds in offshore areas. However, these surveys are typically limited to periods of daylight and favorable weather with suitable conditions for observation, so are less suitable for collecting information at night and during inclement weather when collision risks are elevated (Allison et al. 2008).

Telemetry studies use tracking devices to monitor the locations of marked individuals, and many types of devices are capable of providing information on movements throughout the diel period and during all types of weather conditions (Kunz et al. 2007, Burger and Shaffer 2008). This information can be used to assess demographic variation in use of offshore areas, including species, breeding population, age, and sex (Montevecchi et al. 2012). In addition, tracking studies provide critical information on movement pathways, including those between nocturnal and diurnal roost areas (Allison et al. 2006), feeding and nesting areas (Perrow et al. 2006), and during migration (Griffin et al. 2010). Individual-based information is also useful for assessing temporal variation in offshore movements, including patterns related to time of day, season, and the stage of the annual cycle, such as the breeding versus non-breeding periods (Drewitt and Langston 2006).

To date, several telemetry studies have been conducted throughout the AOCS with a focus on collecting data on the movements of birds offshore to help inform siting decisions of offshore wind energy areas. However, due to limitations of available technologies suitable for tracking wide-ranging birds offshore, these studies have been focused on monitoring relatively large-bodied taxa, such as seaducks (Meattey et al. 2015, Allison et al. 2006, Loring et al. 2014), loons (Gray et al. 2015), gannets (Adams et al. 2015), and raptors (Desorbo et al. 2015). The smallest available satellite-based transmitters are still relatively heavy (5 to 10 g) for use on small-bodied (< 150 g) bird species since tags should be restricted to < 3 to 5% of body mass to minimize impacts to tagged individuals (Fair et al. 2010).

The Roseate Tern (*Sterna dougallii*), is a small-bodied seabird (mean mass 115 ± 7 g, range 90 to 133 g, Nisbet et al. 2014) that is listed as Endangered under the U.S. Endangered Species Act and is known to occur within the Atlantic OCS during breeding, staging, and migration (Burger et al. 2011). Along the Atlantic coast of North America, Roseate Terns breed in mixed colonies in association with the taxonomically similar Common Tern (*Sterna hirundo*) on a limited number of islands distributed from Maritime Canada to Long Island, New York (Nisbet et al. 2014). Relative to the Roseate Tern, the North American Atlantic coast breeding range of the Common Tern is more widespread and extends from Newfoundland and Labrador, Canada to South Carolina, USA (Nisbet

2002a). The Common Tern is considered a USFWS “conservation focal species” (Mid-Atlantic/New England/Maritimes Region Waterbird Working Group 2006) and listed as a Threatened or Special Concern species by states encompassing its U.S. Atlantic coast breeding range. During the post-breeding period, both Common and Roseate Terns may disperse hundreds of kilometers away from their nesting colonies to congregate at staging areas, some of the largest of which are known to occur within Cape Cod and Nantucket Sound region of Massachusetts (Trull et al. 1999). From these staging areas, both species migrate offshore, across the Atlantic OCS, to distal staging areas in the West Indies (Nisbet et al. 2011a, Mostello et al. 2014).

Qualitative risk evaluations indicate that offshore wind facilities on the AOCS may pose risks to Common and Roseate terns during breeding, staging, and migratory periods (Burger et al. 2011). However, due to weight limitations of available tracking technologies, very little empirical data exists on the movements of these species in offshore environments (U.S. Fish and Wildlife Service 2008, Burger et al. 2011). Previous studies have used archival light-level loggers (geolocators) to track the movements of Common and Roseate terns in the western North Atlantic (Nisbet et al. 2011a, Mostello et al. 2014). However, these devices are limited to recording two locations per day that are routinely subject to errors of > 100 km, and thus, cannot identify fine-scale movement tracks which are needed to assess the potential impacts of wind facilities at specific sites. Detailed information on the offshore movements of terns, particularly at night and during inclement weather conditions, is essential for developing quantitative risk evaluations to inform siting and management decisions (Burger et al. 2011).

In this study, we used digital VHF transmitters and array of automated radio telemetry stations to track the breeding and post-breeding movements of Common Terns from two major nesting colonies in U.S. Atlantic that are in proximity to multiple offshore wind energy areas currently under consideration for development in the AOCS. Digital VHF telemetry is a relatively new technology that permits hundreds of individuals to be tagged with lightweight transmitters and monitored simultaneously and around the clock from automated receiving stations (Mills et al. 2011, Taylor et al. 2011, Mitchell et al. 2012, Woodworth et al. 2014). The overarching goal of this study was to pilot the suitability of digital VHF telemetry for monitoring the offshore movements of small-bodied birds, and to address information gaps on the movements of Common Terns in offshore areas.

Our specific objectives were to: 1) quantify the occurrence and extent of offshore movements by adult Common Terns from two major nesting colonies within the southern New England region of the AOCS; 2) model the rate of offshore movement events relative to various temporal (i.e. breeding and post-breeding periods), demographic (sex, nesting colony), and atmospheric (wind speed, visibility, precipitation rate) covariates; and 3) assess the timing of offshore movements relative to daylight. Through this work with Common Terns, we aim to evaluate the utility of using coded VHF transmitters and automated radio telemetry arrays to address the above objectives for the taxonomically similar but Federally-Endangered Roseate Tern in future studies.

Methods

Study area

We conducted fieldwork in the southern New England continental shelf region from Long Island, NY to Cape Cod, MA (40° N to 42° N; Fig. 4.1). Multiple areas for offshore renewable energy development have been delineated within the study area (Bureau of Ocean Energy Management 2016). These include an approximately 34-km^2 nearshore Renewable Energy Zone within Rhode Island state waters (defined as landward of the Submerged Lands Act Boundary, within approximately 5.5 m from shore) southeast of Block Island, where a 5-turbine, 30-MW wind energy facility is currently under construction and scheduled to be operational by fall 2016. Within Federal Waters (defined as seaward of the Submerged Lands Act Boundary, greater than approximately 5.5 m from shore) of the study area are multiple Wind Lease Areas that have been leased to companies with the intent to build a wind energy facility (BOEM). These include a 119 km^2 lease area in Nantucket Sound, Massachusetts, and three separate lease areas offshore of Rhode Island Sound that total 2,101 km^2. Adjacent to the lease areas offshore of Rhode Island Sound is a Wind Planning Area that is being considered for offshore wind energy development and covers an additional 1,572 km^2.

We tagged Common Terns from two major nesting colonies within the region: South Monomoy Island and Great Gull Island. South Monomoy Island (41° 36’ 31” N, 69° 59’ 12” W), is located within Monomoy National Wildlife Refuge (NWR), a 30-km^2 barrier beach and island complex located off of the coast of Cape Cod, Massachusetts, USA (Fig. 4.1). South Monomoy Island is approximately 9-km from north to south, and up to 2-km wide. The island supports, one of the largest Common Tern colonies on the Atlantic Coast, with over 8,500 nesting pairs in 2014 (Gulf of Maine Seabird Working Group (GOMSWG) 2014). Great Gull Island (41° 12’ 23” N, 72° 06’ 25” W) is a 0.08

km^2 site in eastern Long Island Sound, NY, that supports one of the largest concentrations of nesting Common Terns (approximately 9,500 pairs) and Roseate Terns (approximately 1,800 pairs) in the Western Hemisphere (H. Hays and G. Cormons, unpubl. data) and is managed by the Great Gull Island Project with the American Museum of Natural History.

Capture and tagging

From mid to late June, we used walk-in treadle traps to capture Common Terns at their nests, within approximately 3 to 5 days of their hatch date. We individually banded terns with an incoloy U.S. Geological Survey band on one tarsometatarsus and a wrap-around a black plastic field readable band engraved in white with a unique 3-digit alphanumeric code on the opposite tarsometatarsus. We also collected three to five contour feathers from each bird to determine gender using a molecular analysis (Avian Biotech, Gainesville, FL).

We attached a digital 1.5 g VHF transmitter ('Avian NanoTag'; Lotek Wireless, Inc., Newmarket, Ontario, Canada) on one randomly-selected adult per nest. Each transmitter body measured 11 mm x 8 mm x 7 mm, and had custom fitted tubes (inner diameter 1 mm) at the anterior and posterior ends for attachment, and a 15-cm whip antenna. We attached transmitters to the dorsal inter-scapular region using cyanoacrylate adhesive and two sutures (Prolene: 45-cm length, 4.0, BB taper point needle, catalog # 8581H) that were inserted subcutaneously and secured to the end-tubes of the transmitter. Total weight of each transmitter and attachment materials was < 2% of the body mass of the birds in our study. Total handling time, from capture to release, ranged from 20 to 40 min per individual. We examined possible tag effects during the breeding period by monitoring the fledge success of tagged terns in the Monomoy colony versus non-tagged controls and found no differences in fledge success (Loring et al. in prep).

Digital VHF telemetry

Digital coding within each transmitters' pulse allowed up to 521 individuals to be uniquely identified on a single VHF frequency by receiving units. We programmed transmitters to transmit signals on 166.380 MHz every five to six seconds, for a total expected operational life of approximately 160 days.

We tracked the movements of tagged terns using a network of automated radio telemetry stations (hereafter network) established throughout the study area (Fig. 4.1, Appendix 4.1). The network included 11 automated radio telemetry towers, each consisting of an array of six 9-element (11.1 dBd) Yagi antennas end-mounted in a radial configuration atop a 12.2 m mast. The antennas were connected to a solar-powered, automated receiving unit (SRX-600, Lotek Wireless, Ontario, Canada) that scanned for signals with each antenna for 6.5 seconds in succession, around the clock. The network also included a receiving station at each colony site that was configured to monitor nest attendance. The receiving station at the Monomoy colony consisted of an automated receiving unit equipped with a single 5-element (9 dBd) antenna mounted on a 1.2 m mast. The receiving station on Great Gull Island consisted of an automated receiving unit equipped with three 5-element (9 dBd) antenna mounted on a 12.2 m observation tower. We programmed all receiving units to automatically log the following data from each antenna: transmitter ID number, time stamp (synchronized among all receivers in the array using GPS clocks), antenna (defined by receiving station and bearing), and signal strength (non-linear scale: 0 to 255). Through calibration tests, we determined that the range of our telemetry stations to detect transmitters flying at altitudes of 10 to 30 m was approximately 10 km.

Movement models

We modeled movements of all tagged birds in MATLAB (MathWorks 2016). Each time a tagged individual was detected by an automated receiving unit, we estimated its 2-dimensional location along the main beam of the receiving antenna given the corresponding signal strength value (Janaswamy and Loring in prep), and used a rolling mean function to smooth location estimates over a 1-minute time step. The limitation of this model is that it assumed that the signals originated from the main beam of the antenna; however, identical signal strength values could also give rise to locations in the side and back lobes of the antenna. However, we felt that this was a reasonable approximation given the high directionality (20 dB front-to-back ratio) of the 9-element Yagi antennas used in this study. Another limitation of the signal strength model is that it is sensitive to variance in altitude values. We did not have information on altitude associated with each detection, so assumed that all individuals were flying at an altitude of 10 m, which is within the typical altitude range of Common Terns flying at sea that has been reported elsewhere (Burger et al. 2011, Garthe and Huppop 2004).

When individuals were temporarily out of range of the network, we used a Brownian Bridge Movement Model (BBMM; Horne et al. 2007) to estimate their mean position and associated variance during each 1-minute time step. The BBMM assumed that terns were moving at an average flight speed of 10 m s^{-1} (Wakeling and Hodgson 1992). The BBMM also assumed that the start and end points of each movement are those generated by the signal strength models described above.

We defined WEA crossing events as movements where estimated mean trajectories intersected WEAs in state or Federal waters within our study area. The configuration of the network was suitable for tracking flights across the Block Island Renewable Energy Zone, and the BOEM Lease Areas in Rhode Island Sound and Nantucket Sound, but due to range limitations of our tracking network we did not have coverage in the BOEM Wind Planning Area to the south of Rhode Island Sound. Due to logistical challenges, several receiving stations within the network were not installed until mid to late July, so the number of crossing events should be considered a minimum due to limitations in coverage.

Analyses of WEA crossing events included only movements were either: 1) tagged terns were within range of the automated radio telemetry array (positions estimated using signal strength values within antenna beams); or 2) tagged terns were moving between stations and temporarily out of range of the telemetry array, but the maximum variance of the mean flight path estimated by BBMM was < 30 km. We selected the a 30-km threshold to match the spatial resolution of atmospheric covariates, and because we felt it was a reasonable spatial resolution to evaluate exposure to BOEM Lease Areas in Rhode Island Sound and Nantucket Sound (that range in size from approximately 30 km^2 to >1500 km^2).

Diel variation in WEA crossing events

We used the R package 'Circular' (Agostinelli and Lund 2013) to calculate the median time of each WEA crossing event using the circular distribution, and the Rao spacing test of uniformity to determine if the event times were spaced uniformly throughout a 24-hour period (Batschelet 1991, Zar 1999). To examine movements relative to daylight, we used the R package 'maptools' (Bivand and Lewin-Koh 2016) to calculate local sunrise and sunset times for each WEA crossing event. WEA crossing events that occurred entirely between the time of local sunrise and the time of local sunset were considered to have occurred during daytime hours. Conversely, WEA crossing events that occurred entirely between the time of local sunset and the time of local sunrise were considered to have occurred during nighttime hours. WEA crossing events that spanned the timing of local sunrise or sunset were considered to have occurred at dawn or dusk, respectively.

Proportional hazards model

We used a Cox proportional-hazards regression model to examine the rate of WEA crossing events as a function of the baseline hazard and a set of atmospheric and demographic covariates in the Survival package (Therneau 2016) within the program R (R Core Team 2016). The counting process formulation of Andersen and Gill (Therneau and Grambsch 2000) was used to incorporate multiple events (WEA crossings) for individual and time dependent variables. Individuals that moved beyond range of the network and did not return, or that dropped their transmitters prior to their departure from the study area, were considered right-censored, which in survival analysis framework is similar to an individual being removed from the study before the event occurs (Fox and Weisberg 2011).

We assumed that observations within individuals were correlated and used a grouped jackknife method to adjust the variance of parameter estimates to account for the correlation (Therneau and Grambsch 2000). For each bird, we used tag date as the start of the counting process and a time interval of 1-day for time-dependent covariates. For the time dependent covariates, we obtained the following satellite-derived atmospheric data (32-km spatial resolution and 3-hr temporal resolution) from the National Centers for Environmental Prediction (NCEP) and Atmospheric Research (NCAR) Global reanalysis-II dataset (Kalnay et al. 1996): precipitation rate (ground or water surface, kg m^{-2} s^{-1}), barometric pressure (ground or water surface, Pa), temperature (ground or water surface, K), visibility (ground or water surface, m), v-wind (ground or water surface, m s^{1}), u-wind (ground or water surface, m s^{-1}). We matched atmospheric data with each bird location estimate using the nearest time stamp and spatial coordinates of each dataset. We then generated daily mean values of each atmospheric variable per individual for subsequent analyses. We checked for correlation between each pair of atmospheric covariates by calculating Pearson correlation co-efficents (r), and excluded variables with $r > 0.60$.

The time independent covariates that we considered were: sex (male or female) and nesting colony (Great Gull or Monomoy). We fit models using all combinations of covariates and first-order interaction terms. To identify the top model, we used the stepAIC function in R (Ripley 2016) to run a stepwise backwards-selection procedure based on the Akaike Information Criterion (AIC; Venables and Ripley 2002).

To evaluate the top model, we examined three types of diagnostics to determine whether the fitted Cox regression model adequately described the data: 1) violation of the assumption of proportional hazards; 2) influential data; 3) non-linearity in the relationship between the log-hazard and the covariates (Fox and Weisberg 2011). Specifically, we calculated tests of the proportional hazards assumption for each covariate, along with a global test of the model as a whole, based on the scaled Schoenfeld residuals using the 'cox.zph' function in the Survival package. We checked for influential observations by examining index plots of dfbeta (changes in regression co-efficents calculated by deleting each observation in succession). Lastly, we checked for non-linearity by plotting martingale residuals and partial-residuals against each covariate.

Results

Digital VHF telemetry

We tagged a total of 116 terns, 65 from Monomoy and 51 from Great Gull (Appendix 4.2). One of the Monomoy transmitters malfunctioned on the first day of deployment, so we included 115 individuals (females: n = 70, males: n = 45) in the final analysis. We tracked each bird for mean duration of 39.41 days (± 1.33 SE, range 9 to 80 days, n = 115). We tagged majority of adult terns within three days of the hatch dates of their nests, so assuming that at least one of their chicks survived to fledging age of 25 days (Nisbet 2002a), the pre-fledging period occurred during the first 22 to 28 days of the study.

Offshore movements

Overall, we detected a total of 94 offshore flights by 31 different individuals where one or more WEA crossing events occurred. Mean estimated distance of flights where WEA crossing events occurred was 120 km (± 6.33 SE, range 6 to 199 km). We found wide variation in the timing and extent of WEA crossing events, which occurred from late June through late August (three to 55 days following tagging). Frequency of WEA crossing events peaked in late July and occurred with less regularity through late August as the proportion of individuals that were still being detected by our automated radio telemetry array declined (Fig. 4.2).

By colony, 6% (*n* = 4) of individuals from the Monomoy and 53% (*n* = 27 of individuals) from Great Gull had one or more documented WEA crossing events. Among these 31 individuals, mean number of WEA crossings was equal to 3.00 events (± 0.53 SE; range 1 to 12 events). A total of 18 individuals (*n* = 4 from Monomoy and *n* = 14 from Great Gull) were detected crossing the wind energy area in Nantucket Sound, with a mean number of WEA crossings per bird equal to 2.05 events (± 0.60 SE; range 1 to 8 events). We documented movements across the wind energy area in Rhode Island Sound by a total of 19 individuals, all of which were from Great Gull colony, with a mean number of crossing events per individual equal to 1.52 events (± 0.23 SE; range 1 to 5 events). We documented movements across the wind energy area in Rhode Island state waters off the coast of Block Island by a total of 7 individuals, all of which were from Great Gull colony, with a mean (± SE) number of crossing events per individual equal to 3.37 (± 1.27; range 1 to 10 flights).

Diel variation in WEA crossing events

WEA crossing events occurred throughout the diel cycle (Fig. 4.3), although there was evidence that event times were not uniformly distributed (Rao's Spacing Test of Uniformity: U= 267.09, $p < 0.001$, $n = 94$). Of the 94 WEA crossing events that we documented, 62% of occurred during daylight hours, 34% occurred during nighttime hours, 3% occurred at dawn, and none at dusk (Table 4.1). The majority of flights across the WEAs in state and Federal waters off the coast of Rhode Island occurred during daylight hours, whereas flights across the wind energy area in Nantucket Sound occurred more frequently during nighttime hours (Table 4.1).

Proportional hazards model

Correlation (r) between following variables was > 0.6: wind speed and temperature, wind speed and pressure, temperature and pressure, temperature and visibility. We retained the variables wind speed, precipitation, and visibility for use in the Cox proportional-hazards regression models as these variables have been identified as important factors associated with collision risk (Exo et al. 2003).

The top model included the terms location, sex, wind speed, visibility, and interaction terms between location and wind speed, and location and visibility. Diagnostic tests of the top model revealed evidence ($p < 0.05$) of non-proportional hazards against time for the covariates "wind speed" and "visibility", as well as the global test. Following Fox and Weisburg (2011), we addressed the non-proportional hazards by refitting the top model with linear interaction terms for wind speed and time, and visibility and time. In the final model, both interaction terms were highly statistically significant (Table 4.2), and diagnostic tests on the resulting model indicated no evidence ($p > 0.05$) of non-proportional hazards for each covariate and for the global test. Index plots of dfbeta and martingale residual plots of the final model indicated that no additional actions were required to address model fit.

Average daily probability of crossing the WEA increased over the nesting period and varied by nesting colony and sex (Fig. 4.4). Daily probability of WEA crossing events was significantly higher for terns from Great Gull Island relative to Monomoy (Hazard Ratio = 10.86, 95% CI = 1.14, 103.62; Fig. 4.5) and for females relative to males (Hazard Ratio = 3.03, 95% CI = 1.41, 6.51; Fig. 4.6). For the two atmospheric covariates that were included in the top model (wind speed and visibility), there were significant interaction terms with both location and time (Table 4.2). These interaction terms indicated that terns from Great Gull Island were more likely to cross WEAs during periods of higher wind speed and lower visibility relative to terns from Monomoy, and that flights during periods of higher wind speed and lower visibility largely occurred earlier on during the season, whereas flights that occurred later during the season were associated with lower wind speeds and higher visibility. The distribution of wind speed values for WEA crossing events was skewed to the right, with a median of 4.21 m/s (Fig. 4.7). The distribution of visibility values for WEA crossing events had a long left tail and a median of 20.01 km (Fig. 4.8).

Discussion

Through this work, we demonstrate the utility of using coded VHF transmitters, automated radio telemetry stations, and movement modeling techniques to track the flights of small-bodied terns at a regional scale and across offshore WEAs. Our study provided new information on extent of offshore movements during the breeding and post-breeding period. In addition, we addressed a high-priority information gap on the movements of terns at night and during inclement weather (U.S. Fish and Wildlife Service 2008).

Breeding movements

WEA crossing events occurred from three to 55 days following tagging (hatch date), thus spanning the pre-fledging and post-breeding period, and included flights across the entire study area at distances exceeding 180 km. Previous work that documented the movements of terns during the pre-fledgling period used boat-based surveys or conventional radio telemetry, and focused on diurnal foraging locations. Using boat-based surveys, Heineman (1992) documented that Roseate Terns from a colony in

Buzzards Bay, Massachusetts traveled to distances of up to 30-km away from their nesting colony. Duffy (1986) conducted boat-based surveys of Common and Roseate Terns nesting on Great Gull Island, and estimated that the majority of Common and Roseate terns foraged within 4 to 12 km (maximum of 22 km) from the colony. In the German North Sea, Becker et al. (1993) tracked Common Terns with conventional VHF transmitters and estimated cumulative flight distances of 30 km, with a typical foraging radius of 6-km radius of the nesting colony. Rock et al. (2007) radio-tracked Roseate Terns from a plane and found birds foraging up to 7 km from their nesting colony in Nova Scotia. Differences between the flight distances and durations between our study and previous research are likely due in part to methodological differences. The tower network established for this study was much more effective at detecting long-distance movements than conventional VHF transmitters or following birds in a boat (Perrow et al. 2011).

Nest failure is another factor that may have contributed to the long-distance movements that we observed by some individuals from Great Gull Island in early July, within days following their hatch date. We did not have information on chick survival for individual nests on Great Gull, but there was evidence that low food availability combined with a series of storms caused widespread chick loss and nest failure at the colony during early July. Color-banded Roseate Terns have been observed moving between colony sites following nest-loss (Spendelow et al. 1995). In a radio-telemetry study of Little Terns (*Sterna albifrons*), Perrow et al. (2006) found that the ranges of successful breeders were less than 6 km^2, whereas the foraging ranges of failed breeders exceeded 50 km^2. The birds that we tagged on Monomoy were all nesting within established productivity plots, providing detailed information on the fledge or failure date of each nest. However, nest success on Monomoy was relatively high in 2014 (1.56 fledged chicks/nest; Gulf of Maine Seabird Working Group 2014) and very few of the nests of our tagged birds failed, so we did not have an adequate sample size to assess movements relative to nest success.

Post-breeding movements

We found that the number of WEA crossing events by our tagged adults peaked in late July. Assuming chick survival, this peak corresponds to approximately 5 to 15 days following the estimated fledge dates of their chicks. Common Terns are known to disperse from their nesting areas within 10 to 20 days of the fledge dates of their chicks (Nisbet 2002a), therefore it is likely that this peak corresponded with post-breeding dispersal movements. Through surveys and re-sighting of marked birds, researchers have documented extensive movements of Common and Roseate Terns during the post-breeding period, that occurs from late July through mid-September (Nisbet 2002b, Nisbet et al. 2014). Blokpoel et al. (1987) found that, during the post-breeding period, Common Terns in the Great Lakes region of North America dispersed up to 550 km from their breeding colony. Post-breeding, large numbers of Roseate Terns from colonies ranging from western Long Island to the Gulf of Maine have been shown to disperse distances of over 300 km to gather by the thousands at sites within the Cape Cod and Islands region of Massachusetts (Trull et al. 1999, Jedrey et al. 2010). Shealer and Kress (1994) found that large numbers of Roseate Terns dispersed from colonies in Maine, Massachusetts, and New York to a staging area in Saco Bay, Maine, upwards of 500 km away. It is likely that the peak in movements that we observed in late July was related to dispersal movements. However, we also cannot rule out the possibility that the increase in number of flights detected was due in part to increased detection probability of flights by the additional radio telemetry stations that were deployed within our study are in mid to late July.

Demographic variation

Across the breeding and post-breeding periods, we found that terns from Great Gull Island were more likely to have a WEA crossing events relative to terns from Monomoy. During 2014, there was evidence of low productivity on Great Gull Island that was thought to be linked to low food availability, as monitoring data during the breeding period indicated that body mass of breeding adults was unusually low that season (H. Hays, pers. comm). For adults that had at least one chick survive to fledge, low food availability may have resulted in terns dispersing from the colony site shortly after the fledge (Safina and Burger 1989). Shealer and Kress (1994) suggested that Roseate Terns that disperse long distances to Saco Bay, Maine during the post-breeding period do so to take advantage of high prey availability. Additional data on fledge success of our tagged birds and prey availability at each colony site would be useful for understanding the variability in WEA crossing events by terns from different nesting populations.

In addition to colony-based differences, we found that females were more likely to fly across WEAs compared to males. Adult Common and Roseate terns provide extensive post-fledgling care to their chicks that extends for several weeks after fledging (Nisbet 1976, Burger 1980) and continues through dispersal to staging areas (Watson and Hatch 1999). In a movement study of adult Common Terns from a nesting colony in Massachusetts using geolocators, Nisbet et al. (2011b) found that that females initiated migration during early to mid-August, over a month before the males departed, and suggested that male Common Terns are responsible for parental care of fledglings during the post-breeding dispersal period. It is possible that the higher rates of movements that we observed by females relative to males is related in part to the females having higher mobility during the post-fledging period because they were not tied to parental care of their young, although we do not have any direct evidence to support this speculation.

Diel variation

We found that timing of WEA crossing events occurred during all hours of the day and night. During the pre-fledging period, previous studies have shown that Common and Roseate terns primarily foraged diurnally, with peak movements during the early morning and late afternoon (Nisbet 2002b, Nisbet et al. 2014). Information on nocturnal flights of Roseate and Common Terns is limited to a few studies that occurred outside of the breeding period (U.S. Fish and Wildlife Service 2008). In a study of staging terns in Massachusetts, Trull et al. (1999) observed that mixed flocks of Common and Roseate terns roosted at a limited number of sites during the staging period, and arrived at these sites during the late evening through after dark. Hays et al. (1999) described a roost site in Mangue Saco, Brazil where Roseate and Common terns arrived after dark and depart before first light. Using radar, Alerstam (1985) found evidence that Common Terns initiated high altitude migratory flights during evening hours, suggesting that migratory flights took place at night. These findings are consistent with observations described by Veit and Petersen (1993) of large flocks of terns departing from fall staging sites in Massachusetts at high altitudes during dusk. Our observations of terns crossing WEAs at night provide additional evidence of nocturnal flights of terns. This information is useful for assessing adverse effects of wind energy facilities to terns (U.S. Fish and Wildlife Service 2008), as risk of collision with wind turbines is higher at night versus during the day (Exo et al. 2003).

Atmospheric effects

In addition to providing new information on nocturnal movements of terns, our study addressed a high-priority information need on the movements of terns throughout the southern New England region relative to weather conditions (U.S. Fish and Wildlife Service 2008). Previous work that examined the flights of terns relative to weather focused on foraging behavior, and found that capture rates of prey were highest in light to moderate wind speeds (Dunn 1973, Taylor 1983) with some cloud cover (Watson and Hatch 1999). We found that early in the season, WEA crossing events were associated higher wind speed and lower visibility, whereas later in the season, WEA crossing events were associated with lower wind speed and higher visibility. Flying during favorable weather, such as the movements that we observed later in the season, is advantageous, as it is more energetically efficient and there is a lesser risk of becoming disorientated (Richardson 1978). Flights during the early part of the season were associated with storm events in early July that caused widespread chick loss and nest failure on Great Gull. It is likely that movement events associated with these weather patterns early in the season were due to nest failure caused by the storms. Nonetheless, it is important that we documented movements in association with inclement weather, as high wind speeds and reduced visibility that are known to increase the risk of collisions with wind turbines (Exo et al. 2003, Chamberlain et al. 2006). However, in the context of collision risk modeling, relatively few WEA crossing events that we documented occurred under low visibility conditions (< 2 km) that may impair the ability of birds to avoid wind turbines (Cook et al. 2014).

Implications for offshore wind energy development

Our study provides the first empirical evidence of the movements of terns in the AOCS, around-the-clock and during all types of weather conditions. This information is essential for assessing the risk of collisions of terns with offshore wind turbines (U.S. Fish and Wildlife Service 2008, Burger et al. 2011). Collision mortality of terns with wind turbines has been documented by other studies (U.S. Fish and Wildlife Service 2008) and this work has highlighted the importance of assessing the temporal and demographic variation in collision risk. For example, at the Zeebrugge wind energy facility in Belgium, 25 turbines located on a breakwater within 30 to 400 m of tern nesting habitat, and adjacent to foraging habitat. This facility resulted in the deaths of over 150 Common Terns, Sandwich Terns (*S. sandvicensis*), and Little Terns (*S. albifrons*) per year (Everaert and Stienen 2008). Mortality primarily occurred during the breeding period, as bird traveled between nesting and foraging habitat, and disproportionately affected adult males that did more of the chick provisioning relative to females (Stienen et al. 2008).

Through this work, we demonstrate the utility of digital VHF telemetry and automated radio telemetry stations for monitoring the flights of individual terns across offshore wind energy areas, and assessing temporal and demographic variation in exposure. However, challenges with using this technology include limited ranges of tracking equipment to detect offshore movements, and incomplete information on tag retention. Since we likely missed flights that occurred offshore beyond the range of our telemetry array, and since we do not know if the final detections of birds corresponded with departure from the study area of from tag loss, the rates of WEA crossing events reported here should considered a minimum.

In the future, detection probability could be improved by mounting tracking devices on offshore structures. This could be especially useful for monitoring movements of terns and other high priority species through WEAs during and post-construction. In addition, estimates of altitude are needed to determine if flights through WEAs are occurring within the rotor swept zone (20 to 200 m; Robinson Willmott et al. 2013). In a vulnerability assessment of marine birds to offshore wind farms, Furness et al. (2013) found wide variation (0-41%) in the estimated numbers of Common Terns flying at rotor swept altitudes that were reported across various surveys. It is possible to extend existing 2-dimensional movement models to include estimates of altitude if simultaneous detections are received by four or more antennas from spatially separated receivers (Janaswamy and Loring *in prep*). The importance of altitude data in assessing collision risk, and the need for a relatively dense tracking array in order to obtain these data accurately, further highlights the utility of strategic placement of receiving units on offshore wind turbines and other structures in the future.

Meeting the U.S. Department of Energy's initiative for 54 GW of domestic offshore wind power capacity by 2030 would result in approximately 5,000 to 8,000 turbines would be constructed in U.S. waters (Goodale and Milman 2016). Therefore, data on individual movements of birds will be imperative for estimating exposure and associated cumulative adverse effects of birds encountering multiple offshore wind energy facilities throughout their migratory range (Goodale and Milman 2016). An advantage of using digital VHF technology for monitoring the movements of birds through offshore wind energy areas is that the transmitters emit signals frequently (every 5 to 10 seconds), so detection probability is relatively high as long as tagged individuals are within range of a receiving station.

A coordinated network of digital VHF telemetry projects and receiving stations is expanding across the Western Hemisphere (www.motus-wts.org), enabling large numbers of tagged individuals to be tracked over long distances. Through this type of coordinated tracking, it might be possible to assess the exposure of individual birds to multiple wind energy areas throughout their migratory range. Monitoring cumulative risk of exposure to multiple wind energy facilities is especially important for long-lived species of conservation concern (Drewitt and Langston 2006), such as the Roseate Tern (Nisbet et al. 2014). Through this work with Common Terns, we have determined that digital VHF telemetry technology was suitable for expansion to the Federally endangered Roseate Tern, and as a result this species has been the focus of expanded digital VHF telemetry studies that we have conducted from 2015 to the present.

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Literature Cited

Adams, E., I. Steinhouse, A. Gilbert, K. Willaims, and W. Montevecchi. 2015. Using state-space models to identify areas of persistent winter activity and their associated environmental covariates in Northern Gannets. 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. 19 pp.

Agostinelli, C., and U. Lund. 2013. Circular: circular statistics. [online] URL: http://CRAN.R-project.org/package=circular. R package version 0.4–7.

Alerstam, T. 1985. Strategies of migratory flight, illustrated by Arctic and Common Terns, *Sterna paradisaea* and *Sterna hirundo*. Contributions in Marine Science Supplement 27:580-603.

Allison, T. D., E. Jedrey, and S. Perkins. 2008. Avian issues for offshore wind development. Marine Technology Society Journal 42:28-38.

Allison, T. D., S. Perkins, and G. Sadoti. 2006. Estimating Distribution and Abundance of Wintering Sea Ducks in Nantucket Sound, #57. Final Report to the Sea Duck Joint Venture Program, 7 pp.

Baranowski, R., F. Oteri, I. Baring-Gould, and S. Tegen. 2016. U.S. Department of Energy Regional Resource Centers Report: State of the Wind Industry in the Regions. (No. NREL/TP-5000-62942). National Renewable Energy Laboratory (NREL), Golden, CO, USA.

Batschelet, E. 1981. Circular Statistics in Biology. Academic Press, New York, NY, 371 pp.

Beaudry-Losique, J., T. Boling, J. Brown-Saracino, P. Gilman, M. Hahn, C. Hart, J. Johnson, M. McCluer, L. Morton, and B. Naughton. 2011. A national offshore wind strategy: creating an offshore wind energy industry in the United States. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Wind & Water Power Program U.S. and Department of the Interior, Bureau of Ocean Energy Management, Regulation, and Enforcement. Sterling, VA.

Becker, P. H., D. Frank, and S. R. Sudmann. 1993. Temporal and spatial pattern of Common Tern (*Sterna hirundo*) foraging in the Wadden Sea. Oecologia 93:389-393.

Bivand, R., and N. Lewin-Koh. 2016. Maptools. [online] URL: https://cran.r-project.org/web/packages/maptools/maptools.pdf R package version 0.8–39.

Blokpoel, H., G. D. Tessier, and A. Harfenist. 1987. Distribution during post-breeding dispersal, migration, and overwintering of Common Terns color-marked on the lower Great Lakes. J. Field Ornithol. 58:206-217.

Bureau of Ocean Energy Management. 2016. BOEM's Renewable Energy Program. [online] URL: http://www.boem.gov/BOEM-RE-Programs-Fact-Sheet/.

Burger, A. E., and S. A. Shaffer. 2008. *Perspectives in ornithology* application of tracking and data-logging technology in research and conservation of seabirds. Auk 125:253-264.

Burger, J. 1980. The transition to independence and postfledging parental care in seabirds, p. 367-447, In J. Burger, B. L. Olla, and H. E. Winn (eds.), Behavior of marine animals, Vol. 4: Marine birds. Plenum Press, New York, NY.

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.

Chamberlain, D. E., M. R. Rehfisch, A. D. Fox, M. Desholm, and S. J. Anthony. 2006. The effect of avoidance rates on bird mortality predictions made by wind turbine collision risk models. Ibis 148:198-202.

Cook, A.S.C.P., Humphreys, E.M., Masden, E.A. & Burton, N.H.K. 2014. The Avoidance Rates of Collision Between Birds and Offshore Turbines. Scottish Marine and Freshwater Science vol. 5 Number 16, Report Published by Marine Scotland Science, Aberdeen.

Desorbo, C., R. Gray, J. Tash, C. Gray, K. Willaims, and D. Ricordan. 2015. Offshore migration of Peregrine Falcons (*Falco peregrinus*) along the Atlantic Flyway. 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. 31 pp.

Dirksen, S., J. Van der Winden, and A. Spaans. 1998. Nocturnal collision risks of birds with wind turbines in tidal and semi-offshore areas. Wind energy and landscape. Balkema, Rotterdam:99-108.

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

Duffy, D. C. 1986. Foraging at patches: interactions between Common and Roseate terns. Ornis Scandinavica. 17:47-52.

Dunn, E. K. 1973. Changes in fishing ability of terns associated with windspeed and sea surface conditions. Nature 244:520-521.

Everaert, J., and E. M. Stienen. 2008. Impact of wind turbines on birds in Zeebrugge (Belgium). Pages 103-117 *in* D. Hawksworth, and A. Bull, editors. Biodiversity and Conservation in Europe. Springer, Netherlands.

Exo, K.-M., O. Huppop, and S. Garthe. 2003. Birds and offshore wind farms: a hot topic in marine ecology. Wader Study Group Bulletin 100:50-53.

Fair, J. M., E. Paul, J. Jones, A. B. Clark, C. Davie, and G. Kaiser. 2010. Guidelines to the Use of Wild Birds in Research. Ornithological Council. [online] URL: www.nmnh.si.edu/BIRDNET/guide.

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

Fox, J., and S. Weisberg. 2011. Cox proportional-hazards regression for survival data in R. An appendix to An R Companion to Applied Regression, Second Edition. Sage Publications, Thousand Oaks, CA.

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

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.

Goyert, H. F., B. Gardner, R. Sollmann, R. R. Veit, A. T. Gilbert, E. E. Connelly, and K. A. Williams. 2016. Predicting the offshore distribution and abundance of marine birds with a hierarchical community distance sampling model. Ecological Applications. doi: 10.1890/15-1955.1

Gray, C., A. Gilbert, J. Tash, and C. Anderson. 2015. Wintering movements and habitat use of Red-throated Loons (*Gavia stellata*) 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. 26 pp.

Griffin, L., E. Rees, and B. Hughes. 2010. Migration Routes of Whooper Swans and Geese in Relation to Wind Farm Footprints. *in* Wildfown & Wildlands Trust Interim Report to Department of Energy and Climate Change (DECC), Wildfowl & Wetlands Trust, Slimbridge, England. 87 pp.

Gulf of Maine Seabird Working Group (GOMSWG). 2014. 2014 Gulf of Maine Seabird Working Group Census Results. [online] URL: http://gomswg.org/pdf_files/GOMSWG%20Census%20Data%202014.pdf.

Hays, H., P. Lima, L. Monteiro, J. DiCostanzo, G. Cormons, I. C. T. Nisbet, J. E. Saliva, J. A. Spendelow, J. Burger, J. Pierce, and M. Gochfeld. 1999. A nonbreeding concentration of Roseate and Common Terns in Bahia, Brazil. Journal of Field Ornithology 70:455-464.

Heinemann, D. 1992. Foraging Ecology of Roseate Terns on Bird Island, Buzzards Bay, Massachusetts. Unpublished Report to U.S. Fish and Wildlife Service, Newton Corner, MA.

Horne, J. S., E. O. Garton, S. M. Krone, and J. S. Lewis. 2007. Analyzing animal movements using Brownian bridges. Ecology 88:2354-2363.

Jedrey, E. L., R. J. Harris, and E. A. Ray. 2010. Citizens of the world: The Canada to Cape Cod connection. Bird Observer 38:146-150.

Johnson, C. B. 2014. Advances in marine spatial planning: Zoning earth's last frontier. Journal of Environmental Law and Litigation 29:191-245.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, A. Leetmaa, B. Reynolds, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K. Mo, C. Ropelewski, J. Wang, R. Jenne, and D. Joseph. 1996. The NCEP/NCAR 40-year reanalysis project. Bull Amer Meteor Soc 77:437-471.

Kunz, T. H., E. B. Arnett, B. M. Cooper, W. P. Erickson, R. P. Larkin, T. Mabee, M. L. Morrison, M. D. Strickland, and J. M. Szewczak. 2007. Assessing impacts of wind-energy development on nocturnally active birds and bats: A guidance document. The Journal of Wildlife Management 71:2449-2486.

Loring, P. H., P. W. C. Paton, J. E. Osenkowski, S. G. Gilliland, J.-P. L. Savard, and S. R. McWilliams. 2014. Habitat use and selection of black scoters in southern New England and siting of offshore wind energy facilities. Journal of Wildlife Management 78:645-656.

MathWorks. 2016. MATLAB and Statistics Toolbox Release 2016a The MathWorks, Inc., Natick, Massachusetts, United States.

Meattey, D., L. Savoy, A. Gilbert, J. Tash, C. Gray, A. Berlin, C. Lepage, S. Gilliland, T. Bowman, J. Osenkowsi, and C. S. Spiegel. 2015. Wintering movements and habitat use of Surf Scoter (*Melanitta perspicillata*) 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. 24 pp.

Mid-Atlantic/New England/Maritimes Region Waterbird Working Group. 2006. Waterbird Conservation Plan for the Mid-Atlantic/New England/Maritimes Region: 2006-2010. Waterbird Conservation for the Americas. . [online] URL: http://www.waterbirdconservation.org.

Mills, A. M., B. G. Thurber, S. A. Mackenzie, and P. D. Taylor. 2011. Passerines use nocturnal flights for landscape-scale movements during migration stopover. Condor 113:597-607.

Mitchell, G. W., A. E. M. Newman, M. Wikelski, and D. Ryan Norris. 2012. Timing of breeding carries over to influence migratory departure in a songbird: an automated radiotracking study. Journal of Animal Ecology 81:1024-1033.

Montevecchi, W. A., A. Hedd, L. McFarlane Tranquilla, D. A. Fifield, C. M. Burke, P. M. Regular, G. K. Davoren, S. Garthe, G. J. Robertson, and R. A. Phillips. 2012. Tracking seabirds to identify ecologically important and high risk marine areas in the western North Atlantic. Biological Conservation 156:62-71.

Mostello, C. S., I. C. Nisbet, S. A. Oswald, and J. W. Fox. 2014. Non-breeding season movements of six North American Roseate Terns *Sterna dougallii* tracked with geolocators. Seabirds 27:1-21.

Nisbet, I. 2002a. Common Tern (*Sterna hirundo*), The Birds of North America Online (A. Poole, Ed.). Ithaca: Cornell Lab of Ornithology; Retrieved from the Birds of North America Online: http://bna.birds.cornell.edu/bna/species/618 doi:10.2173/bna.618.

Nisbet, I., M. Gochfeld, and J. Burger. 2014. Roseate Tern (*Sterna dougallii*), The Birds of North America Online (A. Poole, Ed.). Ithaca: Cornell Lab of Ornithology; Retrieved from the Birds of North America Online: http://bna.birds.cornell.edu/bna/species/370 doi:10.2173/bna.370.

Nisbet, I. C. T. 1976. Early stages in postfledging dispersal of Common Terns. Bird-Banding 47:163-164.

Nisbet, I. C. T. 2002b. Common Tern *(Sterna hirundo*), The Birds of North America Online (A. Poole, Ed.). Ithaca: Cornell Lab of Ornithology; Retrieved from the Birds of North America Online: http://bna.birds.cornell.edu/bna/species/618doi:10.2173/bna.618.

Nisbet, I. C. T., C. S. Mostello, R. R. Veit, J. W. Fox, and V. Afanasyev. 2011a. Migrations and Winter Quarters of Five Common Terns Tracked using Geolocators. Waterbirds 34:32-39.

Nisbet, I. C. T., P. Szczys, C. S. Mostello, and J. W. Fox. 2011b. Female Common Terns *Sterna hirundo* start autumn migration earlier than males. Seabird 24:103-106.

Perkins, S., A. Jones, and T. Allison. 2003. Survey of tern activity within Nantucket Sound, Massachusetts, during pre-migratory fall staging. Final Report for Massachusetts Technology Collaborative. Massachusetts Audubon Society, Lincoln, MA, USA.

Perrow, M. R., E. R. Skeate, and J. J. Gilroy. 2011. Visual tracking from a rigid-hulled inflatable boat to determine foraging movements of breeding terns. Journal of Field Ornithology 82:68-79.

Perrow, M. R., E. R. Skeate, P. Lines, D. Brown, and M. L. Tomlinson. 2006. Radio telemetry as a tool for impact assessment of wind farms: the case of Little Terns *Sterna albifrons* at Scroby Sands, Norfolk, UK. Ibis 148:57-75.

R Core Team. 2016. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. [online] URL: http://www.R-project.org/.

Richardson, W. J. 1978. Timing and amount of bird migration in relation to weather: A Review. Oikos 30:224-272.

Ripley, B. 2016. MASS: Support Functions and Datasets for Venables and Ripley's MASS. [online] URL: https://cran.r-project.org/web/packages/MASS/index.html R package version 7.3-45.

Robinson Willmott, J., 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 US Department of the Interior, Bureau of Ocean Energy Management, Office of Renewable Energy Programs. OCS Study BOEM 207:275.

Rock, J. C., M. L. Leonard, and A. W. Boyne. 2007. Do co-nesting Arctic and Common Terns partition foraging habitat and chick diets? Waterbirds: The International Journal of Waterbird Biology 30:579-587.

Sadoti, G., T. Allison, S. Perkins, and A. Jones. 2005. A survey of tern activity within Nantucket Sound, Massachusetts, during the 2004 breeding period. Final Report for Massachusetts Technology Collaborative. Massachusetts Audubon Society, Lincoln, MA, USA.

Safina, C., and J. Burger. 1989. Inter-annual variation in prey availability for Common Terns at different stages in their reproductive cycle. Colonial Waterbirds 12:37-42.

Shealer, D. A., and S. W. Kress. 1994. Post-breeding movements and prey selection of Roseate Terns at Stratton Island, Maine. J. Field Ornithol. 65:349-362.

Spendelow, J. A., J. D. Nichols, I. C. T. Nisbet, H. Hays, and G. D. Cormons. 1995. Estimating annual survival and movement rates of adults within a metapopulation of Roseate Terns. Ecology 76:2415-2428.

Stienen, E. W. M., W. Courtens, J. Everaert, and M. Van De Walle. 2008. Sex-biased mortality of Common Terns in wind farm collisions. Condor 110:154-157.

Taylor, I. R. 1983. Effect of wind on the foraging behaviour of Common and Sandwich terns. Ornis Scandinavica. 14:90-96.

Taylor, P. D., S. A. Mackenzie, B. G. Thurber, A. M. Calvert, A. M. Mills, L. P. McGuire, and C. G. Guglielmo. 2011. Landscape movements of migratory birds and bats reveal an expanded scale of stopover. PLoS ONE 6:e27054.

Therneau, T. 2016. Survival. [online] URL: https://cran.r-project.org/web/packages/survival/survival.pdf R package version 2.39-5.

Therneau, T., and P. Grambsch. 2000. Modeling Surivival Data: Extending the Cox Model. Springer, New York, New York, USA.

Trull, P., S. Hecker, M. Watson, and I. Nisbet. 1999. Staging of Roseate Terns *Sterna dougallii* in the post-breeding period around Cape Cod, Massachusetts, USA. Atlantic Seabirds 1:145-158.

U.S. Fish and Wildlife Service. 2008. Final biological opinion, Cape Wind Associates, LLC, wind energy project, Nantucket Sound, Massachusetts, pp. 51-73. Unpublished Report. U.S. Fish and Wildlife Service, New England Field Office, Concord, NH. [online] URL: http://www.fws.gov/newengland/pdfs/CapeWind-BO1November2008_withCovLttr.pdf.

Veit, R., and W. Petersen. 1993. Birds of Massachusetts. Massachusetts Audubon Society, Lincoln, MA.

Venables, W., and B. Ripley. 2002. Modern Applied Statistics with S. Fourth edition. Springer, New York, New York.

Wakeling, J. M., and J. Hodgson. 1992. Short communication optimisation of the flight speed of the Little, Common, and Sandwich Tern. Journal of Experimental Biology 169:261-266.

Watson, M. J., and J. J. Hatch. 1999. Differences in foraging performance between juvenile and adult Roseate Terns at a pre-migratory staging area. Waterbirds 22:463-465.

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.

Woodworth, B. K., C. M. Francis, and P. D. Taylor. 2014. Inland flights of young Red-eyed Vireos *Vireo olivaceus* in relation to survival and habitat in a coastal stopover landscape. Journal of Avian Biology 45:387-395.

Zar, J. H. 1999. Biostatistical Analysis. Fourth edition. Prentice Hall, Upper Saddle River, New Jersey, USA.

Table 4.1. Proportion of Wind Energy Area (WEA) crossing events (*n* = 94) by geographic location and time of day, for 31 adult Common Terns tracked with digital VHF telemetry in the southern New England continental shelf region during 2014.

	Day	Night	Dawn	Dusk	N
Nantucket Sound	0.43	0.57	0	0	37
Rhode Is. Sound	0.72	0.24	0.03	0	29
Block Island	0.78	0.14	0.07	0	28
All	0.62	0.34	0.03	0	94

Table 4.2. Parameter estimates (maximum likelihood), standard errors (grouped jackknife method), hazard ratios, z-scores, and p-values for the best fitting Cox Proportional Hazards model.

Parameter[1]	Parameter estimate	SE (robust)	Hazard ratio	Z-score	*p*-value
Location (Great Gull)	2.385000	1.151000	10.860000	2.072	0.038302
Sex (Female)	1.108000	0.390200	3.029000	2.84	0.004509
Windspeed (m s^{-1})	0.631700	0.188100	1.881000	3.359	<0.0001
Visibility (m)	-0.000081	0.000049	0.999900	-1.67	0.094836
Location (Great Gull) : Windspeed (m $s-^{1}$)	0.411600	0.114900	1.509000	3.583	0.000339
Location (Great Gull) : Visibility (m)	-0.000089	0.000044	0.999900	-2.02	0.043377
Windspeed (m s^{-1}) : Time	-0.027290	0.007928	0.973100	-3.442	0.000577
Visibility (m) : Time	0.000007	0.000002	1.000000	2.894	0.003809

[1] Values of the factor covariates given relative to the reference level. Reference levels were 'Monomoy' for the location parameter and 'male' for the sex parameter.

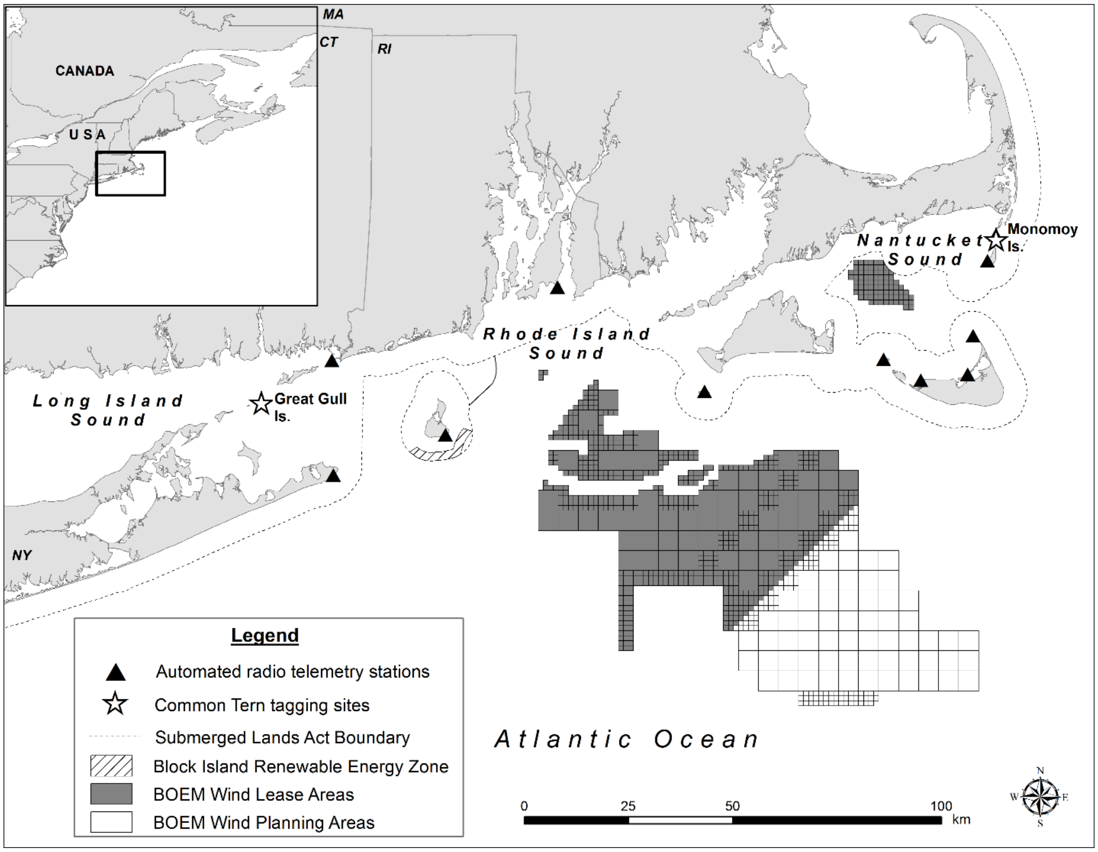


Figure 4.1. Map of the 2014 Study Area across the southern New England continental shelf showing locations of 11 automated radio telemetry towers (black triangles), colony sites where Common Terns were tagged with digital VHF transmitters (stars), and the Submerged Lands Act Boundary separating state and federal waters (dashed line). Polygons show locations of the Block Island Renewable Energy Zone (cross-hatch), Bureau of Ocean Energy Management (BOEM) Wind Lease Areas (grey) and BOEM Wind Planning Areas (white).

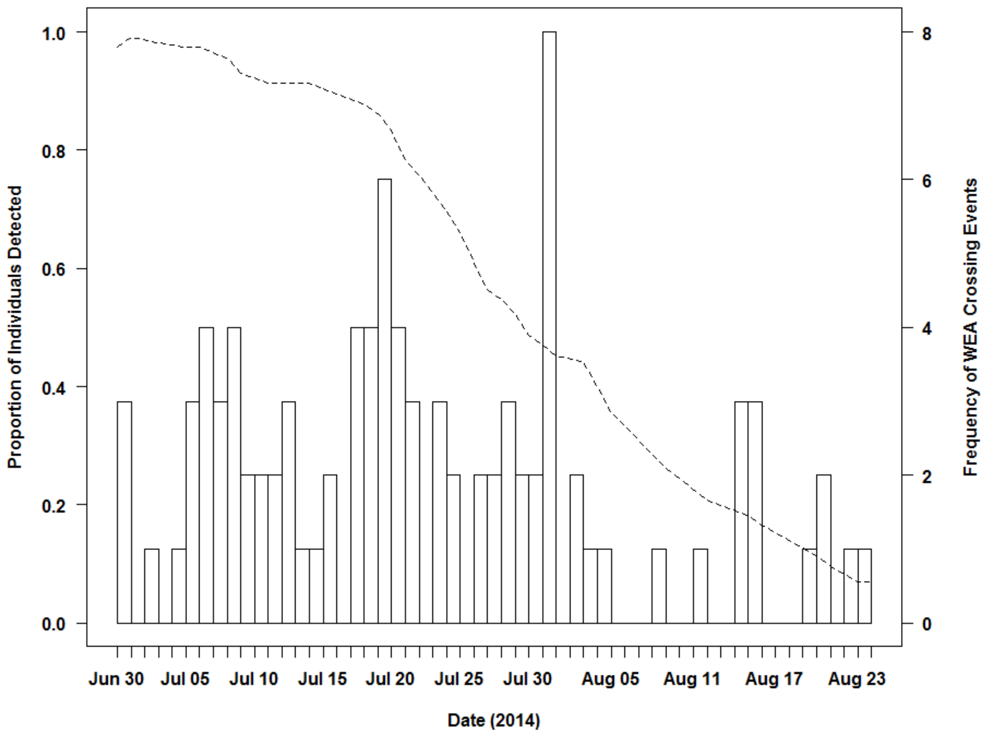


Figure 4.2. Daily proportion (left axis, dashed line) of tagged Common Terns detected and the frequency (bars, right axis) of Wind Energy Area (WEA) crossing events by date in 2014. Data are from 115 Common Terns tagged with digital VHF transmitters and tracked using a network of automated radio telemetry stations in the southern New England continental shelf region.

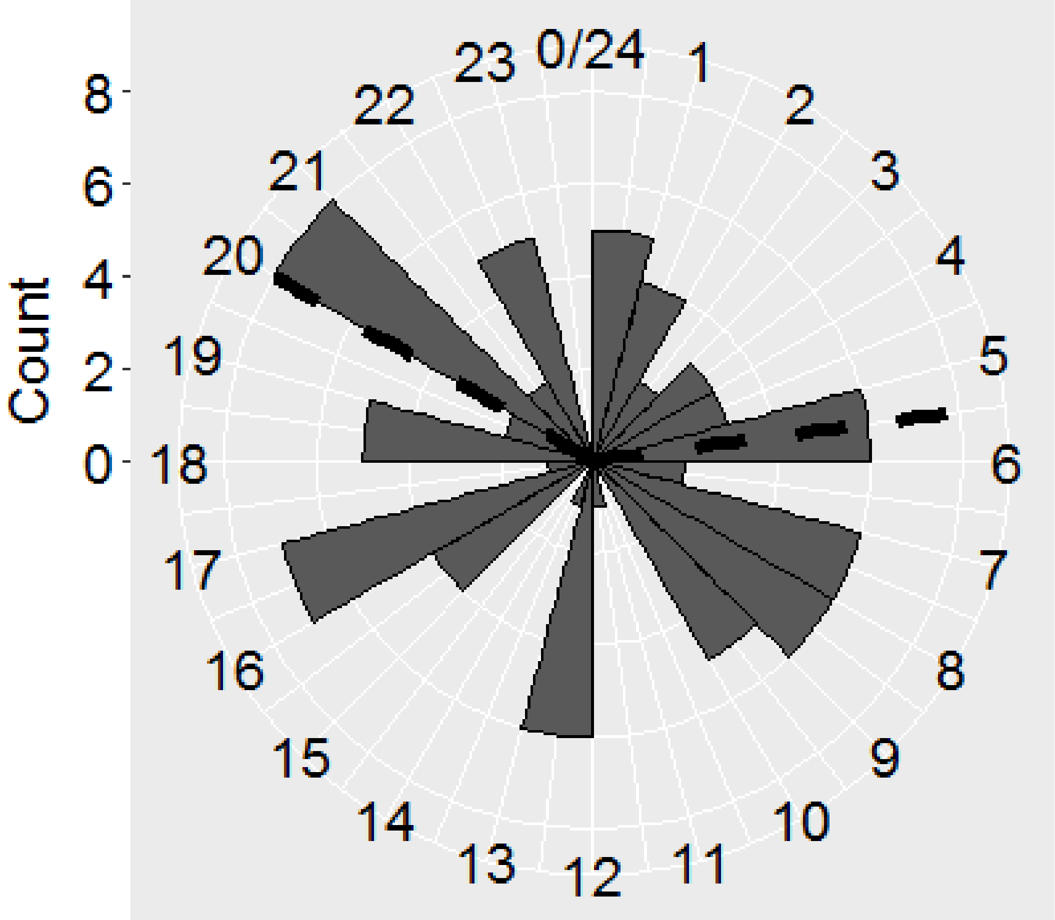
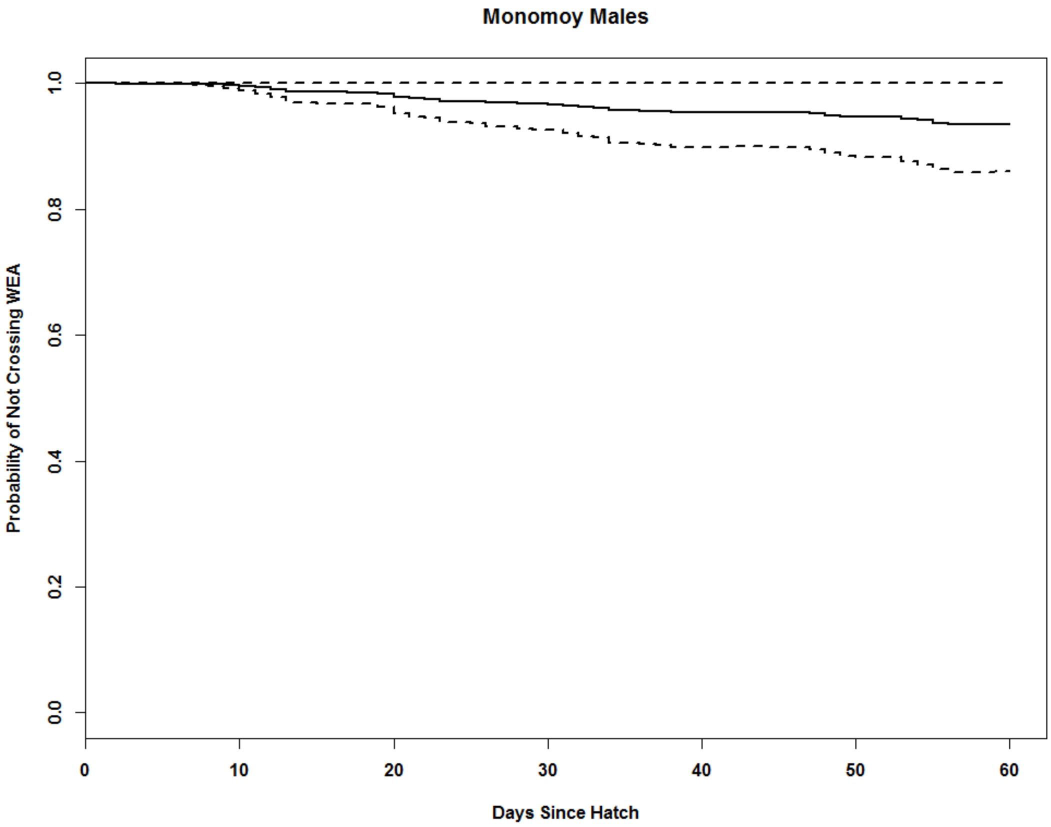
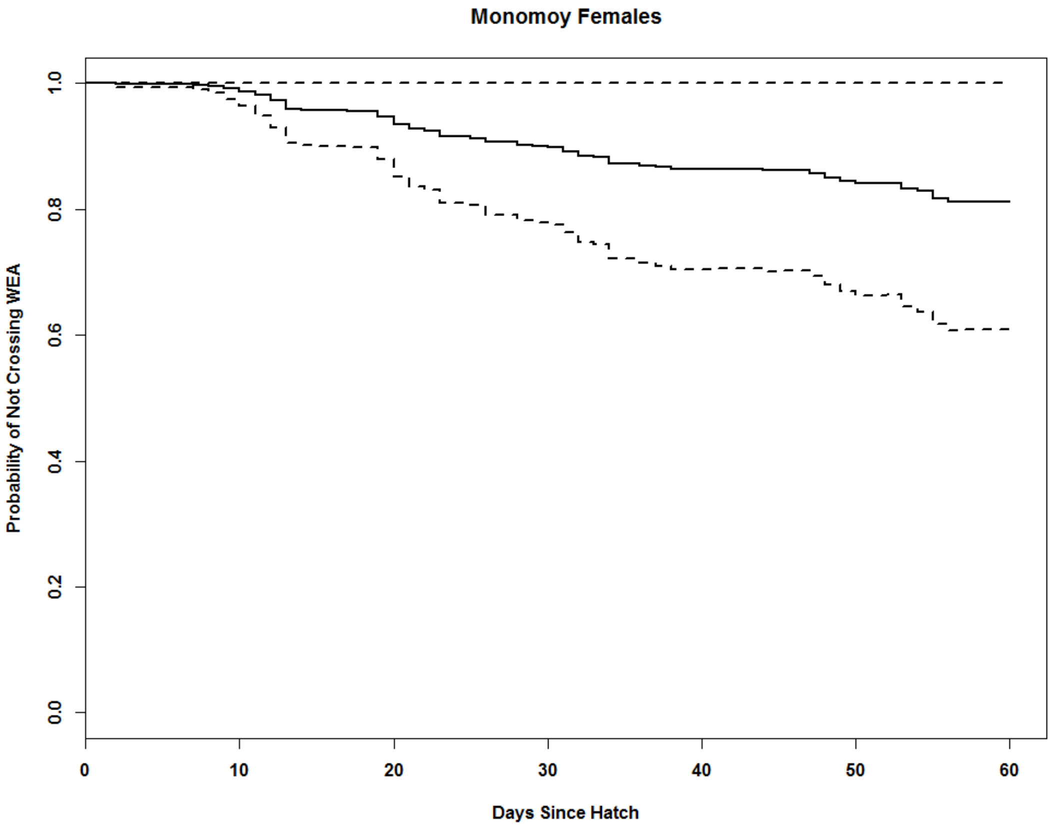


Figure 4.3. Temporal distribution of median times (in hours, Eastern Standard Time) of Wind Energy Area (WEA) crossing events (*n* = 94) by 31 Common Terns tracked with digital VHF telemetry in the southern New England continental shelf region in 2014. Dashed lines show median time of local sunrise (05:30 hrs) and sunset (20:00 hrs) during the study period (June 30 to August 23).

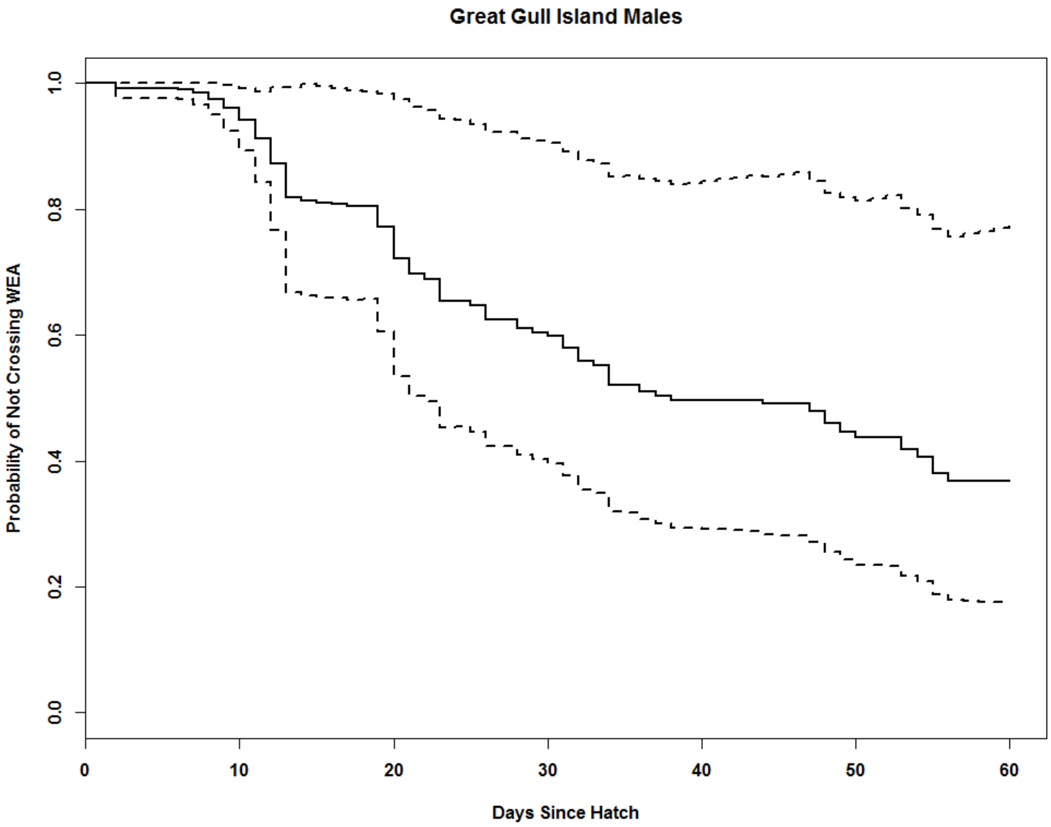
A


Monomoy Males
Probability of Not Crossing WEA
1.0
0.8
0.6
0.4
0.2
0.0
0
10
20
30
40
50
60
Days Since Hatch

B


Monomoy Females
Probability of Not Crossing WEA
0.0
0.2
0.4
0.6
0.8
1.0
0
10
20
30
40
50
60
Days Since Hatch

C


Great Gull Island Males
Probability of Not Crossing WEA
0.0
0.2
0.4
0.6
0.8
1.0
0
10
20
30
40
50
60
Days Since Hatch

D

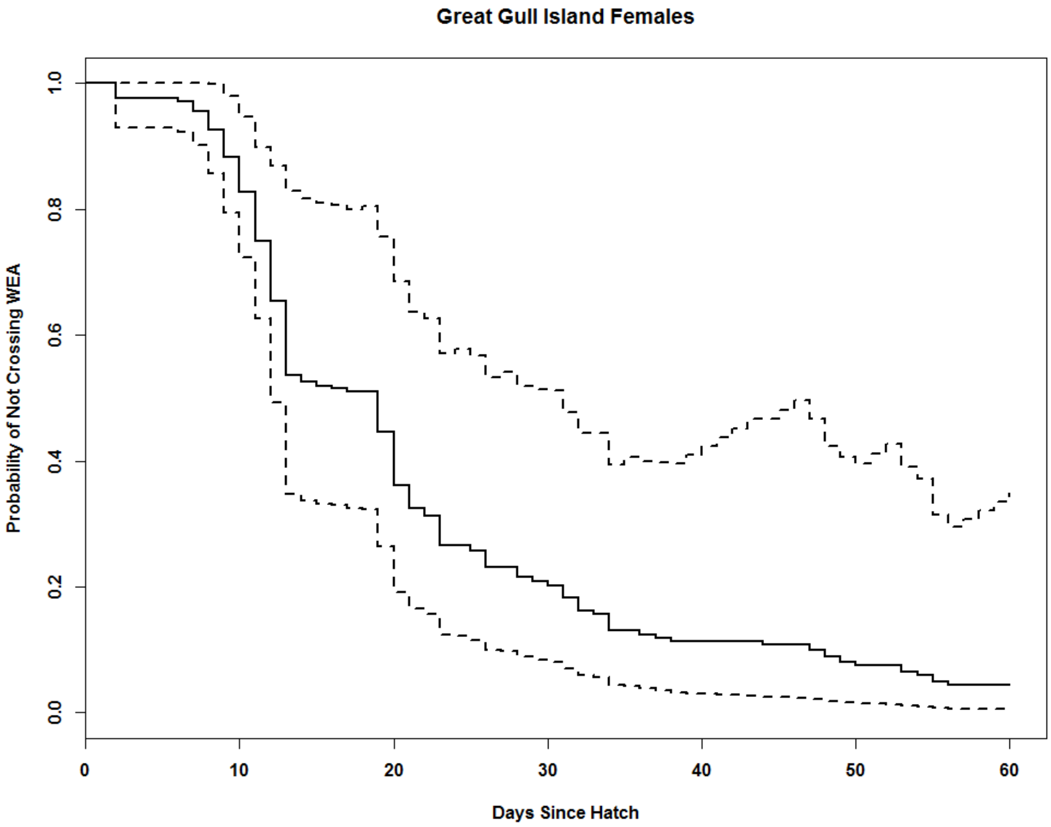


Figure 4.4. Estimated survival function (solid line) for the Cox Proportional Hazards model of offshore flight events by Common Terns per unit time (days since tagging) for: males from Monomoy NWR (4.4A); females from Monomoy NWR (4.4B); males from Great Gull Island (4.4C); and females from Great Gull Island (4.4D). For each estimation, all other covariates fixed at their mean values. The dashed lines show 95% confidence intervals around the survival functions.

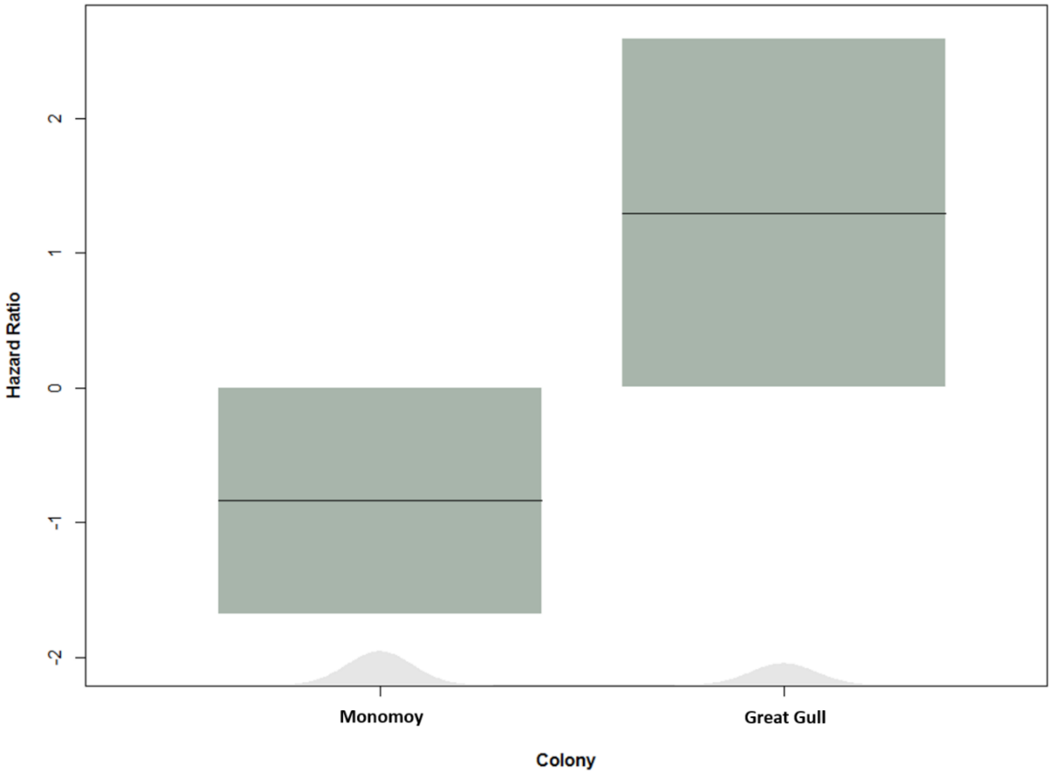


Figure 4.5. Hazard ratio (black horizontal line) with 95% confidence limits (grey box) of Wind Energy Area (WEA) crossing events for Common Terns from the breeding colony at Monomoy Island (Monomoy) versus Great Gull Island (Great Gull). Grey histograms along x-axis show marginal distribution of each variable.

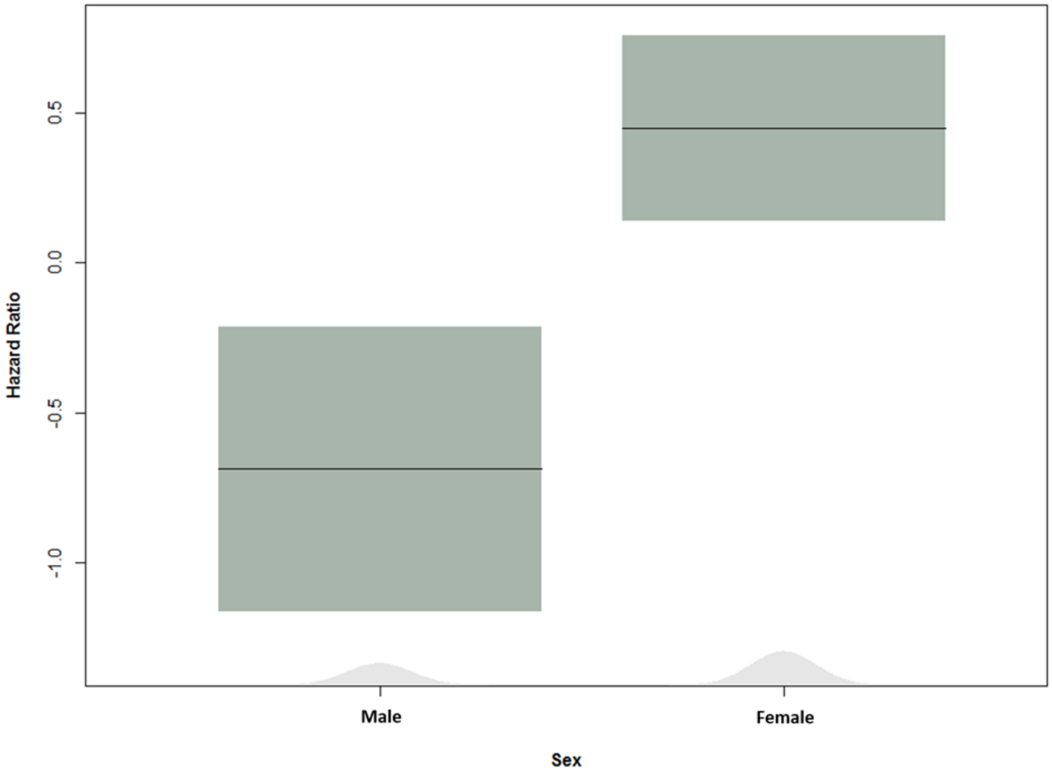


Figure 4.6. Hazard ratio (black horizontal line) with 95% confidence limits (grey box) of Wind Energy Area (WEA) crossing events for male versus female Common Terns. Grey histograms along x-axis show marginal distribution of each variable.

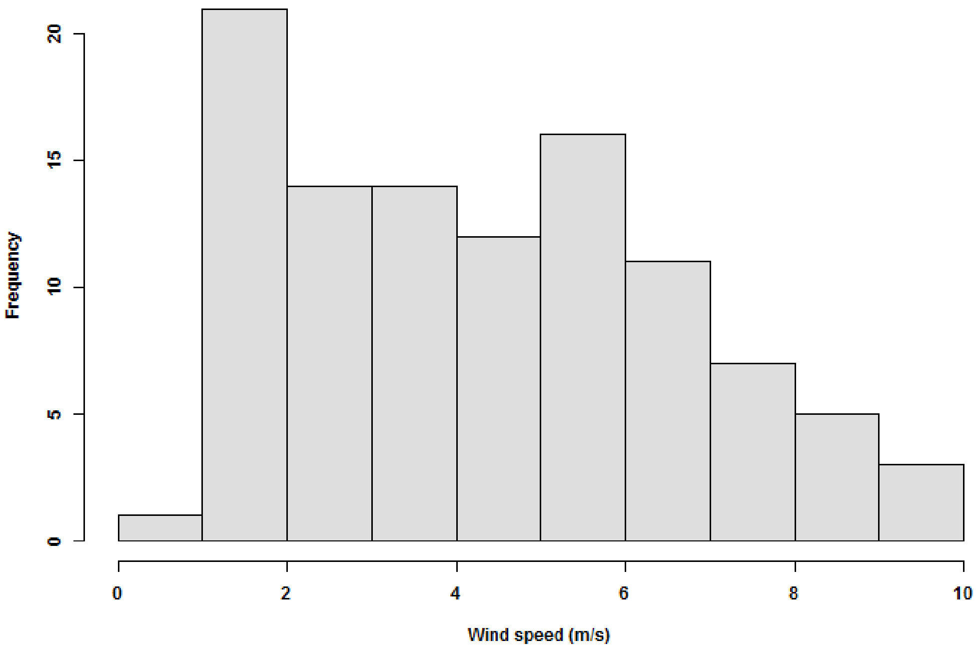


Figure 4.7. Histogram of mean wind speed (m/s) during Wind Energy Area (WEA) crossing events (*n* = 94) by 31 Common Terns tracked with digital VHF telemetry in the southern New England continental shelf region in 2014.

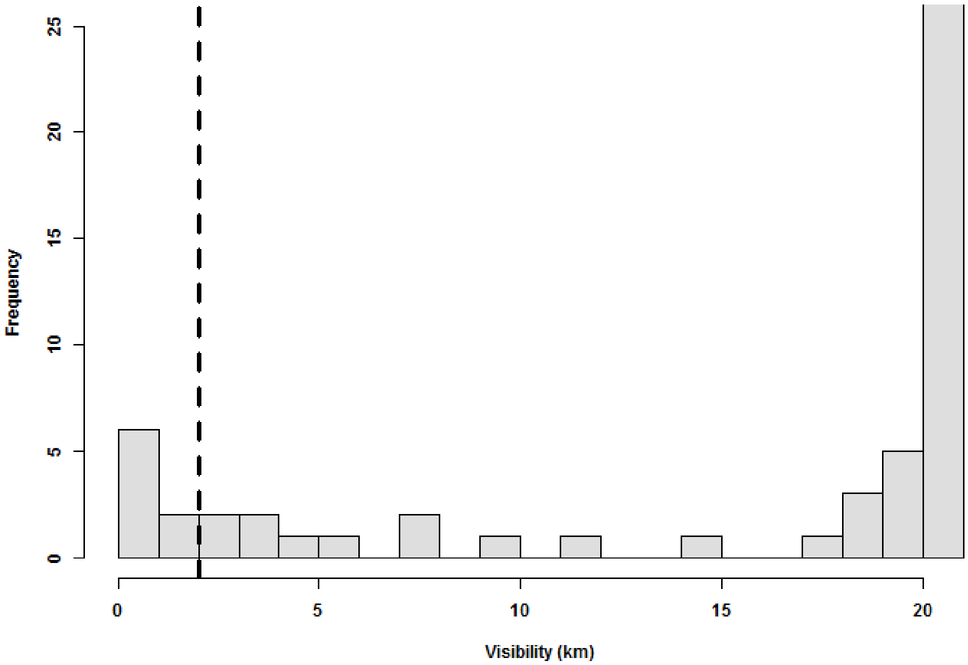


Figure 4.8. Histogram of mean visibility (km) during Wind Energy Area (WEA) crossing events (*n* = 94) by 31 Common Terns tracked with digital VHF telemetry in the southern New England continental shelf region in 2014. Dashed vertical line delineates crossing events with low visibility conditions (< 2 km).

Appendix 4.1. Detailed description of automated receiving stations comprising the 2014 VHF radio telemetry array by site, station code, geographic coordinates (NAD 83, decimal degrees), installation date, and specifications.

Site	Code	Latitude	Longitude	Install Date	Uninstall Date	Installation Specifications
Eel Pt, Nantucket, MA	ELPT	41.2934	-70.1972	5/25/14	11/8/2014	Six, 9-element (11.1 dBd) Yagi antennas oriented radially (60 degree separation) on 12.2-m mast
Coatue Pt, Nantucket, MA	CTPT	41.3073	-70.0637	5/27/14	11/9/2014	Six, 9-element (11.1 dBd) Yagi antennas oriented radially (60 degree separation) on 12.2-m mast
Great Point, Nantucket, MA	GTPT	41.3906	-70.0493	5/29/14	11/10/2014	Six, 9-element (11.1 dBd) Yagi antennas oriented radially (60 degree separation) on 12.2-m mast
Muskeget Island, Nantucket, MA	MUSK	41.3373	-70.3048	5/30/14	Still operating	Six, 9-element (11.1 dBd) Yagi antennas oriented radially (60 degree separation) on 12.2-m mast
S. Monomoy - N,	MNYN	41.6088	-69.9869	6/16/14	11/29/2014	Six, 9-element (11.1 dBd) Yagi antennas oriented radially (60 degree separation)

Chatham, MA						on 12.2-m mast
S. Monomoy - S, Chatham, MA	MNYS	41.5526	-70.0100	6/8/14	11/29/2014	Six, 9-element (11.1 dBd) Yagi antennas oriented radially (60 degree separation) on 12.2-m mast
Tern colony - S. Monomoy, Chatham, MA	TERN	41.6197	-69.9849	6/11/14	11/29/14	One, 5-element (9 dBd) Yagi antenna (oriented S) on 1.4 m post.
Tern colony - Great Gull Island, NY	GGIS	41.2018	-72.1192	6/30/14	10/12/14	Three, 5-element (9 dBd) Yagi antennas (oriented N, E, and W, respectively) on an 11-m observation tower
Great Point Ferry, Nantucket Sound	GTPF	Mobile	Mobile	7/2/14	10/23/14	Omnidirectional antenna (200 W) on ferry (travels between Hyannis, MA to Nantucket, MA)
R/V Henry Bigelow (NOAA)	NOAA	Mobile	Mobile	7/7/14	11/25/14	Omnidirectional antenna (200 W) on NOAA Research Vessel (travels from Newport, RI to various offshore sites)

Nomans Land Island, Chilmark, MA	NOMA	41.2613	-70.8152	7/20/14	10/31/14	Six, 9-element (11.1 dBd) Yagi antennas oriented radially (60 degree separation) on 12.2-m mast
Nomans Land Island (summit), Chilmark, MA	NOMS	41.2531	-70.8134	7/20/14	10/31/14	One, 9-element Yagi antenna oriented SW on a 3 m (10 ft) mast at the summit (110 ft. elevation) of Nomans Land Island
Block Island, New Shoreham, RI	BISE	41.1532	-71.5527	7/29/14	11/23/14	Six, 9-element (11.1 dBd) Yagi antennas oriented radially (60 degree separation) on 12.2-m mast
Napatree Point, Westerly, RI	NAPA	41.3063	-71.8838	7/11/14	10/24/14	Six, 9-element (11.1 dBd) Yagi antennas oriented radially (60 degree separation) on 12.2-m mast
Sachuest Point, Middletown, RI	SACH	41.4787	-71.2438	7/13/14	10/20/14	Six, 9-element (11.1 dBd) Yagi antennas oriented radially (60 degree separation) on 12.2-m mast

Montauk Point, East Hampton, NY	MNTK	41.0591	-71.8691	7/18/14	11/15/14	Six, 9-element (11.1 dBd) Yagi antennas oriented radially (60 degree separation) on 12.2-m mast

Appendix 4.2. Summary of Common Terns fitted with digital VHF transmitters in 2014 including: ID number of transmitter, sex, location (colony site) of transmitter deployment, date of transmitter deployment, date of last detection of transmitter, and total days tracked.

ID	Sex	Nanotag Location	Nanotag Date	Last Detection	Days Detected
282	M	Monomoy	6/9/2014	7/23/2014	44
283	M	Monomoy	6/9/2014	8/11/2014	63
284	F	Monomoy	6/9/2014	7/26/2014	47
285	F	Monomoy	6/9/2014	7/15/2014	36
286	F	Monomoy	6/9/2014	7/3/2014	24
287	F	Monomoy	6/9/2014	8/9/2014	61
288	F	Monomoy	6/9/2014	8/7/2014	59
289	M	Monomoy	6/9/2014	7/7/2014	28
290	M	Monomoy	6/15/2014	7/19/2014	34
291	M	Monomoy	6/15/2014	7/29/2014	44
292	M	Monomoy	6/15/2014	7/20/2014	35
293	F	Monomoy	6/15/2014	8/3/2014	49
294	F	Monomoy	6/15/2014	7/26/2014	41
295	M	Monomoy	6/15/2014	8/20/2014	66
297	M	Monomoy	6/15/2014	7/26/2014	41
298	F	Monomoy	6/15/2014	7/30/2014	45
299	F	Monomoy	6/19/2014	7/14/2014	25
300	M	Monomoy	6/19/2014	7/26/2014	37
301	F	Monomoy	6/19/2014	7/20/2014	31
302	F	Monomoy	6/19/2014	7/8/2014	19
303	F	Monomoy	6/19/2014	7/1/2014	12
304	F	Monomoy	6/19/2014	8/16/2014	58
305	M	Monomoy	6/19/2014	8/26/2014	68
306	M	Monomoy	6/19/2014	7/24/2014	35
307	F	Monomoy	6/20/2014	7/31/2014	41
308	F	Monomoy	6/19/2014	8/19/2014	61
309	F	Monomoy	6/20/2014	7/28/2014	38
310	M	Monomoy	6/20/2014	8/27/2014	68
311	F	Monomoy	6/20/2014	7/21/2014	31
312	F	Monomoy	6/20/2014	7/22/2014	32
313	M	Monomoy	6/19/2014	8/27/2014	69
314	F	Monomoy	6/19/2014	7/17/2014	28
315	M	Monomoy	6/20/2014	9/8/2014	80

316	M	Monomoy	6/19/2014	7/20/2014	31
317	M	Monomoy	6/19/2014	7/25/2014	36
318	F	Monomoy	6/20/2014	7/27/2014	37
319	F	Monomoy	6/20/2014	7/29/2014	39
320	M	Monomoy	6/20/2014	7/21/2014	31
321	F	Monomoy	6/20/2014	7/22/2014	32
322	F	Monomoy	6/20/2014	7/17/2014	27
323	F	Monomoy	6/20/2014	8/2/2014	43
324	F	Monomoy	6/20/2014	7/8/2014	18
325	F	Monomoy	6/20/2014	7/25/2014	35
326	F	Monomoy	6/20/2014	8/8/2014	49
327	M	Monomoy	6/20/2014	8/21/2014	62
328	F	Monomoy	6/20/2014	8/8/2014	49
329	F	Monomoy	6/20/2014	7/20/2014	30
330	F	Monomoy	6/20/2014	8/5/2014	46
331	F	Monomoy	6/20/2014	7/27/2014	37
332	F	Monomoy	6/20/2014	8/4/2014	45
333	M	Monomoy	6/20/2014	8/6/2014	47
334	M	Monomoy	6/20/2014	8/25/2014	66
335	F	Monomoy	6/20/2014	8/3/2014	44
336	M	Monomoy	6/20/2014	8/3/2014	44
337	F	Monomoy	6/21/2014	7/19/2014	28
338	M	Monomoy	6/21/2014	8/4/2014	44
339	F	Monomoy	6/21/2014	8/3/2014	43
340	F	Monomoy	6/21/2014	8/16/2014	56
341	F	Monomoy	6/21/2014	8/4/2014	44
342	M	Monomoy	6/21/2014	7/22/2014	31
343	F	Monomoy	6/21/2014	8/7/2014	47
344	M	Monomoy	6/21/2014	8/9/2014	49
345	F	Monomoy	6/21/2014	8/19/2014	59
346	F	Monomoy	6/21/2014	8/16/2014	56
352	F	Great Gull	6/27/2014	8/17/2014	51
353	F	Great Gull	6/28/2014	7/25/2014	27
354	M	Great Gull	6/28/2014	7/23/2014	25
355	F	Great Gull	6/28/2014	7/9/2014	11
356	M	Great Gull	6/28/2014	8/5/2014	38
357	M	Great Gull	6/28/2014	7/30/2014	32
358	F	Great Gull	6/28/2014	7/18/2014	20
359	F	Great Gull	6/28/2014	8/7/2014	40
360	F	Great Gull	6/28/2014	7/20/2014	22
361	M	Great Gull	6/28/2014	7/28/2014	30

362	F	Great Gull	6/28/2014	8/10/2014	43
363	F	Great Gull	6/28/2014	8/18/2014	51
365	F	Great Gull	6/28/2014	8/14/2014	47
366	M	Great Gull	6/29/2014	8/11/2014	43
367	M	Great Gull	6/29/2014	8/3/2014	35
368	F	Great Gull	6/29/2014	8/8/2014	40
369	M	Great Gull	6/29/2014	8/12/2014	44
370	F	Great Gull	6/29/2014	7/24/2014	25
371	F	Great Gull	6/29/2014	7/24/2014	25
372	F	Great Gull	6/29/2014	8/28/2014	60
373	F	Great Gull	6/29/2014	8/24/2014	56
374	M	Great Gull	6/29/2014	7/31/2014	32
375	M	Great Gull	6/29/2014	7/24/2014	25
376	M	Great Gull	6/29/2014	7/19/2014	20
377	M	Great Gull	6/29/2014	8/25/2014	57
378	F	Great Gull	6/29/2014	8/9/2014	41
379	M	Great Gull	6/29/2014	7/8/2014	9
380	F	Great Gull	6/30/2014	7/28/2014	28
381	M	Great Gull	6/30/2014	8/4/2014	35
382	F	Great Gull	6/30/2014	7/23/2014	23
383	F	Great Gull	6/30/2014	7/29/2014	29
384	F	Great Gull	6/30/2014	8/3/2014	34
385	M	Great Gull	6/30/2014	7/21/2014	21
386	F	Great Gull	6/30/2014	7/18/2014	18
387	F	Great Gull	6/30/2014	7/25/2014	25
388	M	Great Gull	6/30/2014	8/22/2014	53
389	F	Great Gull	6/30/2014	7/26/2014	26
390	M	Great Gull	6/30/2014	8/10/2014	41
391	M	Great Gull	6/30/2014	7/21/2014	21
392	F	Great Gull	6/30/2014	8/21/2014	52
393	F	Great Gull	6/30/2014	7/30/2014	30
395	M	Great Gull	6/30/2014	7/23/2014	23
396	F	Great Gull	6/30/2014	8/19/2014	50
397	F	Great Gull	6/30/2014	8/5/2014	36
398	F	Great Gull	6/30/2014	8/6/2014	37
400	M	Great Gull	6/30/2014	8/18/2014	49
401	M	Great Gull	6/30/2014	7/10/2014	10
402	M	Great Gull	6/30/2014	7/26/2014	26
403	F	Great Gull	6/30/2014	8/17/2014	48
404	F	Great Gull	6/30/2014	8/21/2014	52
405	F	Great Gull	6/30/2014	8/31/2014	62

REFERENCES

Ackerman, J. T., J. D. Bluso-Demers and J. Y. Takekawa. 2009. Postfledging Forster's Tern movements, habitat selection, and colony attendance in San Francisco Bay. Condor 111:100-110.

Adams, E., I. Steinhouse, A. Gilbert, K. Willaims, and W. Montevecchi. 2015. Using state-space models to identify areas of persistent winter activity and their associated environmental covariates in Northern Gannets. 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. 19 pp.

Aebischer, N. J., P. A. Robertson and R. E. Kenward. 1993. Compositional analysis of habitat use from animal radio-tracking data. Ecology 74: 1313-1325.

Agostinelli, C., and U. Lund. 2013. Circular: circular statistics. [online] URL: http://CRAN.R-project.org/package=circular. R package version 0.4–7.

Alerstam, T. 1985. Strategies of migratory flight, illustrated by Arctic and Common terns, *Sterna paradisaea* and *Sterna hirundo*. Contributions in Marine Science Supplement 27:580-603.

Allison, T. D., E. Jedrey, and S. Perkins. 2008. Avian issues for offshore wind development. Marine Technology Society Journal 42:28-38.

Allison, T. D., S. Perkins, and G. Sadoti. 2006. Estimating Distribution and Abundance of Wintering Sea Ducks in Nantucket Sound, #57. Final Report to the Sea Duck Joint Venture Program, 7 pp.

American Oystercatcher Working Group, E. Nol and R. C. Humphrey. 2012. No. 082 in The Birds of North America Online (A. Poole, Ed.). Cornell Lab of Ornithology, Ithaca, New York. http://bna.birds.cornell.edu/bna/species/082, accessed 3 June 2015.

Argos. 2015. Argos user's manual. Collecte Localisation Satellites/Argos, Toulouse, France. http://www.argos-system.org, accessed 30 June 2015.

Austin, O. L. 1953. The migration of the Common Tern (*Sterna hirundo*) in the Western Hemisphere. Bird-Banding 24:39-55.

Baranowski, R., F. Oteri, I. Baring-Gould, and S. Tegen. 2016. U.S. Department of Energy Regional Resource Centers Report: State of the Wind Industry in the Regions. (No. NREL/TP-5000-62942). National Renewable Energy Laboratory (NREL), Golden, CO, USA.

Barron, D. G., J. D. Brawn and P. J. Weatherhead. 2010. Meta-analysis of transmitter effects on avian behaviour and ecology. Methods in Ecology and Evolution 1:180-187.

Batschelet, E. 1981. Circular Statistics in Biology. Academic Press, New York, NY, 371 pp.

Beaudry-Losique, J., T. Boling, J. Brown-Saracino, P. Gilman, M. Hahn, C. Hart, J. Johnson, M. McCluer, L. Morton, and B. Naughton. 2011. A national offshore wind strategy: creating an offshore wind energy industry in the United States. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Wind & Water Power Program U.S. and Department of the Interior, Bureau of Ocean Energy Management, Regulation, and Enforcement, Sterling, VA.

Becker, P. H., D. Frank, and S. R. Sudmann. 1993. Temporal and spatial pattern of Common Tern (*Sterna hirundo*) foraging in the Wadden Sea. Oecologia 93:389-393.

Beyer. 2011. Geospatial modelling environment software v. 0.7.2.1. Spatial Ecology, LLC, Toronto, Canada. http://www.spatialecology.com/gme, accessed 10 June 2015.

Bivand, R., and N. Lewin-Koh. 2016. Maptools. [online] URL: https://cran.r-project.org/web/packages/maptools/maptools.pdf R package version 0.8–39.

Black, A.L. 2006. Foraging area characteristics of Arctic Terns (*Sterna paradisaea*) and Common Terns (*Sterna hirundo*) breeding on Machias Seal Island. Ph.D. dissertation. University of New Brunswick, Canada.

Blokpoel, H., G. D. Tessier, and A. Harfenist. 1987. Distribution during post-breeding dispersal, migration, and overwintering of Common Terns color-marked on the lower Great Lakes. J. Field Ornithol. 58:206-217.

Bolker, B. M., M. E. Brooks, C. J. Clark, S. W. Geange, J. R. Poulsen, M. H. H. Stevens and J.-S. S. White. 2009. Generalized linear mixed models: a practical guide for ecology and evolution. Trends in Ecology and Evolution 24:127-135.

Bridge, E. S., K. Thorup, M. S. Bowlin, P. B. Chilson, R. H. Diehl, R. W. Fléron, P. Hartl, R. Kays, J. F. Kelly, and W. D. Robinson. 2011. Technology on the move: recent and forthcoming innovations for tracking migratory birds. BioScience 61:689-698.

Brown, S., C. Hickey, B. Harrington and R. Gill, Eds. 2001. The U. S. Shorebird conservation plan, 2nd ed. Manomet Center for Conservation Sciences, Manomet, Massachusetts.

Brzustowski, J. 2015. SensorGnome. [online] URL: http://public.sensorgnome.org/Sensorgnome_Package.

Bureau of Ocean Energy Management. 2016. BOEM's Renewable Energy Program. [online] URL: http://www.boem.gov/BOEM-RE-Programs-Fact-Sheet/.

Burger, J., and M. Gochfeld. 1991. The Common Tern: Its breeding biology and social behavior. Columbia University Press, New York, New York, USA.

Burger, A. E., and S. A. Shaffer. 2008. *Perspectives in ornithology* application of tracking and data-logging technology in research and conservation of seabirds. Auk 125:253-264.

Burger, J. 1980. The transition to independence and postfledging parental care in seabirds, p. 367-447, In J. Burger, B. L. Olla, and H. E. Winn (eds.), Behavior of marine animals, Vol. 4: Marine birds. Plenum Press, New York, NY.

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.

Burger, J., L. J. Niles, R. R. Porter, A. D. Dey, S. Koch and C. Gordon. 2012. Migration and over-wintering of Red Knots (*Calidris canutus rufa*) along the Atlantic Coast of the United States. Condor 114: 302-313.

Burkepile, N. A., J. W. Connelly, D. W. Stanley and K. P. Reese. 2002. Attachment of radiotransmitters to one-day-old Sage Grouse chicks. Wildlife Society Bulletin 30:93-96.

Chamberlain, D. E., M. R. Rehfisch, A. D. Fox, M. Desholm, and S. J. Anthony. 2006. The effect of avoidance rates on bird mortality predictions made by wind turbine collision risk models. Ibis 148:198-202.

Cochran, W. W. 1980. Wildlife telemetry. Pages 507-520 *in* Wildlife Management Techniques (S. P. Schemnitz, Ed.), 4th ed. The Wildlife Society, Inc., Washington, D.C.

Cochran, W. W., D. W. Warner, J. R. Tester and V. B. Kuechle. 1965. Automatic radio-tracking system for monitoring animal movements. BioScience 15: 98-100.

Cook, A.S.C.P., Humphreys, E.M., Masden, E.A. & Burton, N.H.K. 2014. The Avoidance Rates of Collision Between Birds and Offshore Turbines. Scottish Marine and Freshwater Science vol. 5 Number 16, Report Published by Marine Scotland Science, Aberdeen.

Desorbo, C., R. Gray, J. Tash, C. Gray, K. Willaims, and D. Ricordan. 2015. Offshore migration of Peregrine Falcons (*Falco peregrinus*) along the Atlantic Flyway. 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. 31 pp.

Dirksen, S., J. Van der Winden, and A. Spaans. 1998. Nocturnal collision risks of birds with wind turbines in tidal and semi-offshore areas. Wind energy and landscape. Balkema, Rotterdam:99-108.

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.

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

Duffy, D. C. 1986. Foraging at patches: interactions between Common and Roseate Terns. Ornis Scandinavica. 17:47-52.

Duffy, D. C., A. McKnight, and D. B. Irons. 2013. Trans-Andean passage of migrating Arctic Terns over Patagonia. Marine Ornithology 41:155-159.

Dunn, E. K. 1973. Changes in fishing ability of terns associated with windspeed and sea surface conditions. Nature 244:520-521.

Egevang, C., I. J. Stenhouse, R. A. Phillips, A. Petersen, J. W. Fox, and J. R. D. Silk. 2010. Tracking of Arctic terns (*Sterna paradisaea)* reveals longest animal migration. Proceedings of the National Academy of Sciences 107:2078-2081.

Ens, B. J., M. Kersten, A. Brenninkmeijer and J. B. Hulscher. 1992. Territory quality, parental effort and reproductive success of oystercatchers (*Haematopus ostralegus*). Journal of Animal Ecology 61: 703-715.

Everaert, J., and E. M. Stienen. 2008. Impact of wind turbines on birds in Zeebrugge (Belgium). Pages 103-117 *in* D. Hawksworth, and A. Bull, editors. Biodiversity and Conservation in Europe. Springer, Netherlands.

Exo, K.-M., O. Huppop, and S. Garthe. 2003. Birds and offshore wind farms: a hot topic in marine ecology. Wader Study Group Bulletin 100:50-53.

Fair, J. M., E. Paul, J. Jones, A. B. Clark, C. Davie, and G. Kaiser. 2010. Guidelines to the Use of Wild Birds in Research. Ornithological Council. [online] URL: www.nmnh.si.edu/BIRDNET/guide.

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

Fox, J., and S. Weisberg. 2011. Cox proportional-hazards regression for survival data in R. An appendix to An R Companion to Applied Regression, Second Edition. Sage Publications, Thousand Oaks, CA.

Galbraith, H., J. J. Hatch, I. C. T. Nisbet, and T. H. Kunz. 1999. Age-specific reproductive efficiency among breeding Common Terns *Sterna hirundo*: measurement of energy expenditure using doubly-labelled water. Journal of Avian Biology 30:85-96.

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

Gaston, A. J., D. F. Bertram, A. W. Boyne, J. W. Chardine, G. Davoren, A. W. Diamond, A. Hedd, W. A. Montevecchi, J. M. Hipfner, M. J. F. Lemon, M. L. Mallory, J. F. Rail, and G. J. Robertson. 2009. Changes in Canadian seabird populations and ecology since 1970 in relation to changes in oceanography and food webs. Environmental Reviews 17:267-286.

Gilg, O., B. Moe, S. A. Hanssen, N. M. Schmidt, B. Sittler, J. Hansen, J. Reneerkens, B. Sabard, O. Chastel, J. Moreau, R. A. Phillips, T. Oudman, E. M. Biersma, A. A. Fenstad, J. Lang, and L. Bollache. 2013. Trans-equatorial migration routes, staging sites and wintering areas of a high-arctic avian predator: the Long-tailed Skua (*Stercorarius longicaudus*). PloS ONE 8:e64614.

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.

Goyert, H. F., B. Gardner, R. Sollmann, R. R. Veit, A. T. Gilbert, E. E. Connelly, and K. A. Williams. 2016. Predicting the offshore distribution and abundance of marine birds with a hierarchical community distance sampling model. Ecological Applications. doi: 10.1890/15-1955.1

Gray, C., A. Gilbert, J. Tash, and C. Anderson. 2015. Wintering movements and habitat use of Red-throated Loons (*Gavia stellata*) 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. 26 pp.

Griffin, L., E. Rees, and B. Hughes. 2010. Migration Routes of Whooper Swans and Geese in Relation to Wind Farm Footprints. *in* Wildfown & Wildlands Trust Interim Report to Department of Energy and Climate Change (DECC), Wildfowl & Wetlands Trust, Slimbridge, England. 87 pp.

Green, M., T. Piersma, J. Jukema, P. De Goeij, B. Spaans and J. Van Gils. 2002. Radio-telemetry observations of the first 650 km of the migration of Bar-tailed Godwits (*Limosa lapponica)* from the Wadden Sea to the Russian Arctic. Ardea 90: 71-80.

Guilford, T., J. Meade, J. Willis, R. A. Phillips, D. Boyle, S. Roberts, M. Collett, R. Freeman, and C. M. Perrins. 2009. Migration and stopover in a small pelagic seabird, the Manx shearwater (*Puffinus puffinus)*: insights from machine learning. Proceedings of the Royal Society of London B: Biological Sciences:rspb-2008.

Gulf of Maine Seabird Working Group (GOMSWG). 2013. 2013 Gulf of Maine Seabird Working Group Census Results. [online] URL: http://gomswg.org/pdf_files/GOMSWG%20Census%20Data%202013.pdf

Gulf of Maine Seabird Working Group (GOMSWG). 2014. 2014 Gulf of Maine Seabird Working Group Census Results. [online] URL: http://gomswg.org/pdf_files/GOMSWG%20Census%20Data%202014.pdf.

Hall, C. S., S. W. Kress, and C. R. Griffin. 2000. Composition, spatial and temporal variation of Common and Arctic Tern chick diets in the Gulf of Maine. *Waterbirds* 23:430-439.

Hatch, J. J. 2002. Arctic Tern (*Sterna paradisaea*), *The Birds of North America Online* (A. Poole, Ed.). Ithaca: Cornell Lab of Ornithology. [online] URL: http://bna.birds.cornell.edu.bnaproxy.birds.cornell.edu/bna/species/707doi:10.2173/bna.707.

Hawkins, P. 2004. Bio-logging and animal welfare: practical refinements. Memoirs of National Institute of Polar Research, Special Issue 58:58-68.

Hays, H., J. DiCostanzo, G. Cormons, P. T. Z. Antas, and J. L. X. do Nascimento. 1997. Recoveries of Roseate and Common terns in South America. Journal of Field Ornithology 68:79-90.

Hays, H., P. Lima, L. Monteiro, J. DiCostanzo, G. Cormons, I. C. T. Nisbet, J. E. Saliva, J. A. Spendelow, J. Burger, J. Pierce, and M. Gochfeld. 1999. A nonbreeding concentration of Roseate and Common Terns in Bahia, Brazil. Journal of Field Ornithology 70:455-464.

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 of London B: Biological Sciences 365: 2303-2312.

Hedd, A., W. A. Montevecchi, H. Otley, R. A. Phillips, and D. A. Fifield. 2012. Trans-equatorial migration and habitat use by sooty shearwaters (*Puffinus griseus)* from the South Atlantic during the nonbreeding season. Marine Ecology Progress Series 449:277-290.

Heinemann, D. 1992. Foraging Ecology of Roseate Terns on Bird Island, Buzzards Bay, Massachusetts. Unpublished Report to U.S. Fish and Wildlife Service, Newton Corner, MA.

Hill, L. A. and L. G. Talent. 1990. Effects of capture, handling, banding, and radio-marking on breeding Least Terns and Snowy Plovers. Journal of Field Ornithology 61:310-319.

Horne, J. S. and E. O. Garton. 2006. Likelihood cross-validation versus least squares cross-validation for choosing the smoothing parameter in kernel home-range analysis. Journal of Wildlife Management 70: 641-648.

Horne, J. S., E. O. Garton, S. M. Krone, and J. S. Lewis. 2007. Analyzing animal movements using Brownian bridges. Ecology 88:2354-2363.

Hosmer, D. W., and S. Lemeshow. 2000. Applied Logistic Regression. Second edition. John Wiley and Sons, New York, New York, USA.

Hothorn, T., F. Bretz, and P. Westfall. 2015. Multcomp. [online] URL: https://cran.r-project.org/web/packages/multcomp/index.html. R package version 1.4–4.

Huettmann, F., and A. W. Diamond. 2000. Seabird migration in the Canadian northwest Atlantic Ocean: moulting locations and movement patterns of immature birds. Canadian Journal of Zoology 78:624-647.

Jedrey, E. L., R. J. Harris, and E. A. Ray. 2010. Citizens of the world: The Canada to Cape Cod connection. Bird Observer 38:146-150.

Johnson, C. B. 2014. Advances in marine spatial planning: Zoning earth's last frontier. Journal of Environmental Law and Litigation 29:191-245.

Johnson, G. D., J. L. Pebworth and H. O. Krueger. 1991. Retention of transmitters attached to passerines ssing a glue-on technique. Journal of Field Ornithology 62:486-491.

Johnson, M., P. Clarkson, M. I. Goldstein, S. M. Haig, R. B. Lanctot, D. F. Tessler and D. Zwiefelhofer. 2010. Seasonal movements, winter range use, and migratory connectivity of the Black Oystercatcher. Condor 112: 731-743.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, A. Leetmaa, B. Reynolds, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K. Mo, C. Ropelewski, J. Wang, R. Jenne, and D. Joseph. 1996. The NCEP/NCAR 40-year reanalysis project. Bull Amer Meteor Soc 77:437-471.

Kenward, R. 1987. Wildlife radio tagging. Academic Press, San Diego, California.

Kernohan, B. J., R. A. Gitzen and J. J. Millspaugh. 2001. Analysis of animal space use and movements. Pages 125-166 *in* Radio tracking and animal populations (J.J. Millspaugh and J.M. Marzluff, eds). Academic Press, San Diego, California.

Klaassen, M., P. H. Becker and M. Wagener. 1992. Transmitter loads do not affect the daily energy expenditure of nesting Common Terns. Journal of Field Ornithololgy 63:181-185.

Klaassen, R. H. G., B. J. Ens, J. Shamoun-Baranes, K.-M. Exo, and F. Bairlein. 2011. Migration strategy of a flight generalist, the Lesser Black-backed Gull (*Larus fuscus)*. Behavioral Ecology 23:58-68.

Kress, S. W., E. H. Weinstein, C. T. N. Ian, G. W. Shugart, W. C. Scharf, H. Blokpoel, G. A. Smith, K. Karwowski, G. R. Maxwell, G. Chapdelaine, W. A. Montevecchi, A. R. Lock, C. F. Smith, E. Miller, J. A. Spendelow, M. Gochfeld, J. Burger, and R. M. Erwin. 1983. The status of tern populations in northeastern United States and adjacent Canada. Colonial Waterbirds 6:84-106.

Kunz, T. H., E. B. Arnett, B. M. Cooper, W. P. Erickson, R. P. Larkin, T. Mabee, M. L. Morrison, M. D. Strickland, and J. M. Szewczak. 2007. Assessing impacts of wind-energy development on nocturnally active birds and bats: A guidance document. The Journal of Wildlife Management 71:2449-2486.

Larkin, R. P., A. Raim and R. H. Diehl. 1996. Performance of a non-rotating direction-finder for automatic radio tracking. Journal of Field Ornithology 67: 59-71.

Leyrer, J., B. Spaans, M. Camara and T. Piersma. 2006. Small home ranges and high site fidelity in Red Knots (*Calidris c. canutus*) wintering on the Banc d’Arguin, Mauritania. Journal of Ornithology 147: 376-384.

Loring, P. H., P. W. C. Paton, J. E. Osenkowski, S. G. Gilliland, J.-P. L. Savard, and S. R. McWilliams. 2014. Habitat use and selection of black scoters in southern New England and siting of offshore wind energy facilities. Journal of Wildlife Management 78:645-656.

Martin, M. L. and J. R. Bider. 1978. A transmitter attachment for blackbirds. Journal of Wildlife Management 42:683-685.

Massey, B. W., K. Keane and C. Boardman. 1988. Adverse effects of radio transmitters on the behavior of nesting Least Terns. Condor 90:945-947.

MathWorks. 2016. MATLAB and Statistics Toolbox Release 2016a The MathWorks, Inc., Natick, Massachusetts, United States.

McKnight, A., A. J. Allyn, and D.B. Irons. 2013. Stepping stone pattern in Pacific Arctic Tern migration reveals the importance of upwelling areas. Marine Ecology Progress Series 491:253-264.

Meattey, D., L. Savoy, A. Gilbert, J. Tash, C. Gray, A. Berlin, C. Lepage, S. Gilliland, T. Bowman, J. Osenkowsi, and C. S. Spiegel. 2015. Wintering movements and habitat use of Surf Scoter (*Melanitta perspicillata*) 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. 24 pp.

Mid-Atlantic/New England/Maritimes Region Waterbird Working Group. 2006. Waterbird Conservation Plan for the Mid-Atlantic/New England/Maritimes Region: 2006-2010. Waterbird Conservation for the Americas. . [online] URL: http://www.waterbirdconservation.org.

Mills, A. M., B. G. Thurber, S. A. Mackenzie, and P. D. Taylor. 2011. Passerines use nocturnal flights for landscape-scale movements during migration stopover. Condor 113:597-607.

Mitchell, G. W., A. E. M. Newman, M. Wikelski, and D. Ryan Norris. 2012. Timing of breeding carries over to influence migratory departure in a songbird: an automated radiotracking study. Journal of Animal Ecology 81:1024-1033.

Montevecchi, W. A., A. Hedd, L. McFarlane Tranquilla, D. A. Fifield, C. M. Burke, P. M. Regular, G. K. Davoren, S. Garthe, G. J. Robertson, and R. A. Phillips. 2012. Tracking seabirds to identify ecologically important and high risk marine areas in the western North Atlantic. Biological Conservation 156:62-71.

Morris, R. D. and G. P. Burness. 1992. A new procedure for transmitter attachment: effects on brood attendance and chick feeding rates by male Common Terns. Condor 94:239-243.

Mosbech, A., K. L. Johansen, N. I. Bech, P. Lyngs, A. M. Harding, C. Egevang, R. A. Phillips, and J. Fort. 2012. Inter-breeding movements of little auks (*Alle alle)* reveal a key post-breeding staging area in the Greenland Sea. Polar Biology 35:305-311.

Mostello, C. S., I. C. Nisbet, S. A. Oswald, and J. W. Fox. 2014. Non-breeding season movements of six North American Roseate Terns *Sterna dougallii* tracked with geolocators. Seabirds 27:1-21.

Mulcahy, D. M. and D. Esler. 1999. Surgical and immediate postrelease mortality of Harlequin Ducks (*Histrionicus histrionicus*) implanted with abdominal radio transmitters with percutaneous antennae. Journal of Zoo and Wildlife Medicine 30:397-401.

Murray, D. L. and M. R. Fuller. 2000. A critical review of the effects of marking on the biology of vertebrates. Pages 15-64 *in* Research techniques in animal ecology: controversies and consequences (L. Boitani, andT. K. Fuller, Eds.). Columbia University Press, New York.

National Oceanic and Atmospheric Administration. 2004. Sensitivity of Coastal Environments and Wildlife to Spilled Oil: Massachusetts. Unpublished report, National Ocean Service, Office of Response and Restoration, Hazardous Materials Response Division, Seattle, Washington and the Coastal Services Center, Charleston, South Carolina. http://response.restoration.noaa.gov/maps-and-spatial-data/download-esi-maps-and-gis-data.html, accessed 15 June, 2015.

Nisbet, I. 2002a. Common Tern (*Sterna hirundo*), The Birds of North America Online (A. Poole, Ed.). Ithaca: Cornell Lab of Ornithology; Retrieved from the Birds of North America Online: http://bna.birds.cornell.edu/bna/species/618 doi:10.2173/bna.618.

Nisbet, I., M. Gochfeld, and J. Burger. 2014. Roseate Tern (*Sterna dougallii*), The Birds of North America Online (A. Poole, Ed.). Ithaca: Cornell Lab of Ornithology; Retrieved from the Birds of North America Online: http://bna.birds.cornell.edu/bna/species/370 doi:10.2173/bna.370.

Nisbet, I. C. T. 1976. Early stages in postfledging dispersal of Common Terns. Bird-Banding 47:163-164.

Nisbet, I. C. T. 2002b. Common Tern (Sterna hirundo), The Birds of North America Online (A. Poole, Ed.). Ithaca: Cornell Lab of Ornithology; Retrieved from the Birds of North America Online: http://bna.birds.cornell.edu/bna/species/618doi:10.2173/bna.618.

Nisbet, I. C. T., C. S. Mostello, R. R. Veit, J. W. Fox, and V. Afanasyev. 2011a. Migrations and winter quarters of five Common Terns tracked using geolocators. Waterbirds 34:32-39.

Nisbet, I. C. T., P. Szczys, C. S. Mostello, and J. W. Fox. 2011b. Female Common Terns *Sterna hirundo* start autumn migration earlier than males. Seabird 24:103-106.

O'Connell, A., C. S. Spiegel and S. M. Johnston. 2011. Compendium of Avian Occurrence Information for the Continental Shelf Waters along the Atlantic Coast of the United States, Final Report (Database Section - Shorebirds). Unpublished report, U.S. Department of the Interior, Fish and Wildlife Service, Hadley, Massachusetts.

Pennycuick, C. J., P. L. F. Fast, N. Ballerstädt, and N. Rattenborg. 2011. The effect of an external transmitter on the drag coefficient of a bird's body, and hence on migration range, and energy reserves after migration. Journal of Ornithology 153:633-644.

Perkins, S., A. Jones, and T. Allison. 2003. Survey of tern activity within Nantucket Sound, Massachusetts, during pre-migratory fall staging. Final Report for Massachusetts Technology Collaborative. Massachusetts Audubon Society, Lincoln, MA, USA.

Perrow, M. R., E. R. Skeate, and J. J. Gilroy. 2011. Visual tracking from a rigid-hulled inflatable boat to determine foraging movements of breeding terns. Journal of Field Ornithology 82:68-79.

Perrow, M. R., E. R. Skeate, P. Lines, D. Brown, and M. L. Tomlinson. 2006. Radio telemetry as a tool for impact assessment of wind farms: the case of Little Terns *Sterna albifrons* at Scroby Sands, Norfolk, UK. Ibis 148:57-75.

Ponchon, A., D. Gremillet, B. Doligez, T. Chambert, T. Tveraa, J. González-Solís and T. Boulinier. 2013. Tracking prospecting movements involved in breeding habitat selection: insights, pitfalls and perspectives. Methods in Ecology and Evolution 4: 143-150.

R Core Team. 2016. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. [online] URL: http://www.R-project.org/.

Richardson, W. J. 1978. Timing and amount of bird migration in relation to weather: A review. Oikos 30:224-272.

Ripley, B. 2016. MASS: Support Functions and Datasets for Venables and Ripley's MASS. [online] URL: https://cran.r-project.org/web/packages/MASS/index.html R package version 7.3-45.

Robinson Willmott, J., 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 US Department of the Interior, Bureau of Ocean Energy Management, Office of Renewable Energy Programs. OCS Study BOEM 207:275.

Rock, J. C., M. L. Leonard, and A. W. Boyne. 2007. Do co-nesting Arctic and Common Terns partition foraging habitat and chick diets? Waterbirds 30:579-587.

Ronconi, R. A., J. R. Stephens, Z. J. Crysler, I. L. Pollet, D. T. Fife, A. G. Horn, P. D. Taylor 2016. Distribution, abundance and trends of gulls and terns breeding on Sable Island, Nova Scotia, Canada. *Waterbirds, in press*.

Sadoti, G., T. Allison, S. Perkins, and A. Jones. 2005. A survey of tern activity within Nantucket Sound, Massachusetts, during the 2004 breeding period. Final Report for Massachusetts Technology Collaborative. Massachusetts Audubon Society, Lincoln, MA, USA.

Safina, C., and J. Burger. 1989. Inter-annual variation in prey availability for Common Terns at different stages in their reproductive cycle. Colonial Waterbirds 12:37-42.

Sanzenbacher, P., S. M. Haig and L. W. Oring. 2000. Application of a modified harness design for attachment of radio transmitters to shorebirds. Wader Study Group Bulletin 91: 16-20.

SAS Institute, Inc. 2008. SAS statistical software v. 9.2. SAS Institute, Inc., Cary, North Carolina.

Schwemmer, P. and S. Garthe. 2011. Spatial and temporal patterns of habitat use by Eurasian Oystercatchers (*Haematopus ostralegus*) in the eastern Wadden Sea revealed using GPS data loggers. Marine Biology 158: 541-550.

Shealer, D. A., and S. W. Kress. 1994. Post-breeding movements and prey selection of Roseate Terns at Stratton Island, Maine. Journal of Field Ornithology 65:349-362.

Schwemmer, P. and S. Garthe. 2011. Spatial and temporal patterns of habitat use by Eurasian Oystercatchers (*Haematopus ostralegus*) in the eastern Wadden Sea revealed using GPS data loggers. Marine Biology 158: 541-550.

Sherfy, M. H., M. J. Anteau, T. L. Shaffer, M. A. Sovada and J. H. Stucker. 2012. Foraging ecology of least terns and piping plovers nesting on central Platte River sandpits and sandbars. Open-File Report 2012-1059, U.S. Department of the Interior, U.S. Geological Survey, Reston, Virginia.

Sirdevan, J. E., and J. S. Quinn. 1997. Foraging patterns of Caspian Terns (*Sterna caspia*) determined using radio-telemetry. Colonial Waterbirds 20:429-435.

Söhle, I. S., H. Moller, D. Fletcher, and C. J. R. Robertson. 2000. Telemetry reduces colony attendance by Sooty Shearwaters (*Puffinus griseus*). New Zealand Journal of Zoology 27:357-365.

Spendelow, J. A., J. D. Nichols, I. C. T. Nisbet, H. Hays, and G. D. Cormons. 1995. Estimating annual survival and movement rates of adults within a metapopulation of Roseate Terns. Ecology 76:2415-2428.

Stienen, E. W. M., W. Courtens, J. Everaert, and M. Van De Walle. 2008. Sex-biased mortality of Common Terns in wind farm collisions. The Condor 110:154-157.

Suryan, R. M., F. Sato, G. R. Balogh, K. D. Hyrenbach, P. R. Sievert, and K. Ozaki. 2006. Foraging destinations and marine habitat use of short-tailed albatrosses: a multi-scale approach using first-passage time analysis. *Deep Sea Research Part II: Topical Studies in Oceanography* 53:370-386.

Swihart, R. K. and N. A. Slade. 1997. On testing for independence of animal movements. Journal of Agricultural, Biological, and Environmental Statistics 2: 48-63.

Taylor, I. R. 1983. Effect of wind on the foraging behaviour of Common and Sandwich terns. Ornis Scandinavica 14:90-96.

Taylor, P. D., S. A. Mackenzie, B. G. Thurber, A. M. Calvert, A. M. Mills, L. P. McGuire, and C. G. Guglielmo. 2011. Landscape movements of migratory birds and bats reveal an expanded scale of stopover. PLoS ONE 6:e27054.

Therneau, T. 2016. Survival. [online] URL: https://cran.r-project.org/web/packages/survival/survival.pdf R package version 2.39-5.

Therneau, T., and P. Grambsch. 2000. Modeling Surivival Data: Extending the Cox Model. Springer, New York, New York, USA.

Tomkiewicz, S. M., M. R. Fuller, J. G. Kie and K. K. Bates. 2010. Global positioning system and associated technologies in animal behaviour and ecological research. Philosophical Transactions of the Royal Society of London B: Biological Sciences 365: 2163-2176.

Trull, P., S. Hecker, M. Watson, and I. Nisbet. 1999. Staging of Roseate Terns *Sterna dougallii* in the post-breeding period around Cape Cod, Massachusetts, USA. Atlantic Seabirds 1:145-158.

U.S. Fish and Wildlife Service. 2008. Final biological opinion, Cape Wind Associates, LLC, wind energy project, Nantucket Sound, Massachusetts, pp. 51-73. Unpublished Report. U.S. Fish and Wildlife Service, New England Field Office, Concord, NH. [online] URL: http://www.fws.gov/newengland/pdfs/CapeWind-BO1November2008_withCovLttr.pdf.

Vandenabeele, S. P., E. Grundy, M. I. Friswell, A. Grogan, S. C. Votier, and R. P. Wilson. 2014. Excess baggage for birds: Inappropriate placement of tags on gannets changes flight patterns. PLoS ONE 9:e92657.

Vandenabeele, S. P., E. L. Shepard, A. Grogan, and R. P. Wilson. 2011. When three per cent may not be three per cent; device-equipped seabirds experience variable flight constraints. Marine Biology 159:1-14.

van der Winden, J., R. C. Fijn, P. W. v. Horssen, D. Gerritsen-Davidse, and T. Piersma. 2014. Idiosyncratic migrations of Black Terns (*Chlidonias niger*): Diversity in routes and stopovers. Waterbirds 37:162-174.

Veit, R., and W. Petersen. 1993. *Birds of Massachusetts*. Massachusetts Audubon Society, Lincoln, MA, USA.

Venables, W., and B. Ripley. 2002. Modern Applied Statistics with S. Fourth edition. Springer, New York, New York.

Verkuil, Y. I., J. J. Wijmenga, J. C. E. W. Hooijmeijer and T. Piersma. 2010. Spring migration of Ruffs *Philomachus pugnax* in Fryslân: estimates of staging duration using resighting data. Ardea 98: 21-33.

Virzi, T. and J. L. Lockwood. 2010. Conservation of American Oystercatchers in New Jersey. Unpublished report. Unpublished report, Rutgers, New Brunswick, New Jersey.

Wakeling, J. M., and J. Hodgson. 1992. Short communication optimisation of the flight speed of the Little, Common, and Sandwich Tern. Journal of Experimental Biology 169:261-266.

Wanless, S., M. P. Harris, and J. A. Morris. 1988. The effect of radio transmitters on the behavior of Common Murres and Razorbills during chick rearing. Condor 90:816-823.

Warnock, N. 2010. Stopping vs. staging: the difference between a hop and a jump. Journal of Avian Biology 41:621-626.

Warnock, N., and J. Y. Takekawa. 2003. Use of radio telemetry in studies of shorebirds: past contributions and future directions. Wader Study Group Bulletin 100:138-150.

Watson, M. J., and J. J. Hatch. 1999. Differences in foraging performance between juvenile and adult Roseate Terns at a pre-migratory staging area. Waterbirds 22:463-465.

Weimerskirch, H., M. L. Corre, F. Marsac, C. Barbraud, O. Tostain, and O. Chastel. 2006. Postbreeding movements of frigatebirds tracked with satellite telemetry. Condor 108:220-225.

Wheeler, W. E. 1991. Suture and glue attachment of radio transmitters on ducks. Journal of Field Ornithology 62:271-278.

Whidden, S. E., C. T. Williams, A. R. Breton, and C. L. Buck. 2007. Effects of transmitters on the reproductive success of Tufted Puffins. Journal of Field Ornithology 78:206-212.

White, G. and R. Garrott. 1990. Analysis of wildlife radio-tracking data. Academic Press, San Diego, California.

Whittier, J. B., and D. M. Leslie. 2005. Efficacy of using radio transmitters to monitor Least Tern chicks. Wilson Bulletin 117:85-91.

Wiggins, D.A. and R.D. Morris. 1987. Parental care of the Common Tern *Sterna hirundo*. Ibis 129: 533-540.

Wilson, R. P., and C. R. McMahon. 2006. Measuring devices on wild animals: what constitutes acceptable practice? Frontiers in Ecology and the Environment 4:147-154.

Wilson, R. P., and M.-P. T. Wilson. 1989. A peck activity record for birds fitted with devices. Journal of Field Ornithology 60:104-108.

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.

Woodworth, B. K., C. M. Francis, and P. D. Taylor. 2014. Inland flights of young Red-eyed Vireos *Vireo olivaceus* in relation to survival and habitat in a coastal stopover landscape. Journal of Avian Biology 45:387-395.

Worton, B. J. 1989. Kernel methods for estimating the utilization distribution in home-range studies. Ecology 70: 164-168.

Zar, J. H. 1999. Biostatistical Analysis. Fourth edition. Prentice Hall, Upper Saddle River, New Jersey, USA.