November 2018

NOT GONE WITH THE WIND: Addressing Effects of Offshore Wind Development on Bat Species in the Northeastern United States

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Recommended Citation

Dowling, Zara Rae, "NOT GONE WITH THE WIND: Addressing Effects of Offshore Wind Development on Bat Species in the Northeastern United States" (2018). *Doctoral Dissertations*. 1427.
https://scholarworks.umass.edu/dissertations_2/1427

NOT GONE WITH THE WIND: ADDRESSING EFFECTS OF OFFSHORE WIND DEVELOPMENT ON BAT SPECIES IN THE NORTHEASTERN UNITED STATES

A Dissertation Presented

by

ZARA RAE DOWLING

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

DOCTOR OF PHILOSOPHY

September 2018

Environmental Conservation

NOT GONE WITH THE WIND:
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DEDICATION

This dissertation is dedicated to my grandparents, Vincent and Evelyn Dowling, who respect the value of education, and who kept asking when I was going to come chase animals in Downeast Maine.

ACKNOWLEDGMENTS

A dissertation has the potential to become a solitary and isolating pursuit. I was lucky throughout this process to work with a multitude of smart, caring, conscientious, and hard-working people, who made this project a collaborative activity. This dissertation benefitted from their labor, cooperation, advice and support, for which I am indebted to them, and incredibly grateful.

First, thank you to my dissertation committee, my advisor Paul Sievert, co-advisor Elizabeth Dumont, and members Dwayne Breger and Jonathan Reichard. I greatly appreciate all your help, advice, and guidance over the course of my graduate program.

I have also benefitted enormously from the support, academic and otherwise, I have received from the faculty, staff, and students in the UMass Department of Environmental Conservation and IGERT Offshore Wind Program. Particular thanks are due to Jennifer Smetzer for teaching me about telemetry station deployment (many times over until I understood it!), for introductions to other researchers in the field, and for assistance with data analysis far above and beyond the call of duty. Many thanks also to Pam Loring for logistical and field support, as well as equipment loans, and to Blake Massey for willing help with R analysis. Thank you to Yahya Modarres-Sadeghi, Dan Carlson, and Sheila Werth of the Department of Mechanical and Industrial Engineering, for the opportunity to collaborate across disciplines on bat deterrent research. Thank you also to Michael Smotherman of Texas A & M University, for generous hospitality, support and collaboration regarding bat deterrents.

To Bruce and Judy Connery, thank you for extensive research support, not to mention taking me into your home, for fresh garden cucumbers, dinners left to re-heat on the top of the microwave, and not minding 4 AM wake-up calls when I drove in late and disturbed the dogs. Thank you to the Acadia Wildlife crew, especially Bik Wheeler, Chris Heilakka, Cori Michaud, Lara Katz, Erickson Smith, and Kevin Miller, for endless mist-net re-shuffling, traffic control, late nights, late night snacks, and bad jokes. Thank you to all of the fine staff at Acadia National Park and the Schoodic Institute, including Abe Miller-Rushing and Emma Albee.

Thank you to the Biodiversity Research Institute, especially Dave Yates, for taking me along batting when I didn't know a thing, and showing me the ropes. Thank you to BRI staff, including Carl Anderson, Robby Lambert, Morgan Ingalls, Caroline Byrne, Mandy Bailey and Jen Bonta, for cooperative mist-netting, cards, and conversation, well into the wee hours. Thank you to Stantec Consulting, Inc, especially Trevor Peterson, Steve Pelletier, Lindsey Wight, and Joel Perkins, for your generosity, providing a wealth of guidance, collaboration, ideas, and equipment loans.

Thank you to BiodiversityWorks staff and volunteers, especially Luanne Johnson and Liz Baldwin, for the opportunity to work closely together, and to get to see a little of the island through your eyes. Thanks to Danielle O'Dell, Karen Beattie, and the rest of the Nantucket Conservation Foundation staff for your enthusiasm, an incredible amount of work, chauffeur services, and a continuing spirit of discovery.

Thank you to Nancy Pau, Katlyn Hojnacki, and David Tibbetts, of the Parker River National Wildlife Refuge for the opportunity to collaborate, as well as logistical and field support. Thank you to Linda Welch, Sara Williams, and the rest of the Maine Coastal Islands National Wildlife Refuge staff for logistical and field support, advice, and assistance. Thank you to Susan von Oettingen of the U.S. Fish & Wildlife for guidance and support.

Thank you to Ian Trefry and Matt Thyng of the U.S. Navy, and my cousin Kevin Dowling, for support in erecting a telemetry station at the Cutler Navy Base. Thank you to Nancy Sferra, Dan Grenier, Kyle Pinjuv, and other Nature Conservancy staff, for intrepidly trekking out to Great Wass Island to set up a telemetry station at the site. Great thanks are due to Dan DeDanto, Toby Stephenson, Chris Tremblay, and Tanya Lubansky, of College of the Atlantic and Allied Whale, for supporting deployment of a telemetry station on Mt. Desert Rock (and in Dan's case, doing most of the work!). Thank you to Paul Elias, Michelle Losert, Naushon Trust staff, Cuttyhunk Historical Society, and the U.S. Coast Guard for making it possible to deploy a telemetry station on Naushon Island. Thanks also to Brett Still, Derek Triunfo, and Clara Cooper-Mullin for telemetry station deployment on Martha's Vineyard.

I am very grateful to all the land-owning organizations and individuals who allowed me to work on their property, including Kathy Gardner, Penny Thrush, the Dowling family, the Smith family, and in addition to those organizations already mentioned, the Blue Hill Land Trust, the Sheriff's Meadow Foundation, and Mass Audubon.

To my parents, Phil Dowling and Hilary Nolan, thank you for hauling equipment for miles over rugged terrain, help deploying telemetry stations, and in general for humoring your crazy daughter over the last thirty-odd years. To my sister and brother, Tessa and Luke Dowling, for likewise allowing yourselves to be dragged along on dubious expeditions, including telemetry station assembly and deployment. To Ida

Weiss, thank you for your ever-ready enthusiasm and able assistance. To Layla Hazen and Chris Trevethan, thank you for mist-netting help, as well as Wallace Stevens readings and other entertainment during the slow night hours.

A final big thank you to all of my friends and family, and the goats, and the chickens, and the kitten, for distraction from this dissertation when I needed it.

Financial support came from the NSF-sponsored IGERT: Offshore Wind Energy Engineering, Environmental Science, and Policy, from the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy, the Bureau of Ocean Energy Management, the Eastern Maine Conservation Initiative, the Schoodic Institute, the Nantucket Biodiversity Inititiave, the National Park Service, and the UMass Graduate School, with additional equipment contributions from the UMass Coop Unit, the U.S. Fish & Wildlife Service, MassWildlife, and Stantec Consulting, Inc.

ABSTRACT

NOT GONE WITH THE WIND: ADDRESSING EFFECTS OF OFFSHORE WIND DEVELOPMENT ON BAT SPECIES IN THE NORTHEASTERN UNITED STATES

SEPTEMBER 2018

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Development of coastal and offshore wind energy resources has the potential to add considerable renewable electricity capacity to the United States electrical grid, but could have detrimental impacts on wildlife. Land-based wind energy facilities are estimated to kill hundreds of thousands of bats every year in the United States, and could threaten population viability of some species. Little is known about the potential impacts of offshore wind development on bat populations along the North Atlantic coast, but a number of species are known to frequent marine islands or fly over the ocean during migration. This dissertation helps to characterize risks of offshore wind development to bats through increasing our knowledge of bat habitat use and behavior in the coastal and offshore environments of the northeastern United States. Chapter I provides a general introduction to the topics of offshore wind energy development and bat mortality at wind energy facilities. Chapter II details the first scientific survey of bat use of the offshore island of Nantucket, Massachusetts, with a focus on the federally threatened Northern Long-eared Bat. Chapter III describes bat flight behavior on and around the offshore

island of Martha’s Vineyard, Massachusetts. Chapter IV explores the fall migratory behavior of eastern red and hoary bats radio-tagged at sites along the New England coast and tracked using an extensive network of automated telemetry stations. In Chapter V, I estimate the economic costs of curtailment as a bat fatality minimization option for a set of theoretical offshore wind energy facilities located at sites along the Eastern Seaboard.

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CHAPTER I

GENERAL INTRODUCTION

The threat that offshore wind energy poses to North American bats is at present largely theoretical. That is to say, there is only one offshore wind energy facility currently in operation off the coast of the United States or Canada – a 30-megawatt (MW) farm off of Block Island, Rhode Island. However, the anticipated scale of development of offshore wind in North America is quite expansive, and the resultant effects on bat populations could be significant. The Bureau of Ocean Energy Management has established eleven leases for offshore wind development in federal waters along the East Coast of the United States (2018). Within the Northeast, over 4,000 MW of offshore wind capacity are currently proposed for development off the coast of Massachusetts, and companies are contemplating plans for development of over 1,000 MW off of Long Island, New York (New York ISO 2017b, ISO New England 2018). Recent legislative initiatives are providing the financial stability and market demand necessary to fund increasing development of this energy resource. The Massachusetts legislature has instructed electrical utilities within the state to contract with generators for development of 1,600 MW of offshore wind capacity (Act to Promote Energy Diversity 2016), while New York has committed to installing 2,400 MW of offshore wind by 2030 (New York State Energy Research and Development Authoirty 2018), and Maine has set a goal of 5,000 MW of offshore wind by 2030 (Act to Implement the Recommendations of the Governor's Ocean Energy Task Force of 2010, M.P.L. ch. 615). Overall, at least 352,000 MW of capacity are estimated to be available off the New England coast, with an additional 74,000 MW available off of New York (Musial et al. 2016).

Energy generated from the wind, whether in the onshore or offshore environment, is commonly considered an environmentally-friendly alternative to energy sourced from greenhouse gas-emitting fossil fuels. However, wind energy development can have negative impacts on wildlife, including bats (Government Accountability Office 2005). Hundreds of thousands of bats are killed in collisions with wind turbine blades at land-based facilities in the United States every year (Arnett & Baerwald 2013, Hayes 2013, Smallwood 2013). In North America, mortality is heavily skewed towards long-distance migratory tree bat species, including the hoary bat (*Lasiurus cinereus*), eastern red bat (*L. borealis*), and silver-haired bat (*Lasionycteris noctivagans*) (Arnett et al. 2008). Surveys for carcasses under turbines have demonstrated that fatalities tend to peak during the late summer and fall, when these migrants are moving southward (Arnett et al. 2008). While precise population counts of long-distance migrants cannot be easily collected (O’Shea & Bogan 2003, Schorr et al. 2014), population parameter estimates based on expert opinion and data from related species can provide estimates of the population-level consequences of wind-associated mortality. These sources suggest that mortality at wind facilities could drastically reduce populations of the hoary bat, decrease population viability, and increase the risk of extinction; other long-distance migrants may be at similar risk (Frick et al. 2017).

In the northeastern United States, a number of hibernating bat species have already experienced dramatic population declines, in part associated with disturbance of hibernation sites, and over the last decade due to the spread of the fungal disease known as White-Nose Syndrome (WNS) (Turner et al. 2011). Median abundances for the six cave-hibernating bat species that occur in the Northeast have declined by 60-98% since the introduction of WNS; the disease has resulted in local extinctions at 6-69% hibernation sites, depending on the species (Frick et al. 2015). These now-rare populations are vulnerable to any additional sources of mortality, including mortality at wind facilities (Arnett et al. 2008). Population models of the endangered Indiana bat (*Myotis sodalis*) suggest that loss of individuals to wind energy is low relative to WNS, but wind mortality could reduce connectivity and eliminate smaller sub-populations (Erickson et al. 2016). It is clear that wind energy development has potential population-scale consequences for all bat species that occur in the northeastern United States.

What risks might offshore wind development pose to bat populations? Bats are not typically thought of as ocean-going animals. However, a number of species that occur in the Northeast have been known to travel significant distances (>50 km) to hibernation sites or to southern wintering grounds (Griffin 1945, Davis & Hitchcock 1965, Cryan et al. 2003, Neubaum et al. 2006, Norquay et al. 2013, Fraser et al. 2012), and these travels could include over-water movements. Long-distance migratory species are suspected of using coastal routes during migration (Johnson et al. 2011b), and both anecdotal and acoustic data provide evidence of significant coastal and offshore activity (Hatch et al. 2013, Peterson et al. 2014, Sjollema et al. 2014, Smith & McWilliams 2016). Less is known about offshore movements of regional migrants which hibernate in the northeastern United States, but these species are commonly recorded at coastal sites and on offshore islands (Peterson et al. 2014). If regional migrants move between coastal and offshore summering grounds and inland hibernacula, they could also be at risk from offshore wind development.

Given the dearth of information about bats in marine environments, research is warranted to better characterize bat behavior offshore, and to evaluate what risks offshore wind development may pose to populations of bat species. The most efficient way to collect data from a conservation perspective is to focus on answering questions which can help inform known strategies to minimize risk to bats. At this point in time, specific methods for reducing bat mortality in the offshore environment have not yet been developed. In terrestrial situations, however, researchers have proposed a number of approaches to reducing the risk of bat mortality at wind energy facilities. These strategies fall into three general categories, as follows:

1) Siting – Location of wind facilities away from major bat flyways and habitat.
2) Curtailment – Stoppage of rotor motion during specific weather conditions and times of year when bat activity and mortality at wind facilities are expected to be high.
3) Deterrents – Devices mounted on wind turbines to warn bats away from blades.

Siting - In the eastern United States, high bat mortality rates have been documented in the Appalachian region, including at facilities in Tennessee and Pennsylvania (Arnett et al. 2008), relative to sites elsewhere. Baerwald and Barclay (2009) found higher mortality in the foothills of the Rocky Mountains in Canada, compared to Great Plains sites where roosting opportunities were scarce. In general, bats are thought to follow linear features in the landscape when foraging and migrating, such as forest edges, mountain ridgelines, rivers (Serra-Cobo et al. 2000, Furmankiewicz & Kucharska 2009), and coastlines (Johnson et al. 2011b), but specific travel corridors remain largely unknown. The U.S. Fish &Wildlife Service Land-Based Wind Energy Voluntary Guidelines (2012) recommend acoustic surveys pre-construction to document patterns of bat activity, but acknowledge that pre-construction acoustic activity cannot be satisfactorily linked to post-construction mortality. Acoustic data can therefore aid in identification of any protected species present in an area, but are not currently of great use in siting facilities to avoid sites with high bat activity.

Curtailment - The use of curtailment is predicated on the idea that bat mortality can be predicted and, hence, avoided. Bat mortality is expected to be non-random, given that metrics of bat activity are often significantly associated with meteorological variables (e.g. Ciechanowski et al. 2007, Baerwald & Barclay 2011, Wolcott & Vulinec 2012). Bats tend to be active on low-wind speed (<6 m/s) nights, during weather conditions related to the passage of storm fronts (Arnett et al. 2008). Bats showed mixed, but significant, responses to other weather variables, including temperature, moon illumination and barometric pressure changes, depending on the location and species (Arnett et al. 2008). In cooler weather, they tend to be active on nights with relatively warm temperatures (>10ºC) (Arnett et al. 2008). Incorporating multiple meteorological variables leads to better fitting models of bat activity, and is expected to lead to more efficient curtailment practices (Weller & Baldwin 2012). However, curtailment studies to date have focused on simple curtailment regimes, specifically reducing turbine operation at low wind speeds during the fall migration season (Baerwald et al. 2009, Arnett et al. 2011). Several curtailment studies have raised the cut-in speed, the minimum speed at which turbines begin to produce power, from 3.5 m/s to 5.0-6.5 m/s, or have adjusted turbine blade angles to “feather” the blades during low wind speeds. These alterations have the effect of raising the wind speed at which blades begin to rotate, and has been associated with a decrease in mortality of 44-93% (Baerwald et al. 2009, Arnett et al. 2011). These operational adjustments are not favored by wind developers since they do lead to lower energy production. However, curtailment is a requirement at some New England wind facilities during the active season for bats on warm-temperature, low-wind nights (Maine Department of Inland Fisheries & Wildlife 2013, Vermont Agency of Natural Resources 2016), and has also been proposed as a strategy to minimize mortality under the draft Midwest Habitat Conservation Plan, wherever protected species or the little brown bat are present (U.S. Fish & Wildlife Service 2016b).

Deterrents- An effective deterrent has not yet been developed for wind turbines, but efforts are underway to design an ultrasonic device that would warn bats away from turbine blades. The only device tested thus far *in situ* was an ultrasonic white-noise generator, powered by electricity and mounted on the turbine nacelle (Arnett et al. 2013a). The sound intensity of the device was not adequate to extend the full length of the turbine blades, and its large size precluded mounting the device on the blades themselves. In addition, the device suffered from weather damage and associated power failures. Perhaps due to these issues, the device did not significantly reduce bat mortality at turbines (Arnett et al. 2013a). Researchers are currently working to improve the device. Nicholls and Racey (2009) proposed that radar was capable of producing avoidance behavior by bats at foraging grounds, and could offer an alternative approach to deterrence. This strategy has not been thoroughly explored.

In this dissertation, I address a number of the gaps in our knowledge regarding coastal and offshore bat activity, with the goal of evaluating the level of risk offshore wind development could pose to bat populations, and ultimately informing siting and curtailment approaches to minimize risk to bats. I explore bat use of coastal and offshore habitats, spatially and temporally, and characterize movements of radio-tagged individuals. I also examine the economic costs associated with curtailment for bats at offshore wind sites

As part of my graduate work, I also collaborated with colleagues in the UMass Department of Mechanical, Industrial, and Electrical Engineering on several projects related to development of bat deterrent devices for wind turbines. Our main work has focused on development of an ultrasonic whistle that could be mounted along turbine blades, and blown by the wind to generate sound mechanically. Due to the engineering focus of this work, I have played a secondary role in the research, and it is not included in this dissertation. I also conducted a pilot experiment in conjunction with colleagues in Electrical Engineering to test the effects of radar as a deterrent to bats commuting to foraging areas near a known roost site, but we observed no reaction to the radar device.

Following this general introduction, each succeeding chapter is treated as a stand-alone paper with an abstract, an introduction pertinent to the topic, a description of methods used to address the research question, results, and discussion. The subsequent chapters are ordered and formatted as follows:

- Chapter II describes bat use of the offshore island of Nantucket, with an emphasis on the threatened northern long-eared bat (*Myotis septentrionalis*). It is formatted as a research article for submission to the *Northeastern Naturalist*.
- Chapter III considers bat movements on and around the island of Martha's Vineyard, through the use of coded radio-tags and automated telemetry data. It is formatted as a technical report to the Bureau of Ocean Energy Management.
- Chapter IV examines coastal and offshore movements of migratory bats during fall migration, through the use of coded radio-tags and an extensive array of automated telemetry stations. It is formatted as a research article for submission to the *Journal of Wildlife Management*.
- Chapter V focuses on output of a model to estimate economic costs of curtailment regimes designed to reduce bat mortality. It is formatted as a letter for submission to *Conservation Letters*.

CHAPTER II

BAT USE OF AN ISLAND OFF THE COAST OF MASSACHUSETTS

Abstract

Nantucket, Massachusetts, could provide unique habitat for bats, but few data are available regarding bat populations on the island. We conducted passive acoustic surveys in 2015 and 2016 to inventory bat species and identify seasonal activity patterns. We detected at least 6 species of bats on Nantucket. *Lasiurus cinereus* (Hoary Bat) and *Lasionycteris noctivagans* (Silver-haired Bat) were detected as probable migrants, while *Lasiurus borealis* (Eastern Red Bat), *Eptesicus fuscus* (Big Brown Bat), and *Myotis* species were also present in summer. *Perimyotis subflavus* (Tricolored Bat) was detected in fall and early winter, suggesting the species may hibernate on-island. In 2016, we mist-netted and radio-tagged *Myotis septentrionalis* (Northern Long-eared Bat), and documented individuals reproducing and hibernating on Nantucket. Given the persistence of this rare species on the island, we suggest land conservation organizations should consider maintenance of mature forest stands in management activities.

Introduction

There is growing concern regarding conservation of bat populations in temperate North America. This is due in large part to the devastating impact of the fungal disease known as White-nose Syndrome (WNS) on cave-hibernating bats (e.g. Frick et al. 2010, Turner et al. 2011), as well as the population-level threat mortality at wind energy facilities could pose to long-distance migratory tree bats (Arnett and Baerwald 2013, Frick et al. 2017, Hayes et al. 2013). Three cave-hibernating bat species, *Myotis septentrionalis* Trouessart (Northern Long-eared Bat), *Myotis lucifugus* Le Conte (Little Brown Bat), and *Perimyotis subflavus* Cuvier (Tricolored Bat), are now listed as endangered in the state of Massachusetts (MA NHESP 2017) due to population reductions of greater than 90% associated with WNS (Turner et al. 2011); the Northern Long-eared Bat has also been designated as federally threatened under the Endangered Species Act (U.S. Fish & Wildlife Service 2016a). In addition, three long-distance migratory tree bats, *Lasiurus cinereus* de Beauvois (Hoary Bat), *Lasiurus borealis* Muller (Eastern Red Bat), and *Lasionycteris noctivagans* Le Conte (Silver-haired Bat), are listed as Species of Greatest Conservation Need in Massachusetts (MA NHESP 2015).

One major challenge in bat conservation is a lack of knowledge about bat populations and their distribution across the landscape (O’Shea and Bogan 2003). Relatively little is known about bat use of coastal areas and offshore islands in the Northeast, but these environments can offer unique habitat to bats. Bat surveys conducted on Martha’s Vineyard and Cape Cod, Massachusetts detected large numbers of Northern Long-eared Bats prior to the outbreak of WNS (Buresch 1999, Kelly and Ciaranca 2000). Recent surveys on Martha’s Vineyard from 2014-2016 found that capture rates of Northern Long-eared Bats were lower than pre-WNS surveys, but healthy maternity colonies were still documented producing pups (Baldwin et al. 2017). This contrasts with sharp declines at many inland sites in the Northeast, where the species is now rarely found (Ford et al. 2011, Francl et al. 2012). The offshore island of Nantucket, Massachusetts could also be providing habitat for persistent populations of Northern

Long-eared Bats, but only anecdotal information is available regarding historic bat populations.

Long-distance migratory tree bats frequent coastal areas, and will often utilize islands as stopover habitat during their fall migration (Miller 1897; Peterson et al. 2014, 2016; Smith and McWilliams 2016), roosting temporarily in lighthouses and other sites (Cryan and Brown 2007, Johnson et al. 2011b). Specimens of all 3 long-distance migratory tree bat species have been collected on Nantucket in August and September (Maria Mitchell Association 2017), and Eastern Red Bats were captured on nearby Tuckernuck Island (Veit 2012). If migratory bats are passing through Nantucket as part of their fall migration route, it will be important to consider risks to bats associated with large-scale offshore wind energy development planned for federal waters southwest of the island (BOEM 2017).

The goals of this study were to 1) inventory bat species present on Nantucket using passive acoustic monitoring, 2) characterize the seasonal use of Nantucket by these species as migrants or summer residents, and 3) if present, determine if Northern Long-eared Bats were reproducing or hibernating on the island.

Methods

Acoustic detector deployment

The island of Nantucket, Massachusetts (120 km^2) is situated 43 km south of Cape Cod, and 15 km east of Martha’s Vineyard, another offshore island. Between 2015 and 2016, we deployed passive acoustic detector stations at 15 locations on Nantucket (Fig. 2.1). Sites were selected oportunistically in areas we deemed potential bat habitat, including forest corridors (trails, wood roads) and beside wetlands. From April to mid-November 2015, we deployed 8 stations at 4 localities, with the 2 stations at each locality at least 100 m apart, which represented non-overlapping detection radii (Table 2.1). In mid-August, 1 station was moved from the Squam Farm site to Gibbs Pond, in order to sample a broader range of sites. In 2016, we deployed 8 stations at more widely-dispersed localities between April and December (Table 2.1). Each station consisted of an Anabat II acoustic detector (Titley Scientific, www.titley-scientific.com) set in a PVC junction box, with the microphone pointed downward into a PVC elbow. We used a frequency division ratio of 16 and a sensitivity level of 6-7. All units were powered by a 12-volt battery charged by a small solar panel. Detectors were mounted 1–3 m above the ground, either hung from a tree, a shrub, or two poles set in the ground. Detectors operated between 6:00 PM and 8:00 AM every night. Stations were checked periodically throughout the season to download data and ensure proper operation.

Bat call identification

We followed U.S. Fish & Wildlife Service Indiana Bat Survey Guidelines (2017) in identifying bat calls; first, we processed probable bat call files through two auto-classification software systems, then manually examined candidate calls as identified by the software, and finally consulted with experts in the field, as appropriate. With the exception of data collected at the Ram Pasture station, all files were viewed manually using AnalookW 4.1 software prior to auto-classification. We used manual identification as a first pass to differentiate noise files from probable bat call files that contained at least two pulses. Files containing probable bat calls were then analyzed using both EchoClass

V3.1 (U.S. Army Engineer R and D Center 2015) and KaleidoscopePro (Wildlife Acoustics Inc. 2015). The Ram Pasture station generated over 58,000 files, therefore we did not manually pre-screen files at this site before running them through the auto-classification software. Data from nights with an average of 100 files per hour or higher (>1400 files per night) were ignored during analysis; we found they contained few to no bat calls, and were associated with either high average wind speeds (>8 m/s) when bats were unlikely to be active, or showed evidence of device malfunction and mechanical noise. At Ram Pasture, the busiest site, true spikes in bat activity led to averages of ~70 call files per hour, but never exceeded 100 call files per hour.

Bat call files were run through EchoClass using the Species Set 2 list, which includes the 9 bat species known to occur in Massachusetts currently [*Eptesicus fuscus* de Beauvois (Big Brown Bat), *M. leibii* Audubon and Bachman (Eastern Small-footed Bat), Eastern Red Bat, Hoary Bat, Little Brown Bat, Northern Long-eared Bat, Silver-haired Bat, Tricolored Bat] or historically [*Myotis sodalis* Miller and Allen (Indiana Bat)]. EchoClass returns a maximum likelihood estimate indicating the probability that the presence of a species at a site on a given night was falsely identified, therefore a low *P*-value indicates a species is likely present at the site. Bat call files were also analyzed using KaleidoscopePro, with the software set to the “0 Balanced” (Neutral) setting, and the Massachusetts region selected for the same 9 bat species. KaleidoscopePro also provides a maximum likelihood estimator describing the probability that a species was misidentified at a site, based on how many detections of each bat the classifier found, and a confusion matrix representing how likely a species was to be mis-identified. Both auto-classification programs were approved by the U.S. Fish and Wildlife Service for identification of Indiana and Northern Long-eared Bats in zero-cross acoustic data.

As a final step, we viewed and qualitatively vetted calls identified by EchoClass and KaleidoscopePro using comparisons with established keys (Humboldt State University 2011, Keinath 2011) and reference call libraries. At a minimum, we required the following conditions for positive identification: Hoary Bats – calls a minimum frequency of <22 kHz; Eastern Red Bats - a minimum frequency between 32–42 kHz which varied 1–2 kHz across pulses; Tricolored Bats - a minimum frequency of 38–42 kHz, with consistency across pulses and a strong constant-frequency component; Eastern Small-footed Bats- a minimum frequency of >45 kHz; other *Myotis* species - a minimum frequency of 38–42 kHz, best distinguished by the slope of the call, with some overlap, probable Northern Long-eared Bats - slope >200 octaves per second (Johnson et al. 2011a), potential Little Brown or Indiana Bat - calls with a slope <200 octaves per second; Big Brown or Silver-haired Bat - minimum frequency ~25 kHz, with flat calls of ~25–30 kHz diagnostic of Silver-haired Bats.

We manually vetted at least one call per station-night per species, as identified by KaleidoscopePro. We also vetted all calls identified by the auto-classification programs as Big Brown Bat, Tricolored Bat, Eastern Small-footed Bat, or Indiana Bat, since these calls were relatively few in number. We shared selected examples of identified calls of each bat species with experts with a greater proficiency and experience in identifying bat calls.

Seasonal variation in detections

We categorized sampling nights into five seasons: spring migration (April 15-May 31), maternity period (June 1-July 15), volancy period (July 16-August 15), fall migration (August 16-November 15), late season (November 16-December 15). These five seasons roughly reflected regional patterns of behavior of cave-hibernating and migratory bats in terms of timing of migration, pup volancy, and hibernation (e.g., Burns et al. 2014, Davis and Hitchcock 1965, Dowling et al. 2017, Kunz et al. 1998, Peterson et al. 2016, Townsend et al. 2008). We evaluated seasonal variation in detection rates in two ways. First, for each season, we summed the number of nights bats were detected for each station-year, and divided by the total number of sampling nights during that station-year, to obtain a detection probability. We used ANOVA (R Core Team 2017, package:aov) to test the effect of season on probability of detection for all bat calls combined, and separately for *Myotis* spp., Eastern Red Bats, Hoary Bats, Silver-haired Bats, Big Brown Bats, and Tricolored Bats, as identified by KaleidoscopePro. We used Tukey's HSD to evaluate differences among categories within season.

Second, we qualitatively assessed seasonal activity patterns based on call identifications confirmed through manual vetting. Differentiation between the calls of Big Brown Bats and Silver-haired Bats is challenging (Betts 1998); therefore, we only classified a call as from a Silver-haired Bat when a flat call was present in the appropriate frequency range. We shared clear examples of calls auto-classified as Big Brown Bat with multiple experts, in order to determine if the species was present in each season. Differentiating among *Myotis* spp. is also prone to error (Britzke et al. 2013), therefore we pooled detections of all four *Myotis* spp. The majority of *Myotis* calls detected were steep in slope (>200 octaves per second), suggesting they were from Northern Long-eared Bats.

Bat capture and tagging

We mist-netted potential travel corridors and wetland areas on 3 nights in the spring (29 April, 30 April and 2 May 2016 at Squam Farm), 2 nights in the summer (19 July at Squam Farm, 20 July at Ram Pasture), and 2 nights in the fall (30 October at Ram Pasture, 31 October at Lost Farm), using 38 mm mist nets. Each night we deployed 1 triple-high mist net set-up (3 stacked nets, each 4 m across x 2.6 m high, total height ~6.5 m) and 2–4 single-high mist nets (1 net, 4 or 6 m across x 2.6 m high). In addition, on 1 November, we hand-captured bats roosting at an identified roost site in a crawl space. We only operated mist nets in conditions with low wind and no precipitation, although temperatures fell below preferred conditions of ≥10°C during spring and fall trapping. Captured bats were identified to species, sexed, weighed, and measured along the forearm. We aged bats based on wing joint ossification, but could not differentiate young-of-the-year from adult bats during fall trapping. We attached Lotek NTQB-1 (0.29 g) coded radio-tags to bats using animal ID tag cement (Nasco), after shaving a small area of fur between the scapulae. Radio-tags operated on a single frequency, and emitted a signal every 4.7 seconds 24 hours per day, for an estimated battery life of about 3 weeks (Lotek Wireless, www.lotek.com). To reduce the likelihood of negative effects from tagging, all transmitters were <5% of bat body weight (Aldridge and Brigham 1988). Bat capture and handling efforts were conducted under MassWildlife Scientific Collection Permit # 181.16SCM and University of Massachusetts-Amherst IACUC

Protocol Sievert 2015-0009, and followed American Society of Mammalogists standards (Sikes and Gannon 2011). Mist nets were only used on Nantucket, and all gear was treated in accordance with National WNS Decontamination Protocols (U.S. Fish & Wildlife Service 2012, 2016c) to minimize the likelihood of spreading WNS.

Bat tracking and roost monitoring

We manually tracked tagged bats to roost sites using a Lotek SRX-800 receiver, and recorded roost characteristics. When possible, emergence counts were conducted from shortly before sunset to an hour after sunset. Manual tracking was conducted until bats dropped tags or battery life of the tags expired. We tracked one bat to a crawl space roost site, where we conducted visual surveys of the site on 31 October 2016, 8 November 2016, and 24 February 2017, and used a Maxim Integrated iButton 1-wire Hygrochron to record temperature and humidity at the site through the winter. Movements of bats roosting in the crawl space were monitored from 2 November to 10 December 2016 with the use of an automated telemetry station erected on a balcony at a house ~85 m from the roost. The station consisted of an omni-directional antenna connected to a sensorgnome receiver (www.sensorgnome.org) that continuously monitored for radio-tags 24 hours per day. During this time period, there were 3 other automated telemetry stations on Nantucket, and 12 automated telemetry stations on Cape Cod, deployed as part of the Motus Wildlife Tracking System (Taylor et al. 2017), which could have detected coastal or off-island movements by tagged bats. In the summer, we calculated the number of days tracked based on manual tracking to roost locations and roost emergence. In the fall, we calculated the number of days tracked based on visual inspection at the crawl space, and variation in signal strength as detected via automated telemetry. Manual tracking was used to confirm radio-tag presence at the crawl space, but since bats did not emerge on most nights, we could not differentiate between tags on torpid bats and dropped tags using this method.

Results

Acoustic detector deployment

Acoustic detectors were deployed at station locations for 80 to 198 nights between late April and mid-November 2015, and 37 to 224 nights between early May and mid-December 2016. Detector malfunction and ambient noise led to some missed nights, but most detector stations functioned for the majority of their deployment. We successfully recorded during 51–100% of nights deployed (Table 2.1). Data were recorded for a total of 2,120 detector-nights.

Bat species presence

A total of 58,231 files were collected at the Ram Pasture site; 5,670 were identifed to species using the EchoClass software. At the other stations, where calls were reviewed manually prior to analysis, a total of 13,518 files were identified as probable bat calls, 727 of which were identified to species using EchoClass software. EchoClass software estimated that 8 of 9 bat species found in Massachusetts were likely present on at least 1 station on Nantucket ($P < 0.05$) (Table 2.2). The exception was the Eastern Small-footed Bat, for which individual call sequences were only identified at the Ram Pasture site in 2016. Eastern Red Bats were the most commonly detected species, identified as present ($P < 0.05$) in 13 of 17 station-years surveyed, with individual call sequences recorded at 2 other stations. Northern Long-eared Bats were identified as present ($P < 0.05$) at the Ram Pasture and Lost Farm stations in 2016.

KaleidoscopePro software identified 11,856 calls to species at the Ram Pasture station, and 2,401 calls at the other stations combined. KaleidoscopePro software determined all 9 bat species found in Massachusetts were present on at least 1 station on Nantucket ($P < 0.05$) (Table 2.3). Eastern Red Bats were again the most commonly identified bat species, with their presence identified ($P < 0.05$) in 16 of 17 station-years. The Eastern Small-footed Bat, which was not detected by EchoClass software, was identified ($P < 0.05$) at 4 stations. The Northern Long-eared Bat was identified at 8 stations ($P < 0.05$).

Manual vetting confirmed the presence of Northern Long-eared Bats, Eastern Red Bats, Hoary Bats, Silver-haired Bats, Tricolored Bats, and Big Brown Bats on Nantucket. There is significant overlap in the parameters differentiating calls of *Myotis* species, and expert review did not identify any candidate calls as definitive evidence of Little Brown Bats, Indiana Bats, or Eastern Small-footed Bats.

Seasonal variation in detection rates

Probable bat calls were detected from 30 April through 11 November 2015 and 2 May to 12 December 2016. Bats were present on 19–84% of nights surveyed at each station, with lower detection rates during late fall (Fig. 2.2). We demonstrated a significant effect of season on likelihood of bat detection ($F_{(4,54)} = 2.81$, $P = 0.034$), with detection rates significantly lower on nights in the late season compared to the volancy period ($P_{adj} = 0.013$). There was no effect of season on likelihood of detection ($P > 0.05$) of any individual species or *Myotis* spp. as identified by KaleidoscopePro. This was likely due to low identification rates by the auto-classification software, resulting in low detection rates for species at most stations across all seasons.

Based on manual vetting, *Myotis* spp. were present from 30 April–21 October 2015, and on most warm nights between 2 May–26 November 2016, with particularly high detection rates at the Ram Pasture and Lost Farm sites in 2016. Tricolored Bats were detected on 29 July 2016, on several isolated nights in September and October 2015, and on 8–9 November 2016; a final call was recorded 12 December 2016 at the Lost Farm site, following an unseasonably warm day (high of 12°C, 7°C at dusk). Manual vetting also confirmed that Eastern Red Bats were widespread, and were recorded frequently every month from 15 May–15 November 2015 and 2 May–27 November 2016. Hoary Bat calls were primarily recorded during the migration seasons (2015: 9–29 May, 9 August– 13 October; 2016: 12 August–25 September), but there were isolated detections during the maternity period in June 2015 and early July 2016. Silver-haired Bats in 2015 were detected from 27 October–5 November, with two distinct peaks (27 August–1 September, and 14–16 September), whereas in 2016, Silver-haired Bats were detected from 26 July–30 October with no peaks in activity. There were several confirmed calls in June.

Bat capture, tagging, and tracking

We caught a total of 13 bats on Nantucket in 2016, all of which were Northern Long-eared Bats (Table 2.4). We captured 9 bats in 2.25 hours of trapping on 20 July

2016 at Ram Pasture, and radio-tagged 3 lactating females. Two tagged bats were re-located for 2 days each, before dropping their tags. One tagged bat utilized a roost at a private residence ~1.9 km from the capture site on 22 July and 23 July, where it appeared to be roosting on the side of a house under a trim board. A second bat was tracked to a Pitch Pine snag ~200 m from the capture site in a pine stand on 21 July. That evening, 11 bats were observed emerging from a long crack in the tree. On 22 July, the bat was tracked to a second roost in a live Pitch Pine ~130 m from the first tree and ~140 m from the capture site. Two observers saw 9 and 20 bats respectively in the vicinity of the tree on the night of 22 July, but the emergence location could not be identified.

We captured and tagged one male Northern Long-eared Bat in 2 hours of trapping on 30 October 2016 at Ram Pasture. This bat was tracked to a crawl space beneath a house located ~2.4 km from the capture site, where it was found roosting in association with 4 other Northern Long-eared Bats in narrow (~1 cm) cracks between wooden sistered floor joists. On 1 November, we hand-captured and radio-tagged 1 additional male and 2 female Northern Long-eared Bats roosting in the crawl space (Table 2.4). Radio-tags remained on all 4 bats at least through 8 November, when bats were observed in the crawl space, torpid and unresponsive. Three of the 4 tagged bats were also intermittently recorded by the nearby automated telemetry station, with variation in signal strength demonstrating tags remained on these bats for at least 12-24 days after tagging. Manual tracking further indicated tags of all 4 bats were located in the crawl space through the end of radio-tag battery life on 8 December, and no tagged bats were recorded by coastal or off-island telemetry stations. Based on variations in signal strength recorded by the local automated telemetry station, bats were active in the evening hours (16:00-19:00) following relatively warm days in early-mid November, but it was not clear if bats were simply changing positions within the roost or making short forays outside. No bats exited the roost during an emergence survey on one warm (>10°C) evening (3 November). The crawl space was open to the outside via a ~0.6 x 1.0 m hole which was closed on 27 November, but small (~2 cm wide) cracks along boards covering basement window holes remained, providing potential points of egress. On 24 February 2017, a researcher re-entered the crawl space and found one torpid Northern Long-eared Bat with no visible signs suggestive of WNS. Relative humidity within the crawl space remained above 85% throughout the hibernation season (15 November 2016 to 15 April 2017), and recorded temperatures remained between 6.5–15°C (Fig. 2.3). The crawl space was warmed by water pipes running beneath the house, and the dirt floor may have helped maintain humid conditions.

Discussion

Species presence

This is the first inventory of bat species on Nantucket. Using acoustic detection, we documented the presence of 3 long-distance migratory tree bat species at multiple locations on the island. These 3 species were previously collected on Nantucket during the spring and fall in the 1950-1970s (Maria Mitchell Association 2017), and existing evidence suggests these migratory species use coastal and island areas along the Eastern Seaboard during migration (Cryan and Brown 2007; Johnson et al. 2011b; Peterson et al. 2014, 2016; Sjollema et al. 2014; Smith and McWilliams 2016). We detected Silver-haired and Hoary Bats primarily during the spring and fall migration seasons, but Eastern

Red Bats were detected frequently throughout the active season from early May to late November. Previous studies describe peaks of migratory activity in which high capture rates in mist-nets, bats roosting in visible numbers, or high numbers of calls, indicate waves of migration, possibly associated with favorable weather conditions (e.g. Cryan 2003; Cryan and Brown 2007; Divoll 2012; McGuire et al. 2012; Peterson et al. 2014, 2016). We observed qualitative evidence for this behavior in 2015 among Silver-haired Bats, with peaks of activity that spanned multiple sites from 27 August–1 September, and again 14–19 September. We did not observe similar peaks of activity in 2016 among Silver-haired Bats, or among Hoary Bats or Eastern Red Bats in either year. The presence of Eastern Red Bats during the maternity and volancy periods suggests they could be forming maternity colonies on the island. Cryan (2003) documented both sexes moving into New England in the summer based on analysis of museum specimen collections, and the species has been recorded in inland Massachusetts during summer (Brooks 2011).

Through acoustics, we also documented the presence of *Myotis* species on Nantucket, including the federally-threatened Northern Long-eared Bat. Auto-classification software identified Little Brown Bats, Indiana Bats and Eastern Small-footed Bats as present at multiple sites on the island, but in the manual vetting process we did not identify any definitive calls of these species. The last known observation of the Indiana Bat in Massachusetts was in 1939 (MA NHESP 2012). The historic summer range of this species is poorly known, but there are no records from southeastern Massachusetts (Thomson 1982); formerly, the species was known to hibernate at sites in Berkshire and Hampden counties (MA NHESP 2012). Further mist-netting efforts may reveal whether other *Myotis* spp. are present on Nantucket. We also recorded Big Brown

Bats and Tricolored Bats on Nantucket. The final acoustic detection of a Tricolored Bat was in mid-December, which indicates this species may over-winter on Nantucket.

Northern Long-eared Bats

Northern Long-eared Bats appear to be successfully reproducing and hibernating on the island. We captured 9 Northern Long-eared Bats in summer 2016, and 4 Northern Long-eared Bats in the fall. Bats captured in July included both lactating females and volant juveniles of both sexes. Based on emergence counts, the maternity colony we identified comprised at least 11 individuals, and may have included 20 or more. Capture rates at the Ram Pasture site were high compared to other locations in the Northeast, with 4.0 Northern Long-eared Bats per hour in July, and 0.5 per hour in October. Acoustic activity suggests Northern Long-eared Bats are present at the capture site through much of the active season, from early May into early December. At other stations on the island, Northern Long-eared Bats were also detected from when acoustic detectors were first deployed in late April through early December.

In the fall, Northern Long-eared Bats captured at a hibernation site in a crawl space included males and females of comparable weight to Little Brown Bats entering hibernation in the pre-WNS era (7.2–9.0 g) (Johnson et al. 1998, Kunz et al. 1998). Although bats appeared torpid during an inspection of the hibernaculum on 8 November, automated tracking data suggests bats were intermittently active within the hibernaculum on seasonably warm evenings through mid-November. Final automated detections were 12–24 days after tagging, but the tags were manually detected in the hibernation site through early December, presumably through the end of tag battery life. Conditions within the hibernation site fell within the range suitable for hibernating *Myotis* spp. (Brack 2007, Johnson et al. 2016, Thomas and Cloutier 1992, Webb et al. 1996). The relatively mild temperatures could promote the growth of *Pseudogymnoascus destructans* Gargus (White-nose Fungus), which grows optimally at 12.5-15.8°C (Verant et al. 2012); however, there were no visible signs of the disease on the bat we observed in the hibernaculum on 24 February 2017. The continued presence of Northern Long-eared Bats on Nantucket and at other coastal locations could indicate ecological, genetic, or behavioral differences between coastal and inland populations are allowing these populations to persist in the face of WNS; alternatively, relative geographic isolation could be merely be slowing the spread of WNS to these areas. If coastal areas are serving as refugia from WNS, persistent populations in these areas could be a focus for conservation of cave-hibernating bats.

Northern Long-eared Bats traditionally are considered “deep forest” bats that forage in habitats with a high level of vegetative clutter and roost in trees. However, they also utilize man-made structures as roost sites where natural roost habitat is limited (Henderson and Broders 2008). On Martha’s Vineyard, 36% of Northern Long-eared Bat summer roosts were in human structures (Baldwin et al. 2017), and bats were often found roosting under rakeboards on houses, where trim boards intersected with shingles below the roof line. On Cape Cod, Northern Long-eared Bats used primarily human structures as roost sites (Curry 2016). We found bats utilizing both house and tree roosts during the maternity period. Given the common use of cedar shingles as siding on houses on Nantucket, there may be a profusion of man-made roosts on the island which mimic natural roosts and are acceptable to this species. Both tree roosts we documented were in

Pitch Pines, including one cavity roost in a pine snag, a common roost type in pine-dominated forests (Perry and Thill 2007). Measured characteristics of maternity roosting behavior were within the range of those documented in other studies. Colony sizes of 10–30 individuals are thought to be typical, and females in maternity colonies switch roosts on average every two days (Silvis et al. 2016).

Even within our small sample, we documented high variability in distances bats traveled (several hundred meters to 1.9 km) between the point of capture, and maternity roost sites, with the latter distance exceeding the maximum recorded distance for a female bat from capture site to maternity roost on Martha's Vineyard (Dowling et al. 2017). Average capture site-to-roost distances recorded for Northern Long-eared Bats are <0.7 km, although longer range distances have been reported in the literature (2.7 km) (Silvis et al. 2016). In the Yukon, Randall et al. (2014) found that female Little Brown Bats commuted longer distances to foraging areas than males of the species, and hypothesized this was due to limited roost habitat appropriate for maternity colonies.

It is uncertain whether natural roost habitat is limited for Northern Long-eared Bats on Nantucket, but the island has relatively few stands of mature trees and only 12% forest cover (The Nature Conservancy 1998). In this respect, Nantucket represents a fairly unique habitat for this species. Numerous studies have documented a preference among Northern Long-eared Bats for large tracts of intact forest for foraging and roosting. While these bats are known to occur in forests under a variety of management and cutting regimes (e.g. Menzel et al. 2002; Owen et al. 2001, 2003; Perry et al. 2007), they avoid clear cuts (Owen et al. 2004, Patriquin and Barclay 2003), are uncommon in open landscapes (Henderson and Broders 2008, Owen et al. 2003), and are less likely to occur in fragmented forest stands (Henderson et al. 2008, Morris et al. 2010, Yates and Muzika 2006). We detected widespread occurrence (8 of 15 stations) of Northern Long-eared Bats on Nantucket, including where the predominant vegetation was scrub oak < 6 m tall. However, our acoustic sampling was somewhat opportunistic and focused on areas we deemed potential bat habitat; all sites where Northern Long-eared Bats were identified were within ~500 m of a forested stand. Both sites that had consistently high detection rates of Northern Long-eared Bats (Ram Pasture and Lost Farm) were located adjacent to mature stands of Pitch Pine.

If Northern Long-eared Bats on Nantucket do rely on mature forest patches for roosting or foraging habitat, this could have significant management implications for land conservation organizations. The island has been the focus of extensive efforts to restore and preserve coastal sandplain grassland, heathland and scrubland. Cutting, mowing, prescribed burns, and grazing have all been used as management tools to conserve species that rely on early successional habitats (Omand et al. 2014, Zuckerberg and Vickery 2006). While some consider these efforts a maintenance of the natural landscape, the Cape and Islands region was likely originally dominated by forests of pine, oak, and hardwoods, which were lost following European colonization (Foster and Motzkin 2003). Foster and Motzkin (2003) argue that this history does not invalidate the current biological and cultural value of early successional habitats, but note management should be conducted with clear policy objectives in mind, as well as an understanding of the ecological history. Populations of woodland species are in general increasing across the Northeast; nevertheless, the regional decline of the Northern Long-eared Bat and other forest bats necessitates consideration of these species in management planning in places where they persist. Further research is warranted to determine whether management of protected lands in the Cape and Islands region should include maintenance of hardwood and pine forest patches for Northern Long-eared Bats.

Acknowledgments

The Nantucket Biodiversity Initiative provided funding for travel and equipment for this project. Zara Dowling's time was supported in part by the NSF-sponsored IGERT Offshore Wind Energy Engineering, Environmental Science and Policy Program (Grant Number 1068864). Stantec Consulting, Inc. donated use of ANABAT detectors for both years of acoustic monitoring. Jonathan Reichard and Susi von Oettingen of the U.S. Fish & Wildlife Service provided NanoTags, and tracking equipment, as well as helpful advice. Thanks to Karen Beattie for logistical, institutional, and field support. Thanks to BiodiversityWorks for the loan of single-high mist-netting poles, and to Eileen McGourty of U.S. Fish & Wildlife Service for the use of temperature and humidity dataloggers. Many thanks to Trevor Peterson, Samantha Hoff, and Carl Herzog for providing expert review of selected echolocation calls. Thank you to Paul Sievert, two anonymous reviewers, and the editor, for their careful reading of the manuscript, and helpful comments and suggestions.

CHAPTER III

FLIGHT ACTIVITY AND OFFSHORE MOVEMENTS OF NANOTAGGED BATS ON MARTHA'S VINEYARD, MA

Abstract

The northern long-eared bat (*Myotis septentrionalis*) was listed as threatened under the federal Endangered Species Act in 2016, following dramatic population declines associated with the spread of the fungal disease known as White-Nose Syndrome (WNS). However, the species continues to persist in the Cape and Islands region of Massachusetts, including Martha's Vineyard. Southern New England waters are likely to be an area of increasing offshore wind development in the coming decades, but the potential threat this development may pose to northern long-eared bats and other bat species remains largely unknown. In 2016, we conducted an automated telemetry study of northern long-eared bats on Martha's Vineyard to monitor flight activity and document any offshore movements.

We tracked four northern long-eared bats for 5-12 nights in July 2016 in our northwest Vineyard study area, and one northern long-eared bat for 39 nights in October 2016. BiodiversityWorks also tagged and manually tracked three northern long-eared bats on other parts of the island in July and August 2016. Our sample size was small, due to low capture rates for this species. In this sample, we did not record any offshore movements by northern long-eared bats. To supplement our data for northern long-eared bats, we also tagged and tracked three little brown bats (*Myotis lucifugus*), two big brown bats (*Eptesicus fuscus*), and three eastern red bats (*Lasiurus borealis*) captured on the

island. We detected offshore movements by little brown bats and eastern red bats during the study period, suggesting our automated telemetry network was adequate to detect offshore movements by tagged individuals. Among these detections was the migration of the congeneric little brown bat from Martha's Vineyard in late August. Although northern long-eared bats are capable of accessing the offshore environment during the summer months, our data, as well as data from the literature, indicate they are unlikely to forage over federal waters during the maternity period (June to mid-July). Our data also strongly suggest that some northern long-eared bats are over-wintering on the island, but this does not preclude the possibility that other individuals of this species may migrate to inland hibernacula. Further study is warranted to determine whether northern long-eared bats are making offshore movements, particularly during late summer and early fall when little brown bats appear to depart the island. Unfortunately, research efforts may be hindered by low capture rates, likely associated with the spread of WNS.

Background

The northern long-eared bat (*Myotis septentrionalis*) is a small insectivorous vespertilionid, with a wide distribution across much of the eastern United States and Canada, northwest to British Columbia and the Northwest Territories, west to eastern Montana and Wyoming, and south to Alabama, Georgia, and the Florida Panhandle (Arroyo & Alvarez 2008). The northern long-eared bat was listed as threatened under the federal Endangered Species Act (ESA) in 2016, due to dramatic population declines associated with the spread of the fungal disease known as White-Nose Syndrome (WNS) (U.S. Fish & Widlife Service 2016). The species is also state-listed as Endangered in

Massachusetts, Maine, and New Hampshire. Northern long-eared bat counts have declined by as much as 95-99% at WNS-affected hibernacula in the Northeast (Turner et al. 2011), and echolocation calls of these species have decreased in their summer range (Brooks et al. 2011, Ford et al. 2011). At these low densities, there is concern that additional loss of individuals -whether through mortality at wind energy facilities, disturbance of hibernacula, or other causes - could affect local population viability.

Large numbers of bats are killed in collisions with wind turbine blades in the United States every year (Hayes 2013). Northern long-eared bats and other hibernating species typically represent only a small fraction of fatalities (Arnett et al. 2008). However, recent analyses suggest mortality associated with wind facilities could have population-scale consequences for the federally endangered Indiana bat (*M. sodalis*) across its range (Erickson et al. 2016), and it is possible that related species, including the northern long-eared bat, face similar risks. Incidental take of northern long-eared bats at wind energy facilities is regulated by a 4(d) rule under the federal ESA (U.S. Fish & Wildlife Service 2016a).

As wind energy development expands into the offshore environment, the question arises of whether offshore development poses a risk to the northern long-eared bat, as well as other bat species. Bats are not traditionally thought of as ocean-going animals, but there is a long anecdotal history of bat sightings off the East Coast (Hatch et al. 2013, Peterson et al. 2014), and bats are known to utilize temporary roost sites on lighthouses and other structures on offshore islands (Miller 1897, Cryan & Brown 2007, Johnson et al. 2011b). It is most often long-distance migratory bats that have been observed offshore, but *Myotis* spp. were documented in acoustic surveys 2.8-11.5 km off the coasts of New

Jersey and the mid-Atlantic states (Sjollema et al. 2014). Recent acoustic monitoring efforts in the Gulf of Maine detected *Myotis* spp. on eight of nine forested islands surveyed, and on two tree-less rocks located 33 and 42 km from the mainland (Peterson et al. 2014). Overall, hibernating species (*Myotis* spp., *Eptesicus fuscus*, and *Perimyotis subflavus*) were present on 20% of nights surveyed at offshore sites in the Gulf of Maine in the late summer and fall (Omland et al. 2013). There is also a report from 2003 of a flock of *Myotis* bats roosting on a fishing boat 110 km from shore in the Gulf of Maine in late summer (Thompson et al. 2015). The Environmental Impact Statement for the proposed Cape Wind offshore wind facility in Nantucket Sound notes that big brown bats, tricolored bats, little brown bats, and northern long-eared bats must all at least occasionally make over-ocean movements, since they are known to occur on Martha’s Vineyard (Mineral Management Service 2009).

In Scandinavia, bats, including *Myotis* species, have been observed foraging over the ocean, feeding on insects, and even gaffing prey from the water’s surface (Ahlen et al. 2009). Bats will forage in the vicinity of offshore wind facilities, and even attempt to roost in turbine nacelles (Ahlen et al. 2009). In North America, we know very little about the offshore behavior of *Myotis* species. It is not clear whether *Myotis* species routinely forage over the ocean during the active season, or in the fall, if hibernating bats on islands move to mainland hibernacula. Certainly, little brown bats (*M. lucifugus*) are capable of making long-distance movements (>500 km) to hibernation sites (Norquay et al. 2013). Movements of northern long-eared bats are less studied. Migratory distances traveled by northern long-eared bats are estimated to range 8-270 km (Griffin 1945). One individual banded at a cave in April was observed at a house roost 56 km away in May of the same year; this was interpreted as a movement from a winter hibernaculum to a summer territory (Caire et al. 1979). Recent genetic analyses suggest northern long-eared bats may be comparable to little brown bats in terms of dispersal and population mixing. In Canada, population-level genetic structuring was similar between little brown bats and northern long-eared bats, and structure was not related to geography (Johnson et al. 2015). Analyses of nuclear DNA at swarming sites did not reveal isolation by distance for northern long-eared bats over the distances examined (up to 309 km) (Johnson et al. 2015). Johnson et al. (2014) found that groups of northern long-eared bats in New York and West Virginia were genetically indistinguishable at multiple spatial scales.

Within the WNS-affected zone, northern long-eared bats appear to be persisting in some coastal areas, including the Cape and Island region of Massachusetts, and Long Island, New York. In 2014, a pilot mist-netting survey on Martha's Vineyard by BiodiversityWorks and the U.S. Fish & Wildlife Service (USFWS) resulted in capture of five northern long-eared bats in nine nights (0.56 bats/night). By contrast, Buresch (1999) documented average capture rates of 1.4-4.2 northern long-eared bats per night in mesic and oak woodlands on the island in 1997-1998. Bat biologists speculated that persistent coastal populations could be hibernating locally, rather than migrating to large inland hibernation sites already infected with WNS.

The continuing presence of northern long-eared bats on Martha’s Vineyard offered a unique opportunity to study offshore movements of this rare bat, as well as a chance to learn more about habitat use of persistent northern long-eared bat populations in the face of WNS. In 2015, we assisted local non-profit BiodiversityWorks in a study of northern long-eared bat roosting ecology on the island, identifying maternity colonies, roost trees, and roosting home ranges. Eleven northern long-eared bats were captured and tracked to day roosts between May and September as part of the BiodiversityWorks project. Subsequently, The Bureau of Ocean Energy Management (BOEM) funded the acquisition, installation and removal of three automated telemetry stations, and part-time funding for one year for a researcher to complete this study. In 2016, this funding allowed us to use automated radio-receiving towers and coded transmitters to document activity patterns of tagged bats on Martha's Vineyard, and to detect any offshore movements by bats during the active season. We report here on the results of automated telemetry tracking, and provide context with results of manual tracking, roosting behavior, and acoustic detections, where they are of relevance to bat flight activity. In addition, we report on detections of other tagged bats and birds recorded by the Vineyard and Naushon Island automated telemetry stations in 2016. This study is a collaboration among the USFWS, University of Massachusetts Amherst, the USGS Cooperative Units of Virginia Tech and UMass, and BiodiversityWorks.

Methods

Bat capture and radio-tag deployment

Bat capture work was conducted collaboratively among the USFWS, University of Massachusetts Amherst, and BiodiversityWorks. Bats were captured using single, double, and triple high set-ups of 2.6, 4, 6, 9, and 12 m mist nets strung across woods roads, trails, wetland areas, and adjacent to identified roost sites on Martha's Vineyard, MA. Trap stations consisted of 2-5 mist-net set-ups, with trapping conducted at a given location for 1-3 nights in succession (almost always 2), from near sunset until 3-5 hours post-sunset, depending on trapping success and weather conditions. On cold and windy nights, nets were occasionally closed earlier (e.g. after 1.5 hours).

All bats were handled in accordance with American Society of Mammalogists standards (Sikes & Gannon 2011). Bats were identified to species, aged as adult or juvenile based on ossification of the wing bones, sexed, and weighed. For a subset of captured bats, a small area was shaved between the scapulae, and a radio-tag was attached using eyelash adhesive. Radio-tags were Lotek NTQB-1 (0.29 g) or NTQB-2 (0.35 g) NanoTag series coded units, with burst intervals of 6.7-19.9 seconds and operating lives of 24-71 days (www.lotek.com). To reduce risk to bats, no transmitter constituted greater than 5% of bat body weight (Aldridge & Brigham 1988). All gear was treated in accordance with USFWS National White-Nose Syndrome Decontamination Protocols (2012, 2016c).

Manual tracking

Tagged bats were tracked manually to day roost sites using a Lotek SRX-800 receiver, which allows for differentiation among coded NanoTags. Tracking was conducted until bats dropped tags or battery life of the tags expired. BiodiversityWorks conducted the majority of manual tracking as part of a separately-funded roost study, the results of which will be available from this organization.

Automated tracking

We utilized NanoTags deployed within the Motus network to track bat movements. NanoTags are coded radio-transmitters operating on a single frequency; in combination with automated radiotelemetry stations, they allow for the simultaneous, long-distance tracking of thousands of individual birds, bats, and large insects. The Motus network consists of over 100 automated telemetry stations in the U.S. and Canada, stretching along the East Coast from Nova Scotia south to Florida, and inland at sites along the Great Lakes, the Connecticut River, and portions of the Midwest (Taylor et al. 2017). Stations consist of yagi or omni-directional antennae, deployed on buildings, lighthouses, pop-up masts, or sectional towers; the antennae are attached via BNC cables to radio receivers, which continuously monitor for NanoTags transmitting at a single frequency. Stations typically are built in one of two styles, either a "Motus-style" arrangement of 3 9-element yagi antennae oriented horizontally on a pop-up mast and connected to a hand-built sensorgnome receiver (www.sensorgnome.org), or a "Lotek-style" arrangement, consisting of 6 9-element yagi antennae oriented horizontally on a sectional tower and connected to a Lotek SRX series receiver (http://www.lotek.com). BOEM funded the purchase and installation of three Lotek-style stations, which were deployed on the coast at Cedar Tree Neck sanctuary (Sheriff's Meadow Foundation property) and at the Nature Conservancy's Hoft Farm Preserve about 1.7 km from the coast, both on Martha's Vineyard, as well as at a coastal site on Naushon Island (Table 3.1). We also deployed a Motus-style station at a coastal site at Sheriff's Meadow Foundation's Goethals sanctuary on Martha's Vineyard, funded by a Martha's Vineyard Vision Fellowship grant to BiodiversityWorks.

Interpretation of automated telemetry data

The Motus network returns data from automated telemetry stations indicating station location, antenna bearing, NanoTag ID number, timestamp, and signal strength of detections of registered NanoTags. Detection power is strongest along the direct beam of a receiving antenna, and falls off to either side of that bearing, such that for the antennae used at our stations, detection power drops below 50% beyond 22.5° to either side of the antenna bearing. The antenna also has some detection power behind the antenna, but this is limited in our antennae by a high front/back ratio for power of detection. Thus, for a station with six equally-spaced antennae, there are six regions of relatively high detection power directly in line with each antenna, and six 15° gaps between each pair of antennae where detection power falls below 50%. Of course, for radio signals transmitted immediately adjacent to the telemetry station, power of detection is high, and there are likely to be no gaps in detection. Conversely, for radio signals transmitted far from the telemetry station, power of detection may be below 50% at all antennae, even if the signal is directly in line with the antenna bearing.

The power of detection of a radio transmission within an antenna beam is sensitive to altitude of the radiotransmitter relative to the ground, orientation of the radiotransmitter antenna in space, noise in the frequency range of interest, topography, other obstructions to signal transmission (such as trees), and additional factors. Previous studies have documented detection ranges of up to 12 km for migrating passerines (Mills et al. 2011, Smetzer et al. 2017, in review), and near-simultaneous detections have been recorded at stations 50 km apart for migrating eastern red bats (unpublished data), indicating a maximum detection range of at least 25 km. However, detection range is expected to be significantly lower for bats foraging at low height above ground, especially under forest canopy. Northern long-eared bats tagged in the vicinity of a "Motus-style" telemetry station at Great Bay NWR were detected ~75% of the time by the near station (~100m from the capture site), but only intermittently recorded by a station 2 km away (Nancy Pau, personal communication), suggesting detection range is significantly lower than 12 km for this species during foraging. Birds at ground level outfitted with NanoTags can typically be detected within 0.5-2 km of an automated telemetry station (Taylor et al. 2011). Bat roost sites in houses, tree crevices, and under bark may dampen radio signals relative to bird roosting sites, further decreasing signal detection range during roosting.

In general, we can assume that detections with higher signal strength are likely to represent a radiotransmitter at greater height above ground level, more directly within the center of an antenna beam, and/or closer to the telemetry station where detection occurred. Research efforts funded by BOEM and others are underway to model predicted radiotransmitter location and movement pathways based on signal strength, biangulation between antennae, and other factors. Unfortunately, currently available models are highly simplistic and have error ranges of ~3 km (Jen Smetzer, personal communication). These models are useful for considering long-distance movement pathways of migrating animals, but cannot be practically applied to foraging and roosting bats if detection distance falls below three km. Further, these models are sensitive to input factors including height above ground and the orientation of the radiotransmitter antenna in space. We know little about foraging heights for northern long-eared bats, beyond the fact that they are often captured in mist-nets deployed 0-8 m above ground height, and based on morphology, are unlikely to forage in open spaces above the canopy. In addition, we would expect that antenna orientation would change frequently as bats make multiple foraging passes through an area.

For the purposes of analysis of northern long-eared bat activity, we report roosting and foraging detections by antenna sector, with the assumption that detections by a single antenna likely indicate presence of the bat in a beam within 30° to either side of an antenna bearing, and more likely within 22.5°. Unlike sensorgnome receivers, Lotek receivers cannot provide simultaneous detections from multiple antennae. In our system, Lotek receivers cycled through each of six antennae in turn, "listening" at each antenna for 20.5 seconds. Hence, consecutive detections within a < 3 min period by antennae on a single telemetry station approximate a simultaneous detection. Where there are consecutive detections by more than one antenna, we average signal strength over a 3 min period and assume the bat was within the antenna sector which showed the highest average signal strength. In these cases, the bat is likely closer to the station than at other times, and might more easily pass between adjacent antenna sectors over a short time period while foraging.

Acoustic data

To increase our chances of successful bat capture, we deployed SM3BAT acoustic detectors for periods of 1-8 nights at potential trapping sites in the summer and fall, with length of deployment dependent on weather conditions, trap site needs, and convenience. We analyzed the full spectrum data collected by these detectors using KaliedoscopePro, which includes auto-classification software to identify bat echolocation calls. Because auto-classification is prone to error, especially in discriminating among members of the *Myotis* genus, we grouped all *Myotis* recordings together, rather than considering only calls identified as northern long-eared bats. BiodiversityWorks collaborated to deploy acoustic detectors and conduct analyses of results. We include results of this analysis where it is deemed relevant to the study questions.

Nantucket research

As part of a separate pilot study conducted in concert with UMass, the USFWS, and Nantucket Conservation Foundation, we deployed NanoTags on seven northern long-eared bats on the nearby island of Nantucket in 2016. We report on results of this study as well, insofar as they relate to the question of offshore movements.

Results

Year 2015

The information provided for 2015 is included as background for efforts conducted in 2016 under this agreement.

Bat capture and tagging

In 2015, we trapped for a total of 19 nights in foraging habitats, and six nights at known bat roost locations (based on visual observation of bats or fresh guano). We captured a total of 20 bats, including 12 northern long-eared bats (MYSE), five big brown bats (*Eptesicus fuscus*, EPFU), two little brown bats (MYLU), and one eastern red bat (*Lasiurus borealis*, LABO). The capture rate for free-ranging MYSE at flight corridor locations (not roost sites) was 0.26 bats per night. We tagged the 11 adult MYSE captured. Eight female MYSE were tagged in late May or June during the maternity period, when females are pregnant or lactating, one MYSE was tagged in late July during the volancy period, when juveniles are flying, and two were tagged in September, during the time period when we suspected MYSE would move to hibernation sites.

Manual and automated tracking

All eight bats tagged during the maternity period were captured in the northwest part of Martha’s Vineyard, in the vicinity of Hoft Farm, and roosted in that vicinity until the tag dropped off the animal (4-17 days) (Table 3.2). In July, the lone bat tagged was captured at Job’s Neck in the south-central part of the island, and also roosted in the same vicinity for three days following capture until its tag was recovered in the State Forest, approximately 3 km north. The two bats captured in September were tracked to roosts in the same vicinity for 15 and 17 days following capture.

In 2015, there were no operational telemetry stations on the island. During this time, the closest telemetry stations were at Waquoit Bay on the south shore of Cape Cod, on Noman’s Island southwest of Martha’s Vineyard, on Muskeget Island, east of the Vineyard, and at Eel Point on the western shore of Nantucket, also to the east of the Vineyard (Figure 3.1). None of these telemetry stations recorded detections of the tagged bats.

Year 2016

Telemetry station deployment

In 2016, we erected three automated telemetry stations on the northwest part of Martha’s Vineyard, at the Hoft Farm, Goethals Sanctuary, and Cedar Tree Neck Sanctuary. We also deployed a station on neighboring Naushon Island, 6.5 km to the north of the Cedar Tree Neck station (Figure 3.2). The three Lotek-style stations had a technical issue which was resolved for the Hoft and Cedar Tree Neck stations on July 6. These stations functioned through the remainder of the season until they were dismantled on November 26 and November 28 respectively, except for a period from October 10 to 25, and again from October 26 to 29, when the Cedar Tree Neck station was non-functional, apparently due to a problem with the software in the receiver. The Naushon station continued to have technical issues through July 21, but then functioned through the remainder of the season until it was dismantled on December 4. As in 2015, a number of other telemetry stations were on-line throughout the Cape and Islands region (Figure 3.1), as well as along the Atlantic coast, from Nova Scotia as far south as Florida, and in inland Massachusetts along the Connecticut River.

Bat capture and tagging

Between June 14 and November 3, we trapped for a total of 43 nights in foraging habitats, and nine nights at roost sites. We conducted 20 nights of mist-netting between mid-June and mid-July, 17 of which were at sites in the northwest Vineyard study area adjacent to telemetry stations. We trapped for four nights in late July and six in August, of which three nights each were in the northwest Vineyard study area. We trapped for two nights in September, outside of the study area. Because the two MYSE tagged in 2015 did not make obvious movements towards a hibernaculum in September, we focused our 2016 migration period efforts in October, trapping for 16 nights during that month, 14 of which we spent at sites within the northwest Vineyard study area. On other nights in October, we were not able to trap, due to cold temperatures, rain, or windy conditions, which rendered capture unlikely or potentially hazardous to bats.

We captured a total of 56 bats in 2016, including 13 MYSE, four MYLU, 30 EPFU, and nine LABO. Five MYSE females were captured at a house roost 0.69 km from the Hoft station on July 6; we tagged four of these individuals (Table 3.3), the fifth escaped the net during capture. In mid-July, we captured three adult female MYSE and three juveniles at a house roost on the eastern side of the island, 6.69 km from the Hoft station. Because this was outside the area covered by our telemetry stations, we only tagged two of the adults. We also tagged one adult female captured in the south-central part of the island in late August, 9.06 km from the Hoft station. Finally, in October, we tagged an adult MYSE female within the northwest study area. The capture site was 1.62 km from the Cedar Tree Neck station, 4.82 km from the Goethals station, and 6.11 km from the Hoft station.

Due to low capture numbers of MYSE during the maternity period, we decided to expand our tagging to other hibernating species within the northwest Vineyard study area. In July and August, we tagged three MYLU roosting in a barn 1.54 km from the Cedar Tree Neck station and 5.95 km from the Hoft station. In October, we tagged three EPFU, two near the Hoft station (0.31 km from station) and one near the Cedar Tree Neck station (0.67 km from station). As part of a separate project, we also tagged three LABO, one near the Hoft station (0.31 km), and two near the Cedar Tree Neck station (0.67 km), in October.

In summary, we tagged a total of 17 bats, including 8 MYSE (Table 3.3). Fourteen bats were tagged in the northwest study area within the vicinity of our telemetry stations; three MYSE were tagged on other parts of the island. The capture rate for MYSE in corridor settings (not roost sites) was 0.05 MYSE per night.

Manual and automated tracking

Northern Long-eared Bats

Tagged MYSE were manually tracked daily to roost sites through the life of the tag, or until the tag fell off the bat. In July, BiodiversityWorks tracked the four tagged MYSE to the house maternity roost where they were captured, or to additional tree or house roosts within 0.75 km of the capture site and 1.34 km of the Hoft station (Table 3.4). Tags remained on the bats for 5-12 days following capture. The four tagged northern long-eared bats were only detected by the closest automated station, the Hoft station located 0.69 km from their capture location (Table 3.4). None of these bats were detected by any of the coastal stations including the Goethals station, which was less than 2.6 km from any identified roost (Figure 3.2).

These bats were only intermittently detected while roosting, and only detected at the RT09 roost site (Table 3.5), which was the closest roost to the Hoft station (0.69 km away). They were never detected during daylight hours at other roost sites 0.84-1.42 km away from station. The RT09 roost was at a bearing of 37.5° from the Hoft station. Bats were detected in the roost by the Hoft 2 antenna, bearing 55°, but not by antennae with bearings of 355° or 115°.

Given that we never detected these northern long-eared bats at the Goethals station (2-2.8 km from roosts), and did not consistently detect bats exiting roosts within 1.5 km of the Hoft station, our data suggests detection distance was typically less than 2 km, even when the bats were in flight. These bats were likely foraging under the canopy, where tree cover obstructed signal transmission.

When our tagged northern long-eared bats were detected by the Hoft station, they were primarily detected within the range of the Hoft 2 antenna (Figure 3.3). MYSE 277 was only recorded by this antenna. MYSE 279 was briefly recorded by antenna 1 on July 13, with signal strength higher at this antenna than the preceding detection at antenna 2, suggesting the bat was foraging into Hoft antenna sector 1. MYSE 284 was briefly detected by antenna 5 on July 10, but signal strength was higher at antenna 2, suggesting it remained in the antenna 2 sector. MYSE 280 was frequently detected by multiple antennae consecutively on the nights of July 7 and 8, which indicates it was likely foraging closer to the Hoft telemetry station than other tagged bats, although it also could have been flying higher than the other northern long-eared bats tracked. Variation in the sector with highest signal strength across consecutive detections suggests it flew through multiple sectors over the course of both evenings.

In October, MYSE 281 was tracked to a series of tree roosts located 40-150 m from her capture site, for 39 days following capture. This bat was not detected by any automated telemetry stations. The three MYSE tagged outside of the northwest Vineyard study area were also not detected by automated stations.

Little Brown Bats

Due to low capture rates for northern long-eared bats, we attached NanoTags to three little brown bats, but because little brown bats were not the focal species for our roost study, we did not track little brown bats to their roost every day. However, BiodiversityWorks re-visited the barn roost where the bats were initially captured to determine if they were still roosting on site.

Following capture of MYLU 276 on July 19, the bat was manually detected at the barn roost site during daylight hours on July 21 and 26 (Table 3.6). MYLU 276 was not detected by the local automated stations we deployed, but was detected briefly on the night of July 27 by the telemetry station on Noman's Island, 19 km to the southwest (Table 3.6). Signal strength was low for this detection, but it is likely the bat travelled at least as far as the southern part of Martha's Vineyard to be detected by this station. On August 4, the tag had dropped off the bat and was found at the barn roost site.

Following the capture of MYLU 278 and MYLU 286 on August 15 at the barn roost, the barn was re-visited on August 18, 21, 24, 29, 31, and September 6 (Table 3.6). On August 29 and 31, there was no longer a signal for MYLU 286, but MYLU 278 was still detected at the roost. On September 6, there was no signal from either bat. Between August 15-September 6, MYLU 278 was detected on one night by the Hoft station, six nights by the Cedar Tree Neck station, and five separate nights by the Naushon station (Figure 3.4). Between August 19 at 23:02 and August 23 at 20:29, there were no detections of this bat by Vineyard stations, but the bat was picked up by the Naushon station every night. There were near simultaneous detections (1.5 minutes apart) for this bat between the Naushon south-bearing antenna and Hoft south-bearing and south-southwest bearing antenna on August 23. Signal strength was slightly higher for the Hoft station (54 versus 52 dB). There were again near simultaneous detections (1.5 minutes apart) for this bat between the Cedar Tree Neck east-southeast-bearing antenna and the Naushon south-bearing antenna on August 31. Average signal strength was slightly higher at Naushon (56 dB versus 49 dB). The final night of detection for this bat was September 1 by the Cedar Tree Neck station, for the west-northwest-bearing antenna, which suggests the bat may have departed the island at this time. It was not recorded at the barn roost on the subsequent visit (September 6), but was also not detected by off-island stations. Between August 15-August 25, MYLU 286 was detected on four nights by Cedar Tree Neck and five nights by the Hoft station (Figure 3.4). On the night of August 25, the final night of detection by Hoft, she departed the island. She was next detected in the early hours of August 26 by an automated telemetry station in Falmouth, and ~3:15 in the morning by a station in Wellfleet on the eastern side of Cape Cod (Table 3.7).

Big Brown Bats

The EPFU captured at Hoft Farm in October were tracked daily to roost sites from October 22-30, and were again tracked on November 8 (Table 3.6). Throughout this time period, each bat remained in a single roost. EPFU 275 was located in a house roost 0.55 km from the capture site and 0.84 km from the Hoft station, but was never detected by any telemetry station. This bat roosted in the same location throughout the period it was tracked. It may have dropped its tag immediately, but signal strength at the roost location was stronger in warmer weather and weaker in cooler weather, suggesting the tag remained on the bat as it shifted position in the roost. It is possible this individual entered hibernation and did not emerge in the cold conditions which followed the night of capture. EPFU 258 was located in a hollow tree 0.57 km from the capture site and 0.78 km from the Hoft station. This bat used the EP2 roost at a bearing of 330° relative to the station, and was intermittently detected by the Hoft 1 antenna, bearing 355°, while roosting, but not by antennae with bearings of 295° or 55° (Table 3.5). EPFU 258 was detected on three nights by the Hoft station, and on the fourth night by the Goethals station (Table 3.5, Figure 3.5), at a west-southwest bearing suggestive of offshore movement. EPFU 271, tagged near Cedar Tree Neck, was detected by the Hoft station (Table 3.6). We were not able to obtain permission to track bats to roost sites at Cedar

Tree Neck sanctuary in October, and therefore did not attempt to track EPFU 271 to a defined roost site. However, EPFU 271 was detected from the road to the Cedar Tree Neck sanctuary on October 25 and 29.

Eastern Red Bats

The tags placed on the three LABO operated with a longer burst interval rate, which allows for a longer tag lifespan. However, the longer burst interval rate is not conducive to manual tracking. We therefore did not attempt to track these bats to roost sites.

The eastern red bats tagged in October showed wider detectability than our northern long-eared bats. LABO 470, tagged near the Hoft station, was detected by this station on seven nights, but also detected at the Goethals station on eight nights (Figure 3.6). LABO 475, tagged near the Cedar Tree Neck station, was detected by this station on three nights, but also detected by the Hoft station on one night, the Goethals station on one night, and the Naushon station on three nights (Figure 3.6). LABO 473, tagged in the vicinity of the Cedar Tree Neck station, was detected locally by the Hoft station on one night and the Naushon station on two nights. On October 19, the second night it was detected by the Naushon station, the bat departed the island. It was detected the following morning by an automated telemetry station in Cape May, NJ, and several days later by a station off the Eastern Shore of Maryland (Table 3.7).

Acoustic data

We deployed acoustic detectors for a total of 38 site-nights between early June and mid-July, at 11 sites for 2-6 nights each. *Myotis* species were detected on 28 nights

(74%), and at all sites except one. *Myotis* calls were recorded throughout the night during this time period, from sunset to sunrise. We again deployed acoustic detectors for four nights in late July at one site, four nights in late August at another site, and 1-6 nights each at four sites in early September. *Myotis* bats were recorded on three of the four nights sampled in July (75%), all four nights sampled in August (100%), and 10 of the 15 nights sampled in September (67%). As in the maternity period, *Myotis* calls were recorded throughout the night hours, from just after sunset until ~5:15 in the morning.

In October, we deployed detectors for a total of 83 site-nights, sampling 20 sites for 1-9 nights each. *Myotis* were recorded on 24 nights (29%). Six sites showed no *Myotis* activity, although most of these sites were only sampled 1-2 nights.

In November, we sampled a total of 27 site-nights, at four sites for 5-8 nights each. *Myotis* were recorded on 3 nights (11%), November 15, 16, and 18. The final detection of a *Myotis* bat was November 18 at 5:38 PM in the forest near where we captured and tagged a northern long-eared bat in October.

Temperature and wind data were obtained from the local airport weather station. A qualitative analysis of these data showed that most fall *Myotis* activity was during periods of low-moderate wind speed (<7 m/s) and warm temperatures (>10°C). It is important to note that weather data may not reflect local conditions experienced by the bats. Local temperatures may be lower or higher; wind speeds are likely lower under the forest canopy where acoustic detectors were deployed, as compared to the open airport environment. Further analysis of these results may be conducted by BiodiversityWorks.

Nantucket data

In 2016, we mist-netted for bats at three sites on Nantucket. In July, we caught 9 MYSE in one night of trapping, and attached NanoTags to three adult females. One female was tracked to two tree roosts within 200 m of the capture site, another was tracked to a house roost 1.9 km from the capture site. On October 30 at the same site, we captured and tagged one MYSE in two hours of trapping, before a rainstorm interrupted netting efforts. This bat was tracked to a crawl space beneath a house located 2.39 km from the West Gate capture site. We identified the tagged bat and four other *Myotis* roosting in a crawl space beneath a private residence. On November 1, we deployed NanoTags on three additional MYSE roosting in the crawl space. Nantucket Conservation Foundation staff re-entered the space on December 8 and identified at least one individual MYSE hibernating at the site.

The closest automated telemetry stations during our study were on Coatue Point and Great Point on Nantucket, and neighboring Muskeget Island. These stations were 9, 16, and 15 km respectively from the capture site, and 7, 15, and 17 km from the crawl space hibernaculum. No bats tagged on Nantucket were detected by telemetry stations at coastal sites on the island, or anywhere off-island.

Other tag detections

Table 3.8 shows detections of NanoTags from other projects by our telemetry stations during the 2016 deployment period.

Discussion

We did not observe offshore movement by northern long-eared bats during our study. In 2016, we tagged four adult female northern long-eared bats in the northwest Vineyard study area during the summer maternity period. In general, individual female northern long-eared bats are known to occupy small home ranges during the maternity period. Roosting home ranges typically are <10 ha in size, and average distances between summer roosts <0.8 km (Silvis et al. 2016). Our tagged bats roosted within 0.75 km of their capture site for the 5-12 days they were tracked. From these roost locations, less than 3 km from the coast, they could easily have accessed the offshore environment. Flight speeds for northern long-eared bats have not been reported in the published literature, but we do have data for congenerics. The Indiana bat has been recorded flying at speeds of 2.5-6.7 m/s (Patterson & Hardin 1969), while the little brown bat has been variously reported traveling at speeds of 2.2-8.5 m/s (Gould 1955, Mueller & Emlen 1957, Patterson & Hardin 1969). Other *Myotis* species reportedly fly at speeds of 4.0-10.8 m/s (Hayward & Davis 1964, LaVal et al. 1977). Even at a moderate 5 m/s, a northern long-eared bat could reach three nautical miles from shore in less than 20 minutes of sustained flight. Lactating females could forage offshore and still return to nurse pups multiple times per night. However, it appears unlikely that this species is foraging far offshore during the summer months, given what is known about northern long-eared bat biology and the limited observations made in this study. Our tagged lactating females were only detected by the inland telemetry station close (0.69 km) to where they were captured, and never by the neighboring coastal station (2.6 km away). Foraging home ranges reported in the literature are somewhat larger than roosting home ranges, but still below 100 ha (Owen et al. 2003, Broders et al. 2006, Silvis et al. 2016), with maximum movements of up to 1.8 km recorded (Broders et al. 2006, Henderson & Broders 2008). While we did not have telemetry stations on the Vineyard in 2015, northern long-eared bats captured on the island during the summer of that year showed similar patterns of behavior to 2016, roosting within a small home range (42-665 m from capture site).

We also did not observe northern long-eared bats leaving the island in the fall. Only one northern was tagged in the northwest study area in fall 2016. This bat was not recorded by any telemetry stations, and roosted in a small area. We anticipated cold temperatures in October would cause the bat to move to a warmer hibernation site, but we saw no evidence of this behavior. The bat switched roost sites through November 3, and we recorded changes in signal strength day-to-day (indicative of the tag remaining on the bat) through November 8. It is possible that the bat entered hibernation within the final tree cavity in which it roosted. Tree cavities can maintain above-freezing temperatures throughout much of the winter, and it has been suggested that *Myotis* species on marine islands could hibernate in cavities in northern climes (Burles et al. 2014). The two northern long-eared bats manually tracked in September and October 2015 remained locally until transmitters dropped (BiodiversityWorks, unpublished data). In 2016, late season deployment of acoustic detectors intermittently picked up northern long-eared bat calls at multiple sites on the island throughout October and into mid-November.

One of our goals in conducting this study was to address the question of whether northern long-eared bats are remaining on Martha’s Vineyard throughout the year, or leaving for the winter months. The presence of a WNS-infected northern long-eared bat on the island in February 2017 (BiodiversityWorks, unpublished data, https://vineyardgazette.com/news/2017/03/22/bats) requires that one of two explanations be true – either northern long-eared bats are leaving the island, and becoming infected at mainland hibernation sites, or northern long-eared bats remain on the island, but other species travel between the island and the mainland and have brought WNS to the island, which has since infected local northern long-eared bats. Of course, these alternative explanations are not mutually exclusive. It is possible, and frankly, entirely likely, that these bats exhibit a range of behaviors, with some venturing to mainland hibernation sites, while others remain on-island. Little brown bats in the same maternity colony have been shown to use different hibernation sites 51-554 km away (Norquay et al. 2013). The drop in overall capture rates of northern long-eared bats since the 1990s strongly suggests that WNS has affected populations on the island, but our observations of healthy maternity colonies could lend support to the hypothesis that subpopulations have remained locally on the island in small hibernacula thus far free of WNS. Collectively, our evidence points to the idea that at least some northern long-eared bats are hibernating locally – this is supported by late season residency behavior of tagged individuals, by late-season acoustic data, and perhaps most strongly, by the February occurrence of bats on the island, and the discovery of a hibernaculum on neighboring Nantucket (unpublished data). A number of summer houses on the Vineyard are heated through the colder months, but remain unoccupied; among other locations, these residences could easily be providing habitat to hibernating bats.

Our telemetry system recorded wider-ranging movements of little brown, big brown, and eastern red bats. Off-island movements were detected for at least two individuals, suggesting our system worked to detect these movements when they occurred. Of the eight bats tagged in 2016 that were not northern long-eared bats, seven were detected by stations at least 2.6 km from their capture location. In contrast, none of the northern long-eared bats were detected by stations more than 0.69 km away.

We documented migration of a little brown bat from Martha’s Vineyard to the mainland. One of the three little brown bats tagged was recorded departing the island on the night of August 25, and made migratory movements along the south and east sides of Cape Cod. It was last detected by a telemetry station in Wellfleet, 82 km from its initial capture and roost location. We also recorded evidence that the second little brown bat tagged in August appeared to make offshore movements, traveling to Naushon Island or foraging over Vineyard Sound. This bat was last detected at a bearing of west-southwest off the Cedar Tree Neck station on September 1. The detection direction suggests the bat may have migrated off-island at this time, and it was not detected at its roost site or by Vineyard or Naushon stations after this date, although it was also not detected by off-island stations aside from Naushon. The timing for departure of these bats is consistent with results from other studies, which found most little brown bats departing summer roost sites between mid-August and mid-September (Cope 1976, Kunz et al. 1998, Townsend et al. 2008) or describe capture of these species at cave swarming sites in mid-August to early October (Schowalter 1980, Burns et al. 2014). In addition, one of the tagged big brown bats was last detected by an ocean-bearing antenna on the Goethals station in late November, suggesting it was also moving offshore. It may have departed the island at this time, but was not detected by any off-island stations. One of the three tagged eastern red bats departed the island on October 19, and was recorded making migratory movements as far south as Maryland.

While we did not detect offshore migration by northern long-eared bats in our study, we did not track these bats in late August, and therefore cannot rule out the possibility that some northern long-eared bats may depart summer roosts at a comparable time to little brown bats. We could not identify any studies tracking northern long-eared bats as they move from summering grounds to winter hibernacula, and because their maternity colonies are often smaller than those of little brown bats, it is difficult to determine departure dates from summer roost sites for this species. Several studies do report northern long-eared bats arriving at swarming sites from the end of July through mid-October (Carceres & Barclay 2000, Broders & Forbes 2004). Seasonal patterns of bat activity on Martha's Vineyard vary by habitat (Buresch 1999), so it remains unclear whether a population decrease for northern long-eared bats occurs in late summer.

The timing of northern long-eared bat activity on Martha's Vineyard varied by season. During the maternity period, automated stations recorded activity of our tagged northern long-eared bats throughout the night, from shortly after sunset to shortly before sunrise. In a similar manner, acoustic detectors recorded *Myotis* calls throughout the night hours. In the fall, however, we primarily detected *Myotis* acoustic activity in the 2-2.5 hours post-sunset, although occasional calls were recorded throughout the night. The majority of echolocation calls in October were recorded under low-moderate wind speed conditions and in relatively mild temperatures (>10°C). If northern long-eared bats are making offshore forays, we might expect them to be active throughout the night in summer, but likely only active for several hours post-sunset in the late fall.

Conclusions

The five northern long-eared bats tracked in this study in 2016 were not detected making offshore movements. However, our tracking system was adequate to detect wide-ranging and offshore movements by other bat species tagged as part of these efforts. Data in the published literature suggest female northern long-eared bats occupy small home ranges for foraging and roosting during the maternity season, and these findings are consistent with our limited data from Martha’s Vineyard. During the summer months, female northern long-eared bats on the island were active throughout the night and could easily have accessed offshore environments for foraging under calm conditions. However, published reports suggest northern long-eared bat females are unlikely to forage greater than 2 km from roost sites during the maternity season, which would indicate they are unlikely to travel into federal waters (5.6 km offshore) during this time period, and we recorded no movements which exceeded 2 km. The behavior of adult male northern long-eared bats during the maternity season is largely unreported throughout their range, and we did not capture adult males on the Vineyard in 2015 or 2016.

We did not detect off-island movements by the two northern long-eared bats tagged in September 2015, or the single northern tagged in October 2016. Our study strongly suggests that some northern long-eared bats are hibernating locally on Martha’s Vineyard. In contrast, our limited data show some little brown bats make offshore movements or depart the island in late August. Given the small number of northern long-eared bats we were able to track in the fall, and the timing of those efforts, we cannot rule out the possibility that some northern long-eared bats may migrate off-island.

Low capture rates due to WNS are likely to be a continuing issue for future studies of northern long-eared bats on the island. We offer the following recommendations regarding future studies:

1. Monitoring known northern long-eared bat maternity roosts and trapping at these sites is likely to be the most efficient means of capture for this species during the maternity season. Efforts to further document offshore bat movements during this time period should focus on capture at identified roosts near the coastline in order to increase the sample size of tagged bats.

2. Off-island migration of northern long-eared bats could be occurring in late August. We did not focus our mist-netting efforts during this time period. It could be highly revealing to radio-tag northern long-eared bats during this time, although capture rates are likely to be low. Capture of little brown bats at their barn roost site was more time-efficient, and it would be informative to tag individuals of this species at known roosts on the Vineyard in late August, to further document timing and locations of offshore movement. If possible, individuals of both sexes should be tagged.

3. Capture rates were high at our Nantucket capture site during pilot mist-netting efforts. If northern long-eared bats continue to persist on this island in 2017, it could be a good location for future studies. However, the dynamics of WNS spread on islands is not well understood, and unfortunately, we could easily find similar declines in northern long-eared bat populations on Nantucket in coming years.

4. Offshore acoustic monitoring could be an effective way to identify timing of offshore movements by *Myotis* spp., relative to season and weather conditions. However, it is important to recognize the inherent difficulties in differentiating among *Myotis* spp.

echolocation calls, and the degree of error and uncertainty associated with both manual and automatic classification of these calls.

Acknowledgements

The Bureau of Ocean Energy Management funded the acquisition, installation and removal of three automated telemetry stations, and part-time funding for one year for a researcher to complete this study. The U.S. Fish & Wildlife Service provided coded radiotransmitters, manual telemetry equipment, staff time, and logistical and financial support. Many thanks also to the Martha’s Vineyard Vision Fellowship for funding MV staff and supporting project collaboration. Thanks to the Nature Conservancy of Martha’s Vineyard, Sheriff’s Meadow Foundation, the Martha’s Vineyard Land Bank, Vineyard Open Land Foundation, and numerous private landowners on the island who allowed us to capture and track bats on their properties. This work was partially supported by the NSF-sponsored IGERT: Offshore Wind Energy Engineering, Environmental Science, and Policy (Grant Number 1068864).

CHAPTER IV

TRACKING COASTAL MOVEMENTS OF LONG-DISTANCE MIGRATORY BATS

Abstract

Existing evidence suggests long-distance migratory tree bats may congregate along the Eastern Seaboard during the late summer-fall migration season, but little is known about their migratory routes or behavior. These species experience high fatality rates at some terrestrial wind facilities, and could be at risk from offshore wind development planned for North Atlantic waters. We deployed coded radio-transmitters on 39 eastern red bats and 3 hoary bats at coastal sites in New England during the late summer and fall of 2014-2016, and tracked movements of individuals using the Motus Wildlife Tracking system of automated telemetry stations. Eastern red bats were detected up to 803 km southwest from point of capture, and exhibited average migratory speeds of 4-94 km/night. We also found evidence of stopover of at least 14 days and northeastward movements of at least 44 km. We observed use of coastal routes, and detected red bats at numerous island telemetry stations, including the Block Island, Rhode Island station located near the site of the first offshore wind facility in U.S. waters. A hoary bat tagged in coastal Maine in late August 2015 traveled 130 km northeast along the coast and crossed at least 15 km of open ocean in one night. Further research is necessary to determine how great a risk offshore wind facilities pose to long-distance migratory bats at a population scale, but our data suggest these species should be considered in offshore wind development planning.

Introduction

Eastern red bats [*Lasiurus borealis*] and hoary bats [*L. cinereus*] are insectivorous, tree-roosting vespertilionids native to North America. Along with silver-haired bats [*Lasionycteris noctivagans*], they are characterized as long-distance migrants, capable of travelling hundreds of kilometers between wintering grounds and summer territories. Museum specimen records indicate eastern red bats are largely confined to the southeastern United States and northeastern Mexico during the winter months, but expand across much of the United States and Canada east of the Continental Divide in the summer (Cryan 2003). In winter, hoary bats are found in California, Mexico, and scattered locations elsewhere; in summer, female hoary bats occur across large regions of Canada and the northeastern United States, while males primarily are found in the mountainous West (Cryan 2003). Initial identification of these species as long-distance migrants was based on behavioral observations and occurrence data (e.g. Griffin 1940, Carter 1950, Shump and Shump 1982, Timm 1989, Cryan 2003), but recent isotopic analyses have confirmed these bats can be found at great distances from their summer territories in the fall (Cryan et al. 2014, Pylant et al. 2016).

Museum specimen records further suggest that movement towards coastlines is common during the fall migration season; high numbers of eastern red bats have been collected along the Atlantic Coast during this period, and hoary bats have been observed at both Atlantic and Pacific Coast locales (Cryan 2003). Isotopic signatures support the idea that hoary bats make longitudinal movements towards coastlines in the fall (Cryan et al. 2014). In addition, there is a long anecdotal history of sightings of migratory bats in coastal habitats, on marine islands, and over the ocean during this season (e.g. Nichols 1920, Thomas 1921, Griffin 1940, Carter 1950, Cryan and Brown 2007). Recent acoustic surveys in the Gulf of Maine have recorded increased migratory bat activity at coastal and offshore sites between mid-August and mid-September (Peterson et al. 2014), and red bats are commonly recorded at sites in coastal Rhode Island from July to October (Smith and McWilliams 2016). Eastern red bats have been detected acoustically 1.2-21.9 km off the mid-Atlantic coast (Sjollema et al. 2014) and on coastal barrier islands (Johnson et al. 2011b) in the late summer and fall; daytime surveys have also resulted in sightings 16.9-44 km offshore in September (Hatch et al. 2013). Hoary bats have been acoustically recorded 5.4-11.5 km off the mid-Atlantic coast during migration (Sjollema et al. 2014). Taken together, these pieces of evidence suggest coastal and offshore travel may represent a significant component of fall movements by migratory bats.

An in-depth understanding of bat migratory movements nevertheless remains elusive. It has historically been difficult to track small-bodied animals over long distances (Cryan 2011), and there have been no concerted efforts in North America to band large numbers of long-distance migratory bat species (O'Shea & Bogan 2003, Schorr et al. 2014). Acoustic data can identify periods of high activity, but without tracking of individual animals, it is impossible to characterize movement patterns or migratory behavior. The timing, nature, and routes of bat migration in general, and along the Atlantic Coast in particular, therefore remain poorly understood.

Meanwhile, the recent development of an expansive network of automated telemetry stations has allowed for the long-distance tracking of animals outfitted with coded radio-transmitters (Taylor et al. 2017). The Motus Wildlife Tracking system has proven invaluable in the collection of data on coastal migratory movements of a variety of bird species, including small-bodied passerines (e.g. Brown & Taylor 2015, Woodworth et al. 2015, Crysler et al. 2016). Limited deployment on bats suggests this tracking system can also provide information about nightly activity patterns (White et al. 2017), as well as stopover behavior (Taylor et al. 2011, McGuire et al. 2012, Hatch 2015), and speed of migratory movements (Jonassen 2017). However, no studies to date have characterized movements of long-distance migratory bats along the Atlantic coast.

A greater understanding of migratory bat movements along the Atlantic coast is of special importance in light of increasing wind energy development in the offshore environment. Terrestrial wind development is associated with significant bat mortality (Arnett & Baerwald 2013, Hayes 2013, Smallwood et al. 2013, Frick et al. 2017), and offshore wind facilities could present similar threats to bats. Hoary and eastern red bats experience the highest rates of land-based wind energy mortality among bat species in the eastern United States, and peaks in fatalities appear to coincide with their late summer-fall migration period (Arnett et al. 2008). Within New England, some of the strongest wind resources are in coastal and offshore areas (Schwartz et al. 2010, Musial et al. 2016). These areas tend to be close to high demand centers for electricity, and are likely to be sites of wind development over the coming decades (Manwell et al. 2002, ISO New England 2016). The Bureau of Ocean Energy Management holds 11 current leases with developers for construction of wind energy facilities in federal waters along the Atlantic Coast. Maine has set a goal of 5,000 MW of power generation from offshore wind by 2030 (An Act to Implement the Recommendations of the Governor's Ocean Energy Task Force 2010), and Massachusetts has instructed electricity utility companies within the state to contract with generators for development of up to 1,600 MW of offshore wind capacity (An Act Relative to Energy Diversity 2016). The first offshore wind farm in the United States - 30-MW 5-turbine facility off of Block Island, Rhode Island - came on-line in 2016.

The purpose of this study was to use the Motus Wildlife Tracking system to qualitatively describe the late summer and fall behavior of migratory tree bats along the North Atlantic coast. Our goals were to 1) document long-distance movements of migratory bats, 2) characterize any observable patterns in migratory behavior, 3) consider timing of bat movements, relative to season and time of night, and 4) identify any offshore movements.

Study Area

Mist-netting was conducted at multiple forested sites in coastal regions of New England (Figure 4.1). We trapped in the Downeast region of Maine (ME) within 0.5 km of the coast in Jonesboro and Roque Bluffs, as well at the Petit Manan Point National Wildlife Refuge (NWR) in Steuben. We mist-netted within Acadia National Park on Isle au Haut, the Schoodic Peninsula, and Mount Desert Island, ME. In New Hampshire (NH), we trapped at Great Bay NWR, adjacent to a tidal estuary ~10 km from the coast. In Massachusetts (MA), we mist-netted at a coastal site at Parker River NWR, and on the islands of Martha’s Vineyard and Nantucket. At all locations, mist-nets were strung across roads running through forest or scrub forest, or were deployed to perpendicularly intersect a wetland/forest boundary over marsh habitats and freshwater ponds.

Methods

Bat capture and radio-tag deployment

We mist-netted for bats in the late summer and fall (1 August-31 October) in 2014, 2015, and 2016. We used single, double, and triple-high set-ups of 6, 9, and 12 m mist nets, and deployed 2-5 mist-net set-ups at each location. Trapping was conducted at a given location for 1-3 nights in succession (almost always 2), from near sunset until 3-5 hours post-sunset, depending on trapping success and weather conditions. On cold (<10°C) or windy nights, nets were occasionally closed earlier. Mist-netting work was conducted through collaboration among the U.S. Fish & Wildlife Service, the National Park Service, University of Massachusetts Amherst, Biodiversity Research Institute, BiodiversityWorks, and Nantucket Conservation Foundation.

All bats were handled in accordance with American Society of Mammalogists standards (Sikes & Gannon 2011). Bats were identified to species, aged as adult or juvenile based on ossification of the metacarpal-phalangeal joint (Brunet-Rossini & Wilkinson 2009), sexed, weighed, and measured along the forearm. For captured eastern red and hoary bats, a small area was shaved between the scapulae, and a radio-tag was attached using animal ID tag cement (Nasco). Radio-tags were Lotek NTQB-1 (0.29 g) or NTQB-2 (0.35 g) NanoTag series coded units, with burst intervals of 6.7-19.9 seconds, and operating lives of 24-71 days (Lotek Wireless, www.lotek.com). To reduce the risk of negative effects of tagging, no transmitter constituted greater than 5% of bat body weight (Aldridge & Brigham 1988). Animal handling was conducted under an approved IACUC protocol (UMass Amherst protocol Sievert 2014-0033); all gear was treated in accordance with National White-Nose Syndrome Decontamination Protocols (U.S. Fish & Wildlife Service 2012, 2016c).

Automated tracking

NanoTags (Lotek Wireless, www.lotek.com) are coded radio-transmitters operating on a single frequency; in combination with automated radiotelemetry stations, they allow for the simultaneous tracking of potentially thousands of individual organisms (Taylor et al 2017). In order to track local movements of radio-tagged bats, where possible, we deployed stationary automated telemetry receiver towers in close proximity to trapping sites. We deployed an automated telemetry station within 5 km of most capture locations, except at Acadia National Park (Table 4.1). In 2014, 2015, and 2016, there was one telemetry station located 7.75-9.11 km from all successful capture sites on Mount Desert Island. In 2016, we deployed a second station which was 0.7-2.1 km from capture locations on the island. Unfortunately, a series of deployment issues meant that both Mount Desert Island stations only functioned intermittently during the 2016 study period.

Long-distance movements of radio-tagged bats were tracked using the greater Motus Wildlife Tracking system of automated telemetry stations. Stations consisted of yagi or omni-directional antennae deployed on buildings, lighthouses, pop-up masts, or sectional towers; the antennae were attached via BNC cables to a radio receiver, which monitored for coded radio-tags transmitting at a single frequency. In the Gulf of Maine region, most stations consisted of a “Motus-style” arrangement of 3 9-element yagi antennae oriented horizontally and connected to a hand-built telemetry receiver (www.sensorgnome.org) which monitored all antennae simultaneously. In the Cape Cod and Islands region, most stations consisted of a “Lotek-style” arrangement, consisting of 6 9-element yagi antennae oriented horizontally and connected to a Lotek SRX series receiver (Lotek Wireless, www.lotek.com). This receiver systematically rotated through monitoring each antenna, sampling all antennae over a period of 1-2 minutes.

Bats were tracked using data obtained from the network through the Motus website (www.motus.org). The system returns data from detections of registered radio-tags, including a tag identification number, timestamp of detection, signal strength, antenna bearing, and the latitude and longitude of the telemetry station where the signal was detected. In the presence of radio noise within the target radio-tag frequency, telemetry stations may record false detections, which are not always removed by the Motus detection algorithm. We screened detection records for suspect detections before analysis. We identified “noisy stations” where the radio-tag under consideration or other tags within the same numbered series were frequently reported as detected before tags were deployed, and removed detections from these stations. We also removed records in which fewer than 3 detections were recorded consecutively, unless a run of 2 detections occurred within 25 km and 5 days of another detection (Woodworth et al. 2015, Crysler et al. 2016).

Tracking analysis

Capture site residency and stopover behavior

The minimum duration of capture site residency was calculated for bats detected within 13 km of their capture site after release, either through tag detection by a local automated telemetry station or recapture of the individual. We used 13 km based on the typical maximum detection range for Motus Wildlife Tracking System telemetry stations in other studies (Mills et al. 2011, Taylor et al. 2011). Capture site residency duration was defined as the length of time from the point of capture until the last known record of the individual within 13 km of the capture site. In cases where bats were detected by a local station but not by other stations in the Motus network, we generated signal strength versus time plots to confirm that the capture site residency duration did not include time when the radio-transmitter had fallen off the bat but was still being recorded by the telemetry station, which would have generated a relatively unvarying signal strength over time. For bats which remained in the capture vicinity for multiple days, and were detected by local stations for greater than 50% of this time, we examined plots of signal strength over time to assess patterns of roosting and foraging activity (White et al. 2017). We also calculated stopover duration at sites other than the capture location where individual bats were detected for multiple days, based on first detection at a site and last detection within 13 km of that site.

Single-night between station flights

Ground speeds were calculated for bats making movements between telemetry stations >20 km apart over the course of a single night. Ground speed has been calculated in various ways as part of automated telemetry studies (Mitchell et al. 2015, Jonassen 2017, Smetzer et al. 2017, Wright et al. 2018). We calculated ground speed as the distance between the two stations, divided by the time between the midpoint of detection at the first station and the midpoint of detection at the second station. For departures from the capture site location, we could not use the midpoint of detection, since bats were often detected at the capture site for multiple nights. At these sites, we estimated the depature time from the first station as the time of maximum signal strength within 1/2 hour of final detection at the capture site location.

Migratory speed

For bats tracked >20 km southwest from point of capture, we estimated average migratory speed. The distance between initial capture and southernmost detection was divided by total time between capture and final detection, to determine average migratory speed over the entire tracking period (km/night).

Results

Bat capture and radio-tag deployment

We trapped for a total of 122 nights (~1,665 net-hours) at coastal locations in Maine, New Hampshire, and Massachusetts between 2014-2016 (Table 4.1). We captured 393 bats, and deployed radio-tags on 39 eastern red bats and 3 hoary bats. There was a trend towards a greater proportion of males among eastern red bats captured later in the season [first half of August – 4/9 (44%) bats were males, second half of August – 5/11 (45%) males, first half of September – 7/10 (70%) males, second half of September – 5/6 (83%) males, October – 2/3 (66%) males], but both sexes were captured in all months and at all study locations where more than one individual was captured. Differentiating adult from juvenile bats can be difficult late in the season; we identified 25 red bats as adults, 12 as juveniles, and 2 as indeterminable. Both adults and juveniles were captured at most study locations. On Martha's Vineyard, all 3 red bats tagged were identified as adults, but this was in mid-October, by which point ossification of the wing joint may have occurred for juvenile bats.

We deployed NanoTags on 1 adult female and 1 male adult hoary bat captured on Mount Desert Island, ME, and 1 adult female hoary bat captured at Parker River NWR, MA.

Automated tracking – Eastern Red Bats

Of 39 eastern red bats tagged, 8 were not detected after release, and 18 were solely re-located within 13 km of their capture location. One bat was last detected 21 km northeast of its point of capture. The remaining 12 red bats were detected making movements >20 km southwest from point of capture (Table 4.2).

The likelihood that eastern red bats were detected within the vicinity of their capture location after release was strongly related to the proximity of local telemetry stations. Sixteen bats were tagged within 1 km of a functioning automated telemetry station, and these bats were all recorded by local stations. Of 7 bats tagged within 1-5 km of a functioning station, 5 were recorded by the local station. Of 8 bats tagged within 5-10 km of a functioning station on Mount Desert Island in 2014 and 2015, only 1 was re-detected by a local station. However, 2 of these bats were recaptured locally in mist nets, and 1 was relocated using manual telemetry. On Mount Desert Island in 2016, we deployed 2 telemetry stations, one within 5 km of all capture sites, and the other within 10 km. However, both local stations had deployment issues which resulted in limited function during the study period. These stations recorded 1 of 2 bats tagged within 1 km of a station, and 1 of 6 bats tagged within 1-5 km.

We calculated a minimum capture site residency duration for the 27 eastern red bats relocated within 13 km of their initial capture location (Table 4.2). Red bats were re-detected locally for up to 11.9 days following release at Great Bay NWR, for up to 14.0 days at Parker River NWR, and up to 24.0 days on Martha's Vineyard. The lone bat captured at Petit Manan Point NWR was re-detected in the capture vicinity for 3.2 days following release, and dropped its tag in the vicinity, although not within range of the station. On Mount Desert Island, one bat was intermittently detected by a local station for up to 12.8 days after release, and another bat was recaptured at its original capture site 14 days later. Across sites, several bats were detected in the vicinity of their capture location for only 0.1 days following release, but these data points could either have represented an immediate departure from the area or a dropped tag, since these bats were not subsequently re-detected elsewhere. Mean minimum capture site residency across all red bats re-detected locally was 6.8 ± 6.9 days (median=4.0 days, range=0.1-24 days). Minimum capture site residency calculations could over-estimate residency duration, if bats left the area but returned thereafter to the same vicinity. However, we did not record any bats at non-local stations in between detections at local stations, and some bats were detected nearly continuously by local stations.

Local detectability was low at most sites, but where bats were tagged within 0.5 km of an automated station, local detections could represent a significant fraction of the time bats remained in the vicinity. At Parker River NWR in 2016, 12 eastern red bats were tagged 0.41 km from an omni-directional antenna and 4.19 km from a station with 3 directional antenna. Three of the bats which remained in the vicinity for multiple days were recorded by one or both stations for > 50% of the time they remained there. The first of these bats, tagged in late August, was detected for 70.0% of the time from release for 11.9 days following capture. This bat was active nightly from approximately 1/2 hour after sunset until within an hour of sunrise. In early September 2016, 2 red bats captured in the same net at Parker River NWR were detected for 52.2% and 92.2% of the time from release for 3.9 days following capture. These bats were detected in flight from within five minutes after sunset through as late as 05:15 the following morning, although activity appeared to cease as early as 22:00 on some nights. At Great Bay NWR in mid-September 2014, 2 bats tagged 0.15 km from the closest telemetry station and 1.89 km from the second-closest station were detected for 84.3% of 9.0 days, and 89.0% of 11.9 days, respectively, following capture. These bats emerged close to sunset, and were active as late as midnight on some nights, although on cooler nights (temperature at dusk ~13°C) they were only active for ~1 hour following emergence. On one cold night (temperature at dusk ~8.5°C), there was no clear indication that either bat emerged to forage.

Twelve eastern red bats were recorded making movements 27-803 km southwest from their capture location (Table 4.2). The greatest movement recorded was for a bat tagged on Mount Desert Island, which was last recorded along the coast of Cape May, NJ, 12.1 days after release. The second-longest movement recorded was 656 km for a bat tagged on Martha’s Vineyard, MA, and last recorded by a station on Skidmore Island, VA, 7.0 days after release. We recorded one case of reverse migration, in which a red bat tagged on Mount Desert Island in early September was recorded by 2 stations 29.3 and

43.5 km northeast from its capture site between 11 and 19 days after capture, before ultimately being detected travelling south through mid-coast Maine (22 days after capture), northeastern Massachusetts (23 days after capture), and southwest Rhode Island (29 days after capture). Average southwestward travel among bats that ultimately migrated southwest averaged 31 km/night, but these calculations revealed a high degree of variability in average migratory speed (4.3-93.5 km/night) (Table 4.2). Among bats tracked, we saw no obvious trend towards shorter stopover durations or faster average migratory speeds as the season progressed. The red bat showing the fastest average migratory speed was tagged on 17 October 2017 on Martha's Vineyard, MA, but 2 other red bats tagged on the island during the same week remained in the capture vicinity for 21.0 ad 24.0 days following release.

Calculations of speed over one night between telemetry stations indicate migrating eastern red bats were flying at speeds of 10.1-27.8 m/s (Table 4.3), with the exception of 1 span between 2 stations located 23.4 km apart in which estimated speed was only 1.5 m/s (overall mean=14.8 ± 7.0 m/s). The longest flight between stations recorded in one night (333 km) was by a red bat traveling between Montauk Point, NY and Cape May, NJ. The bat maintained an average speed of 14.9 m/s over 6.18 hours.

The majority of eastern red bats were only detected at non-local stations while making "fly-bys", in which they spent < 2 hr within detection range of a station antenna, and were either next detected elsewhere, or where this represented the final detection for the bat. Detection periods at a single antenna were typically quite brief – out of 38 fly-bys recorded, only 4 exceeded 30 minutes in duration, and only 1 exceeded 45 minutes (mean: 12 ± 20.5 min, median: 4 min). Fly-bys were recorded at all hours of the night, from 18:26-05:15. In addition to fly-bys, we recorded 2 incidents of longer-term detection at non-local sites, both cases in which bats were detected by a non-local station antenna for > 24 hr. One red bat captured on Mount Desert Island was recorded by a telemetry station on Metinic Island, ME on 27 September 2014, the night following its capture, from 21:57 to 22:25. After a break in detection, this bat was again detected by the Metinic Island station on 29 September 2014 from 18:35-18:55. A red bat tagged at Parker River NWR was detected after its departure from the capture vicinity by a telemetry station on Cape Cod, MA. This bat continued to be intermittently recorded by 6 stations in the Cape Cod region for an additional 13.9 days, with the final detection at the same Cape Cod station where it was first recorded. Over this time period, the bat was recorded as early as 18:49 and as late as 01:30.

The maximum detection range observed for tagged bats was ~32 km for an individual bat simultaneously detected by two automated telemetry stations located 64 km apart in the Cape Cod, MA region. Most other instances of simultaneous detections between “Lotek-style” stations occurred between stations located ≤ 25 km apart, suggesting a typical maximum detection range of 12-13 km. This is the expected maximum detection range for use of Motus-style towers to detect NanoTags on songbirds, although greater detection distances are known (Mills et al. 2011, Taylor et al. 2011). Among “Motus-style” stations, we only recorded simultaneous detections where stations were < 5 km apart.

Of the 12 eastern red bats recorded making long-distance migratory movements, 8 were recorded by island telemetry stations other than the local station near where they were captured. Several islands were close to the mainland (e.g. Orr’s Island, ME; Plum

Island, NY), but bats were also recorded by stations on Great Duck Island, ME (9 km to mainland), Metinic Island, ME (9 km), Noman's Island, MA (30 km), and Muskeget Island, MA (30 km). Five bats were detected by a Block Island, RI station (21 km from the mainland), 1 of which was detected by southeast and south-bearing antennae of a station on the south end of the island, pointed in the direction of the Deepwater Wind energy facility. Given the maximum detection range we recorded for tagged bats, it would be theoretically possible for bats to be detected by island telemetry stations while flying over the mainland rather than the ocean at most locations. However, 6 bats traveling through the Cape Cod & Islands region were detected by offshore-bearing antennae of coastal and island stations, which would indicate these bats were traveling over the ocean.

Automated tracking - Hoary Bats

All 3 hoary bats tagged were detected after release, but the bat tagged at Parker River NWR was only detected by local stations for several hours. The bat tagged on Mount Desert Island, ME in 2016 was detected on the night following capture by a telemetry station 27.1 km southwest of the capture site. The bat captured on Mount Desert Island in 2015 was not detected by local telemetry stations, but was detected using manual telemetry, roosting in the vicinity of its trapping location on the evening following capture. That night, the individual was detected flying 130 km northeast along the coast, and crossing at least 15 km of open ocean to reach Grand Manan Island, New Brunswick, Canada (Figure 4.2c).

Discussion

This study is one of the first efforts in North America to track migratory tree bats over long distances (>20 km), and one of the few world-wide to follow individual bats using a system of automated telemetry stations. We recorded evidence that migratory bats use coastal routes during the fall migration season, and regularly travel offshore. Twelve of 39 eastern red bats radio-tagged in the course of this study were detected making movements along the New England coast 27-803 km southwest from their point of capture. These bats were frequently detected by island telemetry stations and antennae pointed offshore. We also recorded a hoary bat moving 130 km northeast along the coast, and crossing at least 15 km of open ocean to reach Grand Manan Island. The fact that this bat was only tracked for 1.1 days from time of capture suggests long-distance movements of this nature may not be unusual for this species.

We observed a variety of fall behaviors among tracked bats, including directed flights southwestward, lengthy periods of residency behavior, stopover behavior, and at least occasional northeastward movements. Ten eastern red bats were recorded making directed flights southwestward; with one exception, between-station flight speeds for red bats were >10 m/s. Flight speeds recorded for bats exceeded known foraging speeds for the species (Salcedo et al. 1995), and on average were about 2.5 m/s higher than those recorded in a previous migration study (Jonassen 2017). Few studies of North American bat migration are available for comparison, but hoary bats averaged 10.8 m/s, and silver-haired bats averaged 13.8 m/s, during fall migration through Ontario (Jonassen 2017). Smaller-bodied Indiana bats [*Myotis sodalis*] tracked by airplane have been recorded migrating between winter and summer habitats at speeds averaging 10 m/s (Roby et al. 2016).

We also observed northeastward movements by two eastern red bats and one hoary bat in our study. These movements may reflect distinct fall behavior, given that long-distance movements (>20 km) are not typical of most North American bats in the summer season. Eastern red bats generally have small summer home ranges and make only short commutes to foraging grounds (McCracken et al. 1997, Carter 1998, Hutchinson and Lacki 1999, Elmore et al. 2005, Walters et al. 2006, Amelon et al. 2014). Little data are available regarding hoary bats, but they also appear to make only short-distance movements during the summer (Sparks et al. 2005, Bonaccorso et al, 2015).

In addition to these behaviors, we observed eastern red bats remaining for extended periods of time at their capture location, which could either be indicative of migratory stopover or summer residency behavior continued late into the putative migration season. Nineteen red bats remained at one location for at least 2 nights during the time they were tracked, and individual bats remained in their capture vicinity for 11-24 days at 4 out of 5 tagging locations. We could not determine whether newly captured bats were local summer residents at tagging locations, or migrants captured along their migratory route. However, subsequent re-detections provided definitive evidence of stopover for two red bats - one bat was detected on Metinic Island, ME for 2 days after migrating from further north, and one bat remained in the Cape Cod region for 14 days after it travelled from northeastern Massachusetts.

According to optimal migration theory, observed migratory behavior should reflect a balance between time spent in movement towards a destination and time spent re-fueling in order to power further movement (Hedenstrom 2009). Some bats may employ a "fly-and-forage" strategy, feeding en route to a destination (Suba et al. 2012), while others forage at a stopover site prior to engaging in directed migratory flight (Roby et al. 2016). Our study provides evidence that eastern red bats use the latter strategy. Rough calculations further suggest that the time spent in directed flight matches well with theory. Red bats tracked southwestward in our study travelled at an average rate of 31 km/night, the equivalent of only a 0.7 m/s flight speed if bats were flying steadily throughout a 12-hour night. This speed is only 1/25-1/15 the rate of speed we observed for bats making directed flights in a single night, suggesting red bats in our study spent on average only ~1/20 of night hours engaged in directed southwestward migratory flight. This estimate matches well with theoretical calculations provided by Hedenstrom for the proportion of time bats would be expected to spend on directed migratory flight based on time and energy optimization models (2009). On the other hand, McGuire et al. (2014) suggest bats may migrate under reduced energy and time constraints relative to birds, given that use of torpor can reduce energy expenditures during stopover by up to 91%. These authors predict that use of torpor should result in limited need for stopover and re-fueling en route (McGuire et al. 2014). If the red bats we observed remaining at one location for long periods of time were not primarily fueling for migratory flight, it is possible they were engaging in other activities, such as lekking (Cryan et al. 2012).

In regard to stopover, eastern red bats may differ from other North American long-distance migrants. McGuire et al. (2012) found that silver-haired bats captured along Lake Erie in the fall typically foraged for a short time on the night following capture, and then left the study area, presumably continuing their migration. The researchers estimated these bats had sufficient fuel reserves to complete their southward migration without additional fat accumulation, and suspected they made directed flights and employed little stopover (McGuire et al. 2012). Outside of our study, there is some evidence for greater stopover rates for red bats relative to other species. Hatch (2015) found that of 17 red bats moving along Lake Erie in the spring, 11 engaged in stopover periods of 2-20 days. Of 12 silver-haired bats captured, only 2 stayed more than one night, and the lone hoary bat radio-tagged had a stopover duration of 2 days (Hatch 2015). Jonassen (2017) described fall stopover by red bats in southwestern Ontario of 6-50 days, but did not report stopover among silver-haired or hoary bats tracked during the same period. Among the 3 hoary bats we tracked, none remained at the capture site for more than one night; however, our sample size was small.

We observed a high degree of variability in average migratory rates among red bats that ultimately travelled south, with a range from 4.3-94 km/night. Jonassen (2017) found similarly wide variation in estimated fall migratory speeds for bats moving along Lake Erie (eastern red bats: 46.7 and 76.9 km/night; hoary bats: 14.6 and 179.4 km/night; silver-haired bats 8.8-281.2 km/night). Individual variability in migratory speed is also commonly documented among European bats, including Nathusius' pipistrelle [*Pipistrellus nathusii*] (Petersons 2004, Rydell et al. 2014) and the common noctule [*Nyctalus noctula*] (Dechmann et al. 2014). Differences in migratory rates in our study could not easily be explained by demographic or morphological features, and we saw no obvious trend towards shorter stopover durations or faster average migratory speeds as the season progressed. The red bat showing the fastest average migratory speed was tagged on 17 October 2017 on Martha's Vineyard, MA, but 2 other red bats of comparable weight tagged on the island during the same week remained in the capture vicinity for 21 and 24 days following release. Interestingly, we did not observe any long-distance movements by eastern red bats before late August. Acoustic and observational data from other sources indicate that migratory tree bats may be accumulating in coastal areas beginning in mid-July (e.g Peterson et al. 2014), but it is possible red bats do not begin to move south until later in the season. It is also possible that some individual long-distance migratory bats may not migrate at all, but hibernate locally in caves (Quay and Miller 1955, Izor 1979).

If bats engage in a variety of behaviors during the migration season, it raises the question of whether certain activities, such as directed flights southward, may render bats more vulnerable to mortality at wind facilities than other activities, such as foraging at a stopover site. In general, eastern red bats are thought to be at greater risk during the fall migration season, and fatalities at wind facilities peak during this period, but it is not clear if this is an effect of season on bat distribution in the landscape, bat physiology during the fall, or particular behaviors that bats engage in during the fall and not during other seasons (Arnett et al. 2008, Cryan and Barclay 2009). Collision risk for little brown bats [*Myotis lucifugus*] changes in mid-late August, associated with hormonal and physiological changes and changes in swarming and mating activities (Orbach and Fenton 2010). It is entirely possible that red bats enter a higher-risk state associated with physiological changes in the fall. However, our detection range data corroborate other evidence that red bats are likely flying at higher altitude during directed flights compared to foraging flights (Menzel et al. 2005, Hatch et al. 2013). Higher altitude flight could make wind turbines visible to bats from a greater distance away, bring bats into the rotorswept zone, and potentially render them more vulnerable to wind farm mortality. Further research is needed to determine if vulnerability to wind turbine mortality varies with different types of activities.

Management Implications

Our study confirms that coastal and offshore movements by long-distance migratory bats are likely to be common and widespread during the fall migration period. The northeastward movements we observed suggests bat exposure to coastal and offshore wind facilities could also involve multiple rather than single passes by turbines, increasing the risk of mortality. Regulatory agencies should consider potential effects of offshore wind development on these species as part of the planning process, and implement strategies to either monitor and respond to fatalities, or prevent them outright.

We found that for eastern red bats, foraging bouts became more limited in duration as the season progressed, but that migrating bats continued to be recorded making directed flights throughout the night hours, from sunset to sunrise. Further research is needed to determine if directed long-distance flights render bats more vulnerable to wind facility mortality than other activities, such as foraging. If red bats are at low risk during stopover foraging bouts, near-ground-mounted acoustic monitoring devices have the potential to record high acoustic activity during periods when bats are not particularly vulnerable to mortality.

CHAPTER V

THE LOW COST OF CURTAILMENT FOR BATS AT OFFSHORE WIND FACILITIES

Abstract

Mounting evidence suggests North American bats could be at risk from the dramatic expansion in offshore wind energy capacity planned for North Atlantic waters. Operational curtailment is presently the sole effective strategy available to curb wind turbine-associated bat mortality in the onshore environment, where it can reduce fatality rates by over 50%. We used publicly-available weather and pricing data to estimate costs of preventative curtailment at offshore sites along the Atlantic coast of the United States. Our calculations indicate that standard curtailment for bats would result in ≤ 1.12% decrease in energy production, and ≤ 0.88% revenue losses based on local marginal price data. Curtailment appears to be a cost-effective strategy for limiting bat fatalities at offshore wind facilities.

Introduction

Wind energy can play an important role in reducing greenhouse gas emissions associated with electricity generation (Sims et al., 2003); however, development of wind resources has environmental trade-offs, including negative effects on bats (Government Accountability Office, 2005). An estimated 600,000 bats were killed at terrestrial wind facilities in the United States in 2012, and this figure is expected to increase as capacity expands (Hayes, 2013). Wind power-associated mortality could have population-scale consequences for both long-distance migrants and cave-hibernating species (Erickson et al., 2016; Frick et al., 2017). In the absence of a successful bat deterrent device (Arnett et al., 2013a), operational curtailment is the only effective means of reducing bat fatalities at wind energy sites.

Curtailment restricts the operation of wind turbines during time periods and weather conditions when bat activity and mortality are expected to be high. Curtailment studies have demonstrated that reducing blade operation or turbine rotational speeds under low wind conditions can decrease bat mortality by 44-93% during the late summer-fall migration season (Baerwald et al., 2009; Arnett et al., 2011, 2013b; Martin, 2015). Curtailment for bats is now a requirement at some New England land-based wind facilities throughout the active season on warm nights during periods of low wind speed (Maine Department of Inland Fisheries & Wildlife, 2013; Vermont Agency of Natural Resources, 2016). The few economic analyses that have been conducted suggest curtailment is likely to result in <2% loss of energy production at onshore sites in the United States if restricted to high mortality periods (Arnett et al., 2011, 2013b; Martin, 2015).

In Scandinavia, bats have been observed foraging in the vicinity of offshore wind turbines, and even attempting to roost in turbine nacelles (Ahlen et al., 2009). Multiple lines of evidence suggest North American bats also fly offshore, and that long-distance migratory bats may follow coastal routes, travel over the ocean during migration, and use marine islands as stopover sites (Cryan & Brown, 2007; Johnson et al., 2011b; Hatch et al., 2013; Peterson et al., 2014; Sjollema et al., 2014; Smith & McWilliams, 2016). The risks offshore wind development may pose to North American bats remain largely unknown, but there is a growing need to consider this conservation issue. The first offshore wind facility in the United States came into operation in 2016, off the coast of Block Island, Rhode Island. The Bureau of Ocean Energy Management (BOEM) maintains eleven active leases with developers for construction of offshore wind energy facilities in federal waters along the Eastern Seaboard. Meanwhile, the Massachusetts legislature has instructed utility companies within the state to contract with developers for up to 1,600 MW of offshore wind capacity (Act to Promote Energy Diversity of 2016, M.G.L. ch.23M §83C), over 10 times the state's current onshore capacity; Maine has set a goal of 5,000 MW of offshore wind by 2030 (Act to Implement the Recommendations of the Governor's Ocean Energy Task Force of 2010, M.P.L. ch. 615), over 5 times its current onshore capacity.

We used publicly-available data to calculate the costs of curtailment for bats in terms of energy production and revenue loss, for theoretical offshore wind facilities located along the Eastern Seaboard.

Methods

We constructed a deterministic model in R (R Core Team 2017) to calculate energy production and revenue at theoretical offshore wind facilities, with and without curtailment for bats. We calculated potential energy production based on wind speed data obtained from seven National Oceanic & Atmospheric Administration (NOAA) weather buoys (2017) located within, or as close as possible to, designated BOEM Wind Energy Areas (Fig. 1). We used the wind profile power law to estimate an adjusted wind speed at hub height (90 m) relative to anemometer height on NOAA buoys (4-5 m), incorporating an alpha value of 0.11 (Hsu et al., 1994). We then used the power curve for the National Renewable Energy Laboratory (NREL) 5-megawatt (MW) reference turbine (Jonkman et al., 2009) to determine energy production. We obtained contemporaneous air temperature data from NOAA buoys, and generated sunrise and sunset times for each site in R (R Core Team, Package: maptools). Our "standard" curtailment regime reflected common curtailment guidelines at land-based facilities, designed to encompass the conditions under which the majority of bat activity occurs. This standard regime ran for six months between April 15 and October 15, was in effect from 30 minutes before sunset to 30 minutes after sunrise, and required curtailment at wind speeds < 6 m/s when temperatures were > 10°C. When all these conditions were present, the power under curtailment was zero. At all other times, energy production was not curtailed and was equal to the potential energy production. Offshore wind power purchase agreements in the United States have typically been negotiated based on a fixed price per megawatt-hour (MWh), and hence revenue losses within these contracts would scale with losses in energy production. Because future offshore wind-generated electricity may be sold on the wholesale competitive market, we also obtained local marginal price (LMP) data for relevant electricity markets from regional transmission organizations, in order to calculate revenue losses in a competitive market scenario (ISO New England, 2017b; New York ISO, 2017a; Pennsylvania-New Jersey-Maryland Interconnection, 2017). We also analyzed energy production under a series of altered curtailment requirements at the Montauk Point station using 2016 data to examine the sensitivity of energy production loss to varied curtailment requirements.

We also used the model to evaluate curtailment costs for the Block Island Wind Farm off of Block Island, Rhode Island. We used temperature and wind speed data from the Montauk Point station (mean wind speed = 9.45 m/s) as a proxy for the Block Island site (mean wind speed = 9.69 m/s) (AWS Truepower, 2012). We calculated energy production losses based on the power curve for the Alstom Haliade 6 MW turbine in use at the Block Island facility (del Arco et al., 2015), and assumed a capacity factor of 0.475 and annual net production of 124,799 MWh of electricity (AWS Truepower, 2012).

We compared the economic impacts of curtailment offshore with comparable calculations for terrestrial sites, using an NREL IEC Class I turbine scaled to a 2 MW capacity (King et al., 2014), weather data from coastal and inland sites in Massachusetts (University of Massachusetts Wind Energy Center, 2017; University of Utah Department of Atmospheric Sciences, 2017), and a standard alpha value of 0.142857.

To explore relationships between wind resource quality and effects of curtailment, we calculated the relative contribution of low wind speeds to total energy production for a series of theoretical sites over a range of mean wind speeds. We used the Rayleigh distribution to model theoretical wind probability distributions for a series of sites with annual mean wind speed values of 5.6, 6.4, 7.0, 7.5, 8.0, 8.5 and 8.8 m/s at 50 m. The values chosen represent the limits of wind resource classes, which are categorized based on mean annual wind speeds at 50 m. Class 1 (0-5.6 m/s) and Class 2 (5.6-6.4 m/s) sites are not considered viable for commercial production, while Class 4 (7.0-7.5 m/s) sites and higher classes are considered commercially viable; Class 3 (6.4-7.0 m/s) sites may be developed under some circumstances.

Results

We found that loss of energy production was between 0.53% and 1.12% for the offshore sites and years sampled, using our standard curtailment regime; all but one site had losses well under 1% (Table 5.1). Standard curtailment for bats had a negligible effect on calculated capacity factors, especially relative to normal inter-annual variation in energy production. Revenue calculations based on LMP showed smaller percentage losses than losses based on a fixed price per MWh, reflecting the tendency for curtailment to occur during hours of lower average LMP. LMP-based revenue losses were below 1% at all sites analyzed, and ranged from 0.36-0.88% (Table 5.1). Standard curtailment had a considerable effect on turbine operation; for example, at the Montauk Point station in 2016, we calculated that turbines would be feathered for 704 hours annually, or 8.03% of the year, concentrated during the six months when curtailment was in effect. However, during 250 of these curtailed hours, the wind speed was below 3 m/s, and the turbine would not have otherwise been generating power. Overall, <6 m/s wind speeds contributed only 2.4% of annual energy production in this site-year.

Energy production loss at the Montauk site in 2016 was fairly insensitive to temperature requirements, sunrise/sunset offsets, and expansion of the season when curtailment was in effect (Table 5.2). Shortening the curtailment season to July 15-October 15, when bat mortality typically peaks at North American wind facilities, saved 0.3% of annual production, relative to standard curtailment. Raising or lowering the curtailment cut-in speed had the strongest effect on annual energy production losses. Cut-in speeds of 6.5 m/s and 7.0 m/s resulted in 0.98% and 1.32% losses of energy production, respectively, compared to a 0.64% loss under standard curtailment.

Reducing the cut-in speed to 5.5 m/s resulted in a 0.46% loss of annual production, while a cut-in of 5.0 m/s resulted in only a 0.28% loss.

We found that standard curtailment at the Block Island Wind Farm would lead to a 0.71% loss of energy production each year. We calculated that without curtailment, the 5-turbine facility would generate ~$30.5 million in revenue in the first year (at $244/MWh) (Rhode Island Public Utilities Commission, 2017). With a 0.71% loss in annual energy production, standard curtailment would cost the facility $216,157 in 2017. Because conventional generation would be needed to cover the curtailed wind generation, standard curtailment would also result in additional greenhouse gas emissions of ~300 metric tons of CO2 annually, assuming an average displaced electricity grid carbon intensity of 339 kg CO2/MWh (ISO New England, 2017a).

Energy production losses due to standard curtailment at terrestrial sites were more variable than at offshore locations (Table 5.S1). In general, lower percentage energy production losses were associated with higher quality wind resources. Coastal sites in Nantucket and Truro had relatively high capacity factors without curtailment (0.492 and 0.447 respectively), and each experienced only 0.62% loss of energy production annually under standard. By contrast, an inland site in Savoy, with a capacity factor without curtailment of 0.107, showed losses of 4.54% annually under curtailment.

Calculations using the Rayleigh distribution supported the finding that at good wind resource sites, <6 m/s wind speeds provide a relatively minor contribution to annual energy production for both onshore and offshore model turbines (Table 5.S2). For Class 4 and above resource areas, <6 m/s wind speeds should contribute less than 5% to annual energy production.

Discussion

Our results indicate that curtailment for bats would have relatively minor economic consequences for offshore wind facilities, resulting in less than 1% loss of energy production and revenue at most sites along the Atlantic coast. The low wind speed conditions (<6 m/s) associated with curtailment contribute relatively little to annual energy production at offshore sites, where the wind resource quality is high. At terrestrial sites with a low quality wind resource, low wind speeds contribute a greater proportion of annual energy production, and curtailment can reduce energy production by a larger percentage (up to 4.54% at the inland sites we examined).

We found that alterations in wind speed and seasonal curtailment requirements have the potential to more significantly moderate effects of curtailment on energy yield than do temperature or time of night specifications. For example, raising or lowering the temperature curtailment requirement by 2°C only altered energy production by 0.04%, but lowering the wind speed requirement by 1 m/s increased energy production by 0.36%. More detailed studies of North American bat activity patterns relative to fine-scale gradations in wind speed are warranted, particularly in the offshore environment, where bat behavior may differ from onshore. Bats are generally known to be more active at low wind speeds, with most fatalities at wind facilities occurring on nights with wind speeds <6 m/s (Arnett et al., 2008). However, if future research reveals that bats are most active at speeds below 5.0 or 5.5 m/s, for example, more efficient curtailment regimes could further minimize loss of energy production while protecting bats from wind farm mortality. If field mortality studies cannot be conducted in such a way as to relate fatalities to fine gradations in wind speed, acoustic data collected at turbine nacelles can help define mortality risk under varying wind speeds (Korner-Nievergelt et al, 2013; Behr et al., 2017). Acoustic studies related to bat collision risk should include collection of local weather data at a fine temporal scale to precisely define relevant conditions.

Our model was based on four factors. Models incorporating additional variables or interactions among variables can also lead to more efficient curtailment practices (Weller et al, 2012), but increases in energy production associated with more - sophisticated curtailment models are not always large enough to warrant the expense involved in collecting and incorporating additional data (Behr et al., 2017).

Efforts are currently underway to design a bat deterrent to be used on wind turbines (Arnett et al., 2013a; U.S. Department of Energy, 2017). If an effective and reliable device can be developed, it may prove a less costly alternative to curtailment. In the absence of such a device, strong consideration should be given to the use of curtailment as a preventative measure to minimize effects of wind development on bats in the offshore environment. Skeptics may question whether preventative curtailment is solving a problem that does not exist, given that bat mortality has not been documented at offshore wind energy sites in North America. The presence of carcasses beneath wind turbines was the first evidence of bat mortality at land-based wind facilities, and carcass counts continue to be the primary measure by which investigators evaluate bat mortality at these sites (Korner-Nievergelt et al, 2011), but bat carcasses would quickly be lost in the offshore environment. Meanwhile, a wealth of evidence suggests both long-distance migratory species and regional migrants are active over the ocean (Johnson et al., 2011b; Hatch et al., 2013; Peterson et al., 2014; Sjollema et al., 2014; Smith & McWilliams, 2016). Migratory bat population sizes are notoriously difficult to estimate (O'Shea & Bogan, 2003), and the sampling efforts required to identify even large declines in species abundance are likely unattainable (Schorr et al., 2014). Current models suggest existing wind capacity may already threaten the population viability of the hoary bat and other long-distance migrants (Frick et al., 2017). If preventative action is not taken, recognition of negative effects at the population scale could come too late.

Acknowledgements

Thank you to Blake Massey for review of the curtailment code generated in R. Many thanks to Elizabeth Dumont, James Manwell, Jonathan Reichard, and Paul Sievert, who reviewed this manuscript. This work was partially supported by the NSF-sponsored IGERT: Offshore Wind Energy Engineering, Environmental Science, and Policy (Grant Number 1068864).

Supporting Information

Data selection and method details

We obtained 10-minute wind speed data and hourly air temperature data from seven NOAA offshore weather data buoys through the National Data Buoy Center (2017). We selected three buoys from the Northeast region, two from the mid-Atlantic, and two from the Southeast, located within, or as close as possible to, designated BOEM Wind Energy Areas. For each site, we identified the three most recent years over the last decade (2007-2016) with >95% complete temperature and wind speed data, for analysis. In addition, we obtained 10-minute wind speed data from six onshore meteorological towers in coastal and inland Massachusetts collected between 2005-2009 (University of Massachusetts Wind Energy Center, 2017). For three onshore sites, hourly temperature data was also available at the tower; for the remaining three onshore sites (Nantucket, Mt. Tom, Savoy), we used temperature data from National Weather Service weather stations located at Nantucket Memorial Airport, Pittsfield Municipal Airport, and Westover Air Force Base, respectively (University of Utah Department of Atmospheric Sciences MesoWest, 2017). The weather stations were located 9.6, 11.5, and 32.7 km from their respective towers. Because only limited 10-minute wind data were available from onshore sites, we used sites with >90% complete temperature and wind data, and included data collected over 12 consecutive months, rather than in a single calendar year. We generated sunrise and sunset times for each site within R (R Core Team, Package: maptools) using the appropriate latitude and longitude.

We used the NREL 5 MW offshore wind turbine (Jonkman et al., 2009) as a model system for the purposes of calculating energy production at offshore sites. The model turbine has a cut-in speed of 3 m/s, a cut-out speed of 25 m/s, and a hub height of 90 m. We used the wind profile power law to estimate an adjusted wind speed at hub height relative to the anemometer height on NOAA data buoys (4-5 m), incorporating an alpha value of 0.11 (Hsu et al., 1994). We did not attempt to adjust air temperature by height, since temperature profiles are inconsistent across time and space. For onshore analysis, we used a normalized power curve derived by NREL for an IEC Class I turbine, and scaled the power output values for a 2 MW capacity (King et al., 2014). The model turbine has a cut-in speed of 3 m/s, a cut-out speed of 25 m/s, and a hub height of 100 m. We used the wind profile power law to estimate an adjusted wind speed at hub height relative to the anemometer height on meteorological towers (20-50 m), incorporating a standard alpha value of 0.142857. We did not adjust air temperature by height.

We used the adjusted wind speed and power curve for the model turbine to calculate potential energy production at each site. We then used adjusted wind speed, air temperature, sunrise and sunset times, and date to determine when the turbine would be curtailed under a given curtailment regime. Because wind data and temperature data were available on different time intervals, we assumed that the decision to curtail or not to curtail was determined at a ten-minute interval for wind, while air temperature held steady from the time when it was measured through the hour until the next measurement.

Our standard curtailment regime ran for six months between April 15 and October 15, was in effect from 30 minutes before sunset to 30 minutes after sunrise, and required curtailment at wind speeds <6 m/s and temperatures >10°C. When all these conditions were present, the power under curtailment was zero. At all other times, energy production was not curtailed and was equal to the potential power. We did not attempt to adjust for any loss of energy production associated with additional start-up time required to bring blades from a feathered, low-rotational speed condition up to full rotational speed. We analyzed energy production under various altered curtailment regimes at the Montauk site using 2016 data to examine the sensitivity of energy output to alternative curtailment regimes. Capacity factors were calculated based solely on meteorological data; we did not attempt to incorporate any assumptions about maintenance or curtailment for other purposes.

We estimated revenue loss under curtailment for offshore sites. Potential revenue loss under a fixed price per MWh scaled with energy production loss; potential revenue loss under a competitive market scenario was calculated based on LMP data. We obtained archived LMP data from the appropriate regional transmission organization for the area likely to be served by a wind facility developed at the site for which we obtained weather data. For Nantucket Sound, MA, we used LMP data obtained from ISO New England for the SEMASS region (2017b). For Montauk and Long Island, NY, we used LMP data obtained from New York ISO for the Long Island region (2017a). For Long Beach, NJ, and Delaware Bay, DE, we used Pennsylvania-New Jersey-Maryland Interconnection data for the Indian River substation (2017), an established interconnection point for offshore wind. We were not able to obtain LMP data for the Carolinas. The time-interval of price data available varied by provider, with data available on a 5-minute basis at some sites, while only available on an hourly basis at others. Because 5-minute data occasionally were recorded at intermittent time intervals (e.g. some 2-3 minute data), we extracted 10-minute time-interval data and assumed the price held consistent over each ten-minute interval. For hourly data, we assumed that the price remained consistent over the entire hour for which data was obtained. In all cases, we had >95% contemporaneous LMP data for the year being analyzed.

We also estimated losses from curtailment for the Block Island wind facility. We used 10-minute wind and hourly temperature data from the Montauk weather buoy in 2016; this was the closest site to the Block Island wind facility with publicly available offshore weather data. We approximated energy production values using a graphical power curve presented by Alstom (del Arco, 2015) to estimate the percent energy production loss under curtailment for an Alstom Haliade 6 MW turbine. For the purposes of estimating absolute energy and revenues losses, we based our calculations on the net facility energy production estimate provided in a wind resource assessment obtained by Deepwater Wind for the Block Island site (AWS Truepower, 2012). This estimate incorporated wake effects, availability, turbine performance, and other factors that could affect energy production, which were not considered elsewhere in our curtailment analysis. We used the 2017 price of $243.95/MWh approved by the Rhode Island Public Utilities Commission in the Power Purchase Agreement between Deepwater Wind and National Grid for purchase of energy and RECs from the Block Island wind facility (2017). This price is scheduled to increase by 3.5% on an annual basis.

We also calculated the cost of curtailment to greenhouse gas reduction, using a rate of 339 kg CO2/MWh (ISO New England, 2017a).

To explore relationships between wind resource quality and effects of curtailment, we calculated the relative contribution of low wind speeds to total energy production for a series of theoretical sites over a range of mean wind speeds. We used the Rayleigh distribution to model theoretical wind probability distributions via the equation:

$$F(U) = 1 - \exp\left[-\frac{\pi}{4}\left(\frac{U}{U_{av}}\right)^2\right]$$

Where F(U)=the cumulative distribution function, U = wind speed, Uav= average wind speed

Calculations were performed for a series of sites with annual mean wind speed values of 5.6, 6.4, 7.0, 7.5, 8.0, 8.5 and 8.8 m/s at 50 m, representing the limits of wind resource classes. Class 1 (0-5.6 m/s) and Class 2 (5.6-6.4 m/s) sites are not considered viable for commercial production, while Class 4 (7.0-7.5 m/s) sites and higher classes are considered commercially viable; Class 3 (6.4-7.0 m/s) sites may be developed under some circumstances. We used cumulative probabilities from the Rayleigh distribution to estimate the proportion of the year the wind speed fell into each 1 m/s bin (e.g. 0-1 m/s, 1-2 m/s, etc.) at each theoretical site. For each site, we then used power curves for the 2 MW and 5 MW NREL reference turbines to calculate annual energy generation for each 1 m/s bin. We summed the energy production over all bins and over the 0-6 m/s bins (these bins represent the wind speeds subject to the standard curtailment regime). We then divided the 0-6 m/s value by total energy production, to evaluate the contribution of energy generated at wind speeds that could be curtailed to total annual energy production at each theoretical site. This calculation resulted in a maximum energy loss due to curtailment, as additional curtailment conditions (temperature, hour of day, and season) further reduce the need for curtailment.

Table 2.1: Acoustic study sites surveyed on Nantucket, 2015-2016. Numbers before station refer to map locations in Figure 1. *Due to the large volume of calls we did not separate noise files from probable bat call files at this site before performing auto-classification analysis.

Station	Site description	Dates deployed	Nights analyzed (% of nights deployed)	Nights with bat activity (% of nights analyzed)	Total bat calls
(1) Gibbs Farm	scrub oak edge of large kettle pond, near active cranberry bog and hardwood forest	8/25/2015 - 11/13/2015	55 (69%)	13 (24%)	93
(2) Medouie 1	shrub treeline on edge of salt marsh	4/29/2015 - 11/13/2015	114 (58%)	40 (35%)	161
(3) Medouie 2	shrub edge of brackish marsh, surrounded by mature forested and shrub swamp	4/30/2015 - 11/13/2015	166 (84%)	44 (27%)	419
(4) Norwood 1	small kettle pond surrounded by scrub oak shrubland	4/30/2015 - 11/13/2015	184 (93%)	102 (55%)	551
(5) Norwood 2	forest edge in mosaic of fields, scrub oak, and hardwood forest	4/30/2015 - 11/13/2015	165 (84%)	119 (72%)	691
(6) Squam 1	hardwood forest edge by grazed field	4/29/2015 - 11/13/2015	138 (70%)	49 (36%)	755
(7) Squam 2	clearing in hardwood forest	4/29/2015 - 8/21/2015	104 (100%)	24 (23%)	61
(8) Stump 1	scrub oak edge of large pond, surrounded by hardwood forest	4/30/2015 - 11/13/2015	182 (92%)	136 (75%)	2821
(9) Stump 2	field adjacent to scrub oak wetland, surrounded by mosaic of hardwood forest and fields	4/30/2015 - 11/13/2015	136 (69%)	67 (49%)	286
(6) Squam 1	hardwood forest edge by grazed field	5/2/2016 - 12/7/2016	201 (91%)	107 (53%)	3876
(8) Stump 1	scrub oak edge of large pond, surrounded by hardwood forest	5/2/2016 -7/24/2016	84 (100%)	39 (46%)	535
(10) Ram Pasture	edge of shrub forest near pitch pine stand, wetland complex	5/2/2016-12/12/2016	186 (83%)	152 (82%)	58,000*
(11) West Hummock	low shrub edge large pond	5/2/2016-8/14/2016	91 (87%)	52 (57%)	627
(12) Lost Farm	pitch pine forest edge by field, large pond nearby	5/2/2016-12/12/2016	115 (51%)	42 (37%)	2024
(13) Sconset	east side of small wetland, in hardwood stand	8/19/2016-10/13/2016	42 (75%)	25 (60%)	339
(14) Pout Pond	grassy pond shore edge	7/25/2016-12/7/2016	120 (88%)	52 (43%)	266
(15) Beattie	forested residential area	11/4/2016-12/10/2016	37 (100%)	7 (19%)	13

Table 2.2: Bat species estimated to be present at 14 stations on Nantucket in 2015 and 2016 based on EchoClass software. *P* value indicates the likelihood the species was misidentified. Squam 2 (2015) and Beatties (2016) are not shown due to lack of calls identified to species at these sites. N=# of nights with calls, C=# of calls. LABO=*Lasiurus borealis*, LACI=*L. cinereus*, LANO=*Lasionycteris noctivagans*, EPFU=*Eptesicus fuscus*, MYLE=*Myotis leibii*, MYLU=*M. lucifugus*, MYSE=*M. septentrionalis*, MYSO=*M. sodalis*, PESU=*Perimyotis subflavus*.

	Species presence								
Station	LABO	LACI	LANO	EPFU	MYLE	MYLU	MYSE	MYSO	PESU
Gibbs Farm 2015	$P > 0.1$ (3N, 3C)	-	-	$P > 0.1$ (1N, 1C)	-	-	-	$P > 0.1$ (1N, 1C)	-
Medouie 1 2015	$P = 0$ (3N, 5C)	$P > 0.1$ (1N, 1C)	-	$P > 0.1$ (1N, 1C)	-	-	-	-	-
Medouie 2 2015	$P=0$ (12N, 28C)	$P = 0.023$ (6N, 10C)	$P = 0$ (3N, 30C)	$P = 0$ (2N, 16C)	-	-	-	-	$P > 0.1$ (1N, 1C)
Norwood 1 2015	$P = 0$ (12N, 19C)	-	-	$P > 0.1$ (1N, 1C)	-	-	-	-	$P > 0.1$ (1N, 1C)
Norwood 2 2015	$P > 0.1$ (4N 4C)	-	-	-	-	-	-	-	-
Squam 1 2015	$P = 0$ (6N, 10C)	-	-	-	-	-	-	-	-
Stump 1 2015	$P = 0$ (29N, 111C)	$P = 0.0054$ (8N, 15C)	$P > 0.1$ (2N, 2C)	$P > 0.1$ (3N, 3C)	-	-	-	$P = 0$ (1N, 2C)	-
Stump 2 2015	$P = 0$ (10N, 12C)	-	-	-	-	-	-	-	-
Squam 1 2016	$P = 0$ (16N, 54C)	-	-	-	-	-	-	-	-
Stump 1 2016	$P = 0$ (3N, 14C)	-	-	-	-	-	-	-	-
Ram Pasture 2016	$P = 0$ (120N, 3932C)	$P = 0$ (24N, 94C)	$P > 0.1$ (2N, 2C)	$P = 0$ (3N, 4C)	$P > 0.1$ (33N, 86C)	$P = 0$ (14N, 24C)	$P = 0$ (100N, 1383C)	$P = 0$ (51N, 138C)	$P = 0$ (5N, 7C)
West Hummock 2016	$P = 0$ (12N, 27C)	$P = 1$ (3N, 3C)	$P > 0.1$ (1N, 1C)	-	-	-	$P > 0.1$ (2N, 2C)	$P > 0.1$ (1N, 1C)	-
Lost Farm 2016	$P = 0$ (27N, 186C)	$P > 0.1$ (1N, 1C)	$P = 0.086$ (3N, 4C)	$P > 0.1$ (2N, 2C)	-	$P > 0.1$ (1N, 1C)	$P = 0$ (17N, 60C)	$P = 0$ (7N, 15C)	-
Sconset 2016	$P = 0$ (1N, 4C)	$P > 0.1$ (1N, 1C)	-	-	-	-	-	-	-
Pout Pond 2016	$P = 0$ (24N, 64C)	-	-	-	-	$P > 0.1$ (1N, 1C)	$P > 0.1$ (5N, 5C)	$P > 0.1$ (3N, 3C)	$P = 0$ (1N, 1C)

Table 2.3: Bat species estimated to be present at 15 stations on Nantucket in 2015 and 2016 based on KaleidoscopePro software. *P*-value indicates the likelihood the species was misidentified at a site. Squam 2 (2015) not shown; 1 LACI call identified at this site. N=# of nights with calls, C=# of calls. LABO=*Lasiurus borealis*, LACI=*L. cinereus*, LANO=*Lasionycteris noctivagans*, EPFU=*Eptesicus fuscus*, MYLE=*Myotis leibii*, MYLU=*M. lucifugus*, MYSE=*M. septentrionalis*, MYSO=*M. sodalis*, PESU=*Perimyotis subflavus*.

	Species presence								
Station	LABO	LACI	LANO	EPFU	MYLE	MYLU	MYSE	MYSO	PESU
Gibbs Farm 2015	$P < 0.0001$ (3N, 6C)	-	$P < 0.0001$ (4N, 8C)	$P = 0.92$ (2N, 2C)	-	-	-	$P = 0.068$ (1N, 1C)	$P = 0.39$ (1N, 1C)
Medouie 1 2015	$P < 0.0001$ (8N, 9C)	$P = 0.27$ (2N, 2C)	$P < 0.0001$ (6N, 56C)	$P = 1$ (4N, 4C)	-	-	-	-	-
Medouie 2 2015	$P < 0.0001$ (17N, 46C)	$P < 0.0001$ (9N, 17C)	$P < 0.0001$ (9N, 130C)	$P = 1$ (5N, 20C)	-	-	$P = 0.15$ (1N, 1C)	-	$P = 0.15$ (3N, 4C)
Norwood 1 2015	$P = 1$ (18N, 41C)	$P < 0.0001$ (14N, 192C)	$P = 1$ (11N, 14C)	$P = 1$ (3N, 4C)	-	-	$P < 0.0001$ (2N, 5C)	$P = 0.59$ (1N, 1C)	-
Norwood 2 2015	$P < 0.0001$ (10N, 12C)	$P = 0.038$ (2N, 2C)	$P < 0.0001$ (5N, 16C)	$P = 1$ (1N, 1C)	-	-	-	-	-
Squam 1 2015	$P < 0.0001$ (10N, 18C)	$P = 0.74$ (1N, 1C)	$P < 0.0001$ (3N, 39C)	$P = 0.74$ (1N, 9C)	-	$P = 1$ (1N, 1C)	-	-	-
Stump 1 2015	$P < 0.0001$ (52N, 266C)	$P < 0.0001$ (12N, 29C)	$P < 0.0001$ (30N, 452C)	$P = 1$ (13N, 20C)	$P = 0.0057$ (2N, 3C)	$P = 1$ (5N, 11C)	-	$P < 0.0001$ (2N, 6C)	$P = 1$ (1N, 2C)
Stump 2 2015	$P < 0.0001$ (6N, 7C)	-	$P = 1$ (3N, 3C)	-	-	-	$P < 0.0001$ (5N, 6C)	-	-
Squam 1 2016	$P = 0$ (57N, 102C)	$P = 0$ (13N, 13C)	P=0.0001 (19N, 19C)	$P = 0.24$ (11N, 11C)	-	$P = 0$ (10N, 25C)	$P = 0.028$ (3N, 4C)	-	$P = 1$
Stump 1 2016	$P = 0.0082$ (2N, 2C)	$P < 0.0001$ (5N, 5C)	$P = 1$ (1N, 1C)	$P < 0.0001$ (2N, 8C)	-	-	$P = 0$ (4N, 18C)	-	-
Ram Pasture 2016	$P = 0$ (98N, 2125C)	$P = 0$ (23N, 132C)	$P = 1$ (31N, 156C)	$P = 0$ (109N, 1363C)	$P = 0$ (65N, 223C)	$P = 0$ (93N, 779C)	$P = 0$ (122N, 6764C)	$P = 1$ (75N, 249C)	$P = 1$ (29N, 65C)
West Hummock 2016	$P = 0$ (6N, 14C)	$P = 0$ (6N, 15C)	$P = 1$ (2N, 2C)	$P = 0.0091$ (4N, 6C)	$P = 0.030$ (1N, 1C)	$P = 1$ (1N, 1C)	$P = 0$ (15N, 24C)	-	$P = 0. 20$ (2N, 2C)
Lost Farm 2016	$P = 0$ (12N, 34C)	$P = 0.17$ (1N, 2C)	$P = 1$ (4N, 5C)	$P = 0$ (15N, 26C)	$P < 0.0001$ (3N, 4C)	$P < 0.0001$ (17N, 37C)	$P = 0$ (27N, 341C)	$P = 1$ (9N, 10C)	$P = 0.00030$ (3N, 4C)
Sconset 2016	$P < 0.00001$ (4N, 6C)	$P < 0.0001$ (2N, 4C)	-	-	-	-	-	-	$P = 0.38$ (1N, 1C)
Pout Pond 2016	$P = 0$ (29N, 110C)	-	$P = 0.012$ (2N, 3C)	$P = 1$ (1N, 1C)	$P = 0.28$ (1N, 1C)	$P = 0.073$ (14N, 19C)	$P = 0$ (22N, 30C)	$P = 0.18$ (6N, 6C)	$P < 0.0001$ (7N, 11C)
Beatties 2016	$P = 0.041$ (1N, 1C)	-	-	-	-	-	-	-	-

Table 2.4: Morphological data and tracking information for Northern Long-eared Bats captured on Nantucket, Massachusetts.

Capture date	Capture location	Bat ID	Age	Sex	Reproductive status	Forearm length (mm)	Body mass (g)	Days tracked	Roosts identified
7/20/2016	Ram Pasture	F259	adult	female	lactating	36.9	7.6	2	2
7/20/2016	Ram Pasture	n/a	juvenile	female	non-reproductive	36.2	5.7	-	-
7/20/2016	Ram Pasture	n/a	juvenile	female	non-reproductive	37.5	6.4	-	-
7/20/2016	Ram Pasture	F264	adult	female	lactating	36.5	7.1	2	1
7/20/2016	Ram Pasture	n/a	juvenile	female	non-reproductive	36.7	6.4	-	-
7/20/2016	Ram Pasture	n/a	juvenile	female	non-reproductive	37.0	6.4	-	-
7/20/2016	Ram Pasture	F247	adult	female	lactating	37.0	6.7	<1	0
7/20/2016	Ram Pasture	n/a	juvenile	male	non-reproductive	35.8	5.8	-	-
7/20/2016	Ram Pasture	n/a	adult	female	lactating	36.4	7.0	-	-
10/30/2016	Ram Pasture	M269	adult	male	non-reproductive	36.1	9.0	12	1
11/1/2016	crawl space	F272	adult	female	non-reproductive	35.3	7.2	7	1
11/1/2016	crawl space	F260	adult	female	post-lactating	36.8	8.7	24	1
11/1/2016	crawl space	M257	adult	male	non-reproductive	35.2	8.4	20	1

Table 3.1: Automated telemetry stations deployed on Naushon Island and Martha's Vineyard in 2016 as part of this study.

Site name	Latitude	Longitude	Installation	Deconstruction	Receiver type	Installation type
Goethals	41.4463	-70.6691	6/16/2016	11/27/2016	Sensorgnome	9 m pop-up mast, 3 antennae
Cedar Tree Neck	41.4274	-70.7021	6/14/2016	11/28/2016	Lotek	6 m Rohn tower, 6 antennae
Hoft Farm	41.4466	-70.6482	6/13/2016	11/26/2016	Lotek	12 m Rohn tower, 6 antennae
Naushon Island	41.4694	-70.7573	6/19/2016	12/6/2016	Lotek	12 m lighthouse tower, 6 antennae

Table 3.2: Bats tagged and tracked in 2015 on Martha's Vineyard. All tagged bats were adult female northern long-eared bats. No bats were recorded by off-island telemetry stations.

Capture details						
ID	**Datetime**	**Site type**	**Latitude**	**Longitude**	**Days tracked post-capture**	**Nearest automated telemetry station (km)**
248	6/2/2015 21:10	Trails, wetland area	41.45024	-70.6438	7	Waquoit, Cape Cod (16)
252	6/2/2015 21:10	Trails, wetland area	41.45024	-70.6438	17	Waquoit, Cape Cod (16)
255	6/2/2015 22:15	Trails, wetland area	41.45024	-70.6438	10	Waquoit, Cape Cod (16)
266	6/18/2015 20:45	House roost	41.45319	-70.6410	17	Waquoit, Cape Cod (16)
253	6/24/2015 20:43	House roost	41.45319	-70.6410	8	Waquoit, Cape Cod (16)
256	6/24/2015 20:41	House roost	41.45319	-70.6410	9	Waquoit, Cape Cod (16)
248B	6/24/2015 20:39	House roost	41.45319	-70.6410	10	Waquoit, Cape Cod (16)
255B	6/24/2015 20:43	House roost	41.45319	-70.6410	4	Waquoit, Cape Cod (16)
256B	7/20/2015 23:00	Forest trails	41.36421	-70.5768	3	Waquoit, Cape Cod (21)
282	9/3/2015 20:25	Forested trails by brook	41.35391	-70.7258	15	Noman's Island (13)
285	9/19/2015 13:32	Bird nest box	41.41166	-70.5719	17	Waquoit, Cape Cod (16)

Table 3.3 Bats tagged in 2016 on Martha's Vineyard. All tagged bats were adult females, with the exception of LABO 470 and 473, which were adult males. MYSE=*Myotis septentrionalis*, MYLU=*Myotis lucifugus*, LABO=*Lasiurus borealis*, EPFU=*Eptesicus fuscus*. House roost coordinates are approximate; distance to nearest telemetry station is accurate.

	Capture details					
ID	**Datetime**	**Site type**	**Latitude**	**Longitude**	**Days tracked post-capture**	**Nearest automated telemetry station (km)**
MYSE 277	7/6/2016 23:38	House roost	41.45063	-70.6424	12	Hoft (0.7)
MYSE 280	7/6/2016 20:38	House roost	41.45063	-70.6424	5	Hoft (0.7)
MYSE 279	7/6/2016 21:00	House roost	41.45063	-70.6424	9	Hoft (0.7)
MYSE 284	7/6/2016 21:05	House roost	41.45063	-70.6424	5	Hoft (0.7)
MYSE 284B	7/14/2016 20:30	House roost	41.42385	-70.57289	7	Hoft (6.7)
MYSE 280B	7/14/2016 20:32	House roost	41.42385	-70.57289	4	Hoft (6.7)
MYLU 276	7/19/2016 15:15	Barn roost	41.4138	-70.7045	16	Cedar Tree Neck (1.5)
MYLU 286	8/15/2016 20:01	Barn roost	41.4138	-70.7045	16	Cedar Tree Neck (1.5)
MYLU 278	8/15/2016 20:02	Barn roost	41.4138	-70.7045	22	Cedar Tree Neck (1.5)
MYSE 283	8/21/2016 22:45	Forested trails	41.3672	-70.6241	9	Hoft (9.0)
MYSE 281	10/13/2016 18:35	Forested trails	41.4133	-70.7065	39	Cedar Tree Neck (1.6)
LABO 473	10/17/2016 18:40	Woods road, parking area, trails	41.4322	-70.6972	0	Cedar Tree Neck (0.7)
EPFU 271	10/17/2016 19:05	Woods road, parking area, trails	41.4322	-70.6972	0	Cedar Tree Neck (0.7)
LABO 475	10/18/2016 18:10	Woods road, parking area, trails	41.4322	-70.6972	0	Cedar Tree Neck (0.7)
LABO 470	10/21/2016 18:10	Woods road	41.4477	-70.6516	0	Hoft (0.3)
EPFU 275	10/21/2016 18:30	Woods road	41.4477	-70.6516	18	Hoft (0.3)
EPFU 258	10/21/2016 18:30	Woods road	41.4477	-70.6516	18	Hoft (0.3)

Table 3.4: Roost sites and tower detections for northern long-eared bats tagged near the Hoft station in July 2016. These bats were never detected by the Goethals station. Coordinates listed for RT_09 are approximate.

ID	Date	Roost ID	Latitude	Longitude	Distance to Hoft station (km)	Distance to Goethals station (km)	Detected by Hoft station (hour:min)
MYSE 277	7/6/2016	RT09	41.45063	-70.6424	0.69	2.24	-
	7/7/2016	RT09	41.45063	-70.6424	0.69	2.24	21:04-21:14; 0:01-0:35; 4:25-4:26
	7/8/2016	RT09	41.45063	-70.6424	0.69	2.24	8:03; 8:39-8:40; 11:45; 23:41-2:13
	7/9/2016	RT09	41.45063	-70.6424	0.69	2.24	21:31-21:32; 23:43-3:49
	7/10/2016	RT09	41.45063	-70.6424	0.69	2.24	1:00-2:47
	7/11/2016	RT09	41.45063	-70.6424	0.69	2.24	0:20-4:34
	7/12/2016	RT26	41.45766	-70.6395	1.42	2.77	0:01-0:16, 2:23-2:26
	7/13/2016[a]	-	-	-	-	-	-
	7/14/2016	RT28	41.45578	-70.6418	1.15	2.51	-
	7/15/2016	RT30	41.45497	-70.6408	1.11	2.55	-
	7/16/2016	RT30	41.45497	-70.6408	1.11	2.55	-
	7/17/2016	RT30	41.45497	-70.6408	1.11	2.55	-
	7/18/2016[b]	-	41.45497	-70.6408	1.11	2.55	-
MYSE 279	7/6/2016	RT09	41.45063	-70.6424	0.69	2.24	-
	7/7/2016	RT09	41.45063	-70.6424	0.69	2.24	19:53; 0:22
	7/8/2016	RT09	41.45063	-70.6424	0.69	2.24	10:02; 10:15; 22:10; 23:05-23:14; 2:19; 4:40; 4:44

	7/9/2016	RT09	41.45063	-70.6424	0.69	2.24	21:44; 0:54; 2:02; 3:04-3:26
	7/10/2016	RT09	41.45063	-70.6424	0.69	2.24	15:27-18:02; 19:21-22:27; 1:30-4:02
	7/11/2016	RT09	41.45063	-70.6424	0.69	2.24	11:10-23:18; 0:26-4:47
	7/12/2016	RT09	41.45063	-70.6424	0.69	2.24	20:46-21:10; 0:11-2:20
	7/13/2016	RT27	41.45236	-70.6369	1.14	2.77	22:48-22:54; 2:38
	7/14/2016	RT29	41.45732	-70.6478	1.19	2.16	-
	7/15/2016[b]	-	41.45868	-70.6478	1.34	2.25	-
MYSE 280	7/6/2016	RT09	41.45063	-70.6424	0.69	2.24	-
	7/7/2016	RT09	41.45063	-70.6424	0.69	2.24	20:57-4:21
	7/8/2016	RT09	41.45063	-70.6424	0.69	2.24	20:46-4:46
	7/9/2016	RT09	41.45063	-70.6424	0.69	2.24	-
	7/10/2016	RT09	41.45063	-70.6424	0.69	2.24	-
	7/11/2016	RT09	41.45063	-70.6424	0.69	2.24	-
MYSE 284	7/6/2016	RT09	41.45063	-70.6424	0.69	2.24	-
	7/7/2016	RT25	41.45414	-70.6469	0.84	2.05	22:50-22:53; 3:08-3:26
	7/8/2016	RT09	41.45063	-70.6424	0.69	2.24	21:50-23:44; 2:11
	7/9/2016	RT09	41.45063	-70.6424	0.69	2.24	11:36; 20:46; 23:12-23:57; 3:00-6:29
	7/10/2016	RT09	41.45063	-70.6424	0.69	2.24	20:40-22:42
	7/11/2016	RT09	41.45063	-70.6424	0.69	2.24	8:13-12:59

[a] Roost not found [b] Dropped tag

Table 3.5: Automated detections of tagged bats while in roost (i.e. during daylight hours). Bats were only detected intermittently while in roosts, and only by the telemetry station antenna with the bearing closest to that of the actual bearing from the telemetry station to the roost site. Northern long-eared bats were only detected at the RT09 house roost, 0.69 km from the Hoft station. EPFU 258 was 0.78 km from the Hoft station.

ID	**Roost**	**Latitude**	**Longitude**	**Station**	**Actual bearing: Station to roost**	**Datetime detected**	**Antenna**	**Antenna bearing**
MYSE 277	RT09	41.45063	-70.6424	Hoft	37.5	7/8/2016 8:03	2	55
	RT09	41.45063	-70.6424	Hoft	37.5	7/8/2016 8:39-8:40	2	55
	RT09	41.45063	-70.6424	Hoft	37.5	7/8/2016 11:45	2	55
MYSE 279	RT09	41.45063	-70.6424	Hoft	37.5	7/8/2016 10:02-10:03	2	55
	RT09	41.45063	-70.6424	Hoft	37.5	7/8/2016 10:15	2	55
	RT09	41.45063	-70.6424	Hoft	37.5	7/10/2016 15:27	2	55
	RT09	41.45063	-70.6424	Hoft	37.5	7/10/2016 18:02-18:05	2	55
	RT09	41.45063	-70.6424	Hoft	37.5	7/10/2016 19:21-19:36	2	55
	RT09	41.45063	-70.6424	Hoft	37.5	7/11/2016 11:10-15:25	2	55
	RT09	41.45063	-70.6424	Hoft	37.5	7/11/2016 19:49	2	55
MYSE 284	RTO9	41.45063	-70.6424	Hoft	37.5	7/9/2016 11:36	2	55
	RT09	41.45063	-70.6424	Hoft	37.5	7/11/2016 8:13-12:59	2	55
EPFU 258	EP2	41.4527	-70.6529	Hoft	330.0	10/22/2016 7:05-13:12	1	355

Table 3.6: Roost sites and local tower detections for little brown bats (MYLU) and big brown bats (EPFU) tagged on Martha's Vineyard in 2016.

ID	Date Tagged	Roost type	Detected at roost	Absent from roost	Hoft	Goethals	Cedar Tree Neck	Naushon
MYLU 276	7/19	Barn, maternity colony	7/21, 7/26	8/4 - dropped tag found	-	-	-	-
MYLU 286	8/15	Barn, maternity colony	8/18, 8/21, 8/24	8/29, 8/31, 9/6	8/16 20:21-21:06; 8/17 20:38-21:29; 8/18 0:54-1:09; 8/24 22:42-22;23; 8:25 20:10-20:12	-	8/17 22:45-23:41; 8/18 1:20-3:15; 8/19 23:36-23:49; 8/23 0:50-5:06; 8/24 1:26-4:39	-
MYLU 278	8/15	Barn, maternity colony	8/18, 8/21, 8/24, 8/29, 8/31	9/6	8/23 20:29-23:11	-	8/17 22:24-23:44; 8/18 2:24; 8/19 4:52, 23:02; 8/31 20:18; 9/1 22:40-22:41	8/19 23:16-23:59; 8/20 0:00-2:48; 8/21 3:50-3:52; 8/22 4:03-4:06; 8/23 20:25-20:26; 8/31 20:16-20:17
EPFU 258	10/21	tree	10/22-10/30, 11/8	-	10/21 22:30-10/22 13:12; 11/3 18:08-20:31; 11/15 21:24-22:01	11/16 2:09-2:12	-	-
EPFU 275	10/21	house	10/22-10/30, 11/8	-	-	-	-	-
EPFU 271	10/17	on sanctuary, not tracked to precise location	10/25, 10/29	-	11/3 19:56-19:58	-	-	-

Table 3.7: Motus network detections for little brown bats (MYLU) and one eastern red bat (LABO) tagged on Martha's Vineyard that were detected by telemetry stations outside of the study area.

ID	Last study area detection		Network detection	
	Datetime	**Location**	**Datetime**	**Location**
MYLU 276	7/27/2016, 8/4/2016 (dropped tag)	manual detection at barn roost site	7/27/2016 20:36-20:38	Noman's Island, MA
MYLU 286	8/25/2016 20:12	Hoft	8/26/2016 0:26-0:34	Falmouth, MA
			8/26/2016 3:15-3:16	Welfleet, MA
LABO 473	10/19/2016 21:41	Naushon	10/20/2016 5:09-5:15	Cape May, NJ
			10/24/2016 18:33-18:59	Skidmore Island, VA

Table 3.8: Detections of NanoTags from other projects by the telemetry stations deployed on Martha's Vineyard and Naushon Island in 2016.

Station	Detection date	ID #	Species	Date deployed	Location deployed
Hoft	7/20/2016	5504	Black-crowned Night-Heron	7/15/2015	Oak Harbor, OH
Hoft	7/24/2016	5504	Black-crowned Night-Heron	7/15/2015	Oak Harbor, OH
Goethals	7/24/2016	6158	Semipalmated Plover	6/25/2016	unknown
Hoft	7/24/2016	6158	Semipalmated Plover	6/25/2016	unknown
Hoft	7/26/2016	8402	Black-crowned Night-Heron	6/14/2016	West Sister Island, OH
Hoft	7/26/2016	8849	Sanderling	5/28/2016	Chaplin Lake, SASK
Naushon	7/26/2016	8849	Sanderling	5/28/2016	Chaplin Lake, SASK
Goethals	7/27/2016	8849	Sanderling	5/28/2016	Chaplin Lake, SASK
Hoft	7/29/2016	8403	Black-crowned Night-Heron	6/14/2016	West Sister Island, OH
Hoft	7/29/2016	8424	Black-crowned Night-Heron	7/5/2016	West Sister Island, OH
Hoft	7/30/2016	5504	Black-crowned Night-Heron	7/15/2015	Oak Harbor, OH
Hoft	7/30/2016	8403	Black-crowned Night-Heron	6/14/2016	West Sister Island, OH
Hoft	7/30/2016	8423	Black-crowned Night-Heron	6/21/2016	West Sister Island, OH
Hoft	7/31/2016	8402	Black-crowned Night-Heron	6/14/2016	West Sister Island, OH
Hoft	8/1/2016	8402	Black-crowned Night-Heron	6/14/2016	West Sister Island, OH
Hoft	8/1/2016	8417	Black-crowned Night-Heron	6/21/2016	West Sister Island, OH
Hoft	8/2/2016	8402	Black-crowned Night-Heron	6/14/2016	West Sister Island, OH
Hoft	8/2/2016	8410	Black-crowned Night-Heron	6/21/2016	West Sister Island, OH
Hoft	8/3/2016	8410	Black-crowned Night-Heron	6/21/2016	West Sister Island, OH
Naushon	8/11/2016	7889	Sanderling	5/22/2016	unknown
Naushon	8/19/2016	10387	Semipalmated Plover	8/8/2016	James Bay, ONT
Naushon	8/29/2016	6198	Sanderling	7/9/2016	Polar Bear Pass, NUN
Naushon	9/1/2016	8935	Semipalmated Sandpiper	8/27/2016	unknown
Naushon	9/4/2016	8602	Semipalmated Sandpiper	8/8/2016	Popham Beach, ME
Naushon	9/5/2016	8939	Semipalmated Sandpiper	8/27/2016	unknown

Naushon	9/23/2016	6162	Semipalmated Plover	9/7/2016	unknown
Naushon	10/11/2016	9526	Red-eyed Vireo	10/8/2016	Block Island, RI
Naushon	10/26/2016	9126	Saltmarsh Sparrow	10/3/2016	Newburyport, MA
Goethals	10/27/2016	9126	Saltmarsh Sparrow	10/3/2016	Newburyport, MA
Goethals	10/31/2016	9490	Saltmarsh Sparrow	10/6/2016	Wells, ME
Goethals	11/12/2016	9133	Sharp-tailed Sparrow	10/13/2016	Newburyport, MA
Goethals	11/19/2016	9557	Hermit Thrush	11/7/2016	Block Island, RI

Table 4.1 Capture effort and bats tagged at mist-netting locations along the New England coast.

Region	Location	Year	Number of nights	Tagged bats	Distance to closest telemetry station (km)
Downeast/Acadia ME	Mount Desert Island, Acadia National Park	2014	7	2 LABO	7.75
		2015	34	6 LABO, 1 LACI	6.96, 7.75, 9.11
		2016	25	8 LABO, 1 LACI	0.73, 1.79, 2.19
	Isle au Haut	2015	4	0	28.90
	Schoodic Peninsula, Acadia National Park	2016	6	0	1.02
	Petit Manan Point NWR	2015	4	1 LABO	0.32
	Roque Bluffs	2015	2	0	5.15
	Jonesboro	2015	2	0	0.10
Coastal NH	Great Bay NWR	2014	8	2 LABO	0.15
		2015	4	3 LABO	1.89
Coastal MA	Parker River NWR	2014	2	1 LABO	2.36
		2015	2	1 LABO	2.36
		2016	7	12 LABO, 1 LACI	0.41
Islands, MA	Martha's Vineyard	2016	13	3 LABO	0.31, 0.67
	Nantucket	2016	2	0	2.38

Table 4.2: Tracking summary data for tagged eastern red and hoary bats. M=male, F=female, A=adult, J=juvenile, I=indeterminate, * indicates a northeastward movement, all other movements were southwestward. PMP, ME= Petit Manan Point, Maine; MDI, ME=Mt. Desert Island, ME; GB NWR, NH = Great Bay NWR, New Hampshire; PKR NWR, MA=Parker River NWR, Massachusetts; MV, MA=Martha's Vineyard, MA.

Individual ID	**Capture location**	**Capture datetime**	**Total time tracked (days)**	**Minimum capture site residency (days)**	**Distance traveled (km)**	**Average migration speed (km/night)**
Lasiurus borealis						
M507 (A)	Parker River NWR, MA	8/4/16 20:50	4.2	4.2	0.4	-
F110 (A)	Parker River NWR, MA	8/4/16 21:30	0.1	0.1	0.4	-
F505 (A)	Parker River NWR, MA	8/4/16 21:30	0.1	0.1	0.4	-
F116 (J)	Parker River NWR, MA	8/4/16 23:05	14.0	14.0	0.4	-
M508 (A)	Petit Manan Point, ME	8/10/15 22:00	3.1	3.1	0.3	-
F501 (A)	Mt. Desert Island, ME	8/19/15 22:00	42.0	14.0	470.2	11.2
F111 (A)	Parker River NWR, MA	8/22/16 20:30	7.1	5.0	145.5	20.4
M118 (A)	Parker River NWR, MA	8/22/16 20:30	12.0	12.0	0.4	-
F509 (A)	Parker River NWR, MA	8/22/16 21:15	1.0	1.0	4.1	-
F516 (A)	Parker River NWR, MA	8/22/16 22:55	1.6	1.6	0.4	-
F395 (A)	Parker River NWR, MA	8/22/16 23:35	1.9	1.9	4.1	-
M515 (J)	Mt. Desert Island, ME	8/23/15 21:15	0.2	0.2	0.0	-
M506 (A)	Mt. Desert Island, ME	8/24/16 0:30	12.8	12.8	0.7	-
M512 (A)	Mt. Desert Island, ME	8/26/16 0:45	2.1	1.8	27.1	13.2
F517 (J)	Mt. Desert Island, ME	9/1/15 20:15	2.3	-	173.7	74.6
F127 (A)	Great Bay NWR, NH	9/1/15 21:24	8.9	7.3	38.2	4.3
M126 (A)	Great Bay NWR, NH	9/2/15 21:26	1.1	1.1	1.9	-
M373 (A)	Mt. Desert Island, ME	9/5/14 19:35	29.3	-	449.0	15.3
M472 (I)	Parker River NWR, MA	9/6/16 22:15	19.0	19.0	0.4	-
M236 (J)	Parker River NWR, MA	9/7/16 20:30	18.0	4.0	134.7	7.5
M237 (A)	Parker River NWR, MA	9/7/16 20:30	4.0	4.0	0.4	-
M129 (J)	Parker River NWR, MA	9/9/15 19:30	5.3	-	187.6	35.6
M521 (A)	Mt. Desert Island, ME	9/16/15 0:15	12.1	-	803.0	66.5
M119 (J)	Great Bay NWR, NH	9/17/14 21:45	11.9	11.9	0.2	-

M115 (J)	Great Bay NWR, NH	9/18/14 21:19	9.0	8.9	38.2	4.3
F374 (I)	Mt. Desert Island, ME	9/23/15 19:00	3.1	3.1	2.7	-
M113 (J)	Parker River NWR, MA	9/25/14 17:45	3.2	3.2	4.2	-
M511 (A)	Mt. Desert Island, ME	9/26/14 22:10	2.9	1.1	85.4	29.8
M473 (A)	Martha's Vineyard, MA	10/17/16 18:40	7.0	2.1	655.9	93.5
F475 (A)	Martha's Vineyard, MA	10/18/16 18:10	24.0	24.0	20.6*	-
M470 (A)	Martha's Vineyard, MA	10/21/16 18:10	21.0	21.0	1.5	-
Lasiurus cinereus						
M393 (A)	Parker River NWR, MA	8/22/16 23:50	0.1	0.1	4.1	-
F520 (A)	Mt. Desert Island, ME	8/24/15 1:15	1.2	0.6	129.6*	-
F518 (A)	Mt. Desert Island, ME	8/31/16 20:05	1.0	-	27.1	26.2

Table 4.3: Speed of travel for bats detected moving > 20 km over the course of a single night.

Individual ID	Distance (km)	Speed (m/s)
Lasiurus borealis		
F501	27.5	27.8
M512	23.4	1.5
F517	24.8	14.5
F127	36.5	10.1
M115	38.2	10.8
M511	41.2	17.4
M129	62.9	18.9
M511	73.3	13.1
M521	83.2	24.8
M473	91.1	12.9
M236	134.3	10.6
M473	332.6	14.9
Lasiurus cinereus		
F520	21.1	12.1
F520	43.9	3.7

Table 5.1: Effects of standard curtailment on capacity factor, energy production and LMP-based revenue loss.

Region	Site (NOAA Station)	Year	**Capacity factor**		**Energy production loss *Standard curtailment* (%)**	**LMP revenue loss *Standard curtailment* (%)**	**LMP Region, source, & interval**
			No curtailment	***Standard curtailment***			
Northeast	Nantucket Sound, MA (44020)	2010	0.546	0.543	0.58	0.55	SEMASS, ISO New England, hourly data
		2011	0.501	0.497	0.76	0.68	
		2012	0.483	0.480	0.72	0.63	
	Montauk Point, NY (44017)	2007	0.531	0.527	0.73	0.54	Long Island, New York ISO, 10-minute data
		2013	0.535	0.531	0.65	0.38	
		2016	0.529	0.526	0.64	0.52	
	Long Island, NY (44025)	2010	0.539	0.535	0.74	0.55	Long Island, New York ISO, 10-minute data
		2012	0.500	0.496	0.76	0.62	
		2016	0.519	0.515	0.71	0.52	
Mid-Atlantic	Long Beach, NJ (44066)	2014	0.539	0.535	0.75	0.36	Indian River Substation, PJM Interconnection, hourly data
	Delaware Bay, DE (44009)	2006	0.467	0.462	0.99	0.75	Indian River Substation, PJM Interconnection, hourly data
		2007	0.470	0.465	1.06	0.79	
		2011	0.440	0.436	1.12	0.88	
Southeast	Frying Pan Shoals, NC (41013)	2006	0.521	0.518	0.70	n/a	n/a
		2012	0.540	0.536	0.65		
		2013	0.571	0.568	0.53		
	Charleston, SC (41004)	2011	0.524	0.520	0.73	n/a	n/a
		2015	0.560	0.556	0.59		
		2016	0.547	0.544	0.57		

Table 5.2: Effects of alternative curtailment requirements on energy production loss and capacity factor, using data from the Montauk Point station in 2016.

Alternative curtailment parameters	**Energy production loss (%)**	**Capacity factor**
no curtailment	0.00	0.529
standard curtailment	0.64	0.526
temperature to 8°C	0.70	0.525
temperature to 9°C	0.67	0.526
standard curtailment	0.64	0.526
temperature to 10.5°C	0.61	0.526
temperature to 11°C	0.59	0.526
temperature to 12°C	0.58	0.526
wind speed to 5.0 m/s	0.28	0.528
wind speed to 5.5 m/s	0.46	0.527
standard curtailment	0.64	0.526
wind speed to 6.5 m/s	0.98	0.524
wind speed to 7 m/s	1.32	0.522
wind speed to 7.5 m/s	1.87	0.519
wind speed to 8 m/s	2.49	0.516
wind speed to 8.25 m/s (equivalent of 6 m/s at 5 m)	2.82	0.514
curtailment July 15 to October 15	0.34	0.521
standard curtailment	0.64	0.526
curtailment year-round	0.74	0.525
curtailment sunset to sunrise	0.57	0.526
standard curtailment	0.64	0.526
curtailment 1 hour before sunset to 1 hour after sunrise	0.70	0.525
cut-in speed of 6 at all times	2.41	0.516
Alstom Haliade 6 MW, standard curtailment	0.71	0.640

Table 5.S1: Effects of standard curtailment at terrestrial sites, using a 2 MW reference turbine.

Site	Year(s)	Mean wind speed at hub height ± SD (m/s)	Energy production loss	Capacity factor		Energy generated at wind speeds <6 m/s (% of annual production)	Time curtailed (hours)
			Standard curtailment (%)	*No curtailment*	*Standard curtailment*		
Nantucket	2005-2006	8.84 ± 3.96	0.62	0.492	0.489	2.65	518
Truro	2006-2007	8.39 ± 3.56	0.62	0.447	0.444	3.18	425
Welfleet	2007	7.11 ± 3.46	1.75	0.312	0.306	7.02	844
Plymouth	2007-2008	5.79 ± 2.72	3.82	0.190	0.183	16.30	1172
Mt Tom	2008	4.15 ± 4.56	1.45	0.170	0.168	5.75	1163
Mt Tom	2009	6.10 ± 3.53	2.61	0.223	0.217	9.49	1096
Savoy	2005	4.66 ± 2.64	4.54	0.107	0.102	18.81	1452

Table 5.S2: The contribution of <6 m/s winds to annual energy production, for theoretical sites of varying mean wind speed, using the Rayleigh distribution. Mean wind speeds at 50 m represent the limits of wind power classes.

Wind power class	**Mean wind speed at 50 m (m/s)**	**Mean wind speed at 100 m ± Rayleigh SD (m/s)**	**Energy generated at wind speeds <6 m/s (% of annual production)**	
			2 MW onshore turbine	***5 MW offshore turbine***
Class 1	0.0	0.0	-	-
	5.6	6.18 ± 3.22	8.68	8.90
Class 2				
	6.4	7.07 ± 3.67	5.74	5.89
Class 3				
	7.0	7.73 ± 4.01	4.39	4.50
Class 4				
	7.5	8.28 ± 4.31	3.59	3.69
Class 5				
	8.0	8.83 ± 4.59	3.00	3.08
Class 6				
	8.8	9.71 ± 5.05	2.32	2.38
Class 7				
	11.9	13.14 ± 6.83	1.15	1.17

Figure 2.1: Acoustic sites (n = 15) monitored for bats on Nantucket from 2015–2016. Numbers refer to stations as listed in Table 1. Basemap courtesy of TerraMetrics (2017).

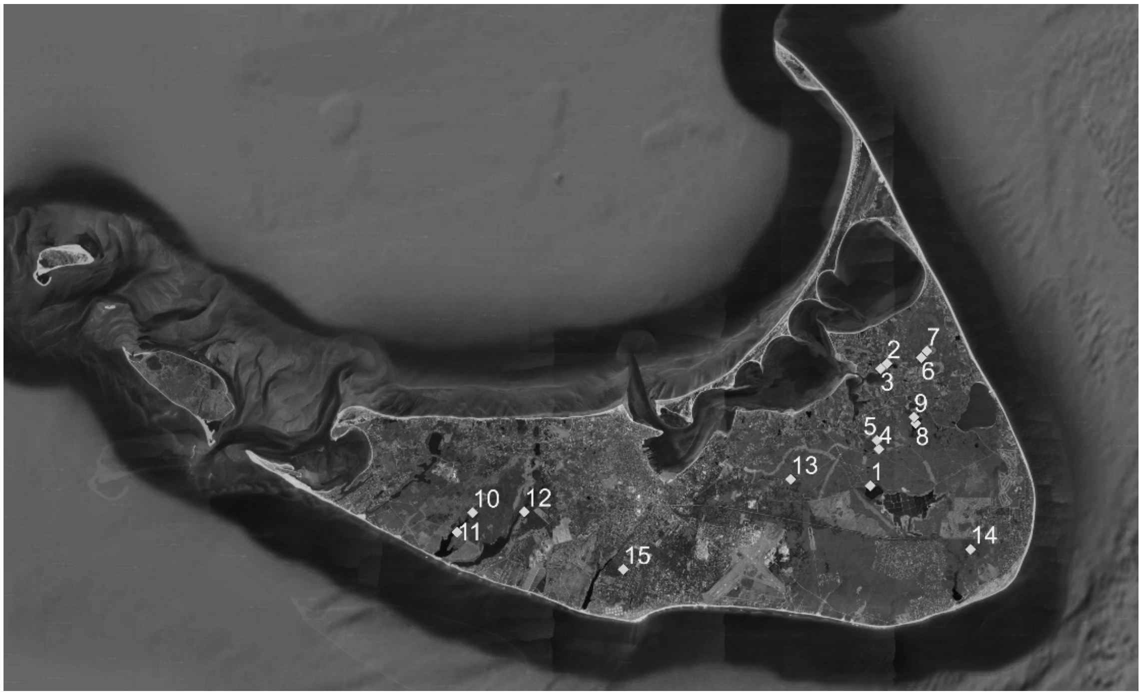


Figure 2.2: Seasonal variation in likelihood of bat detection by two-week period on Nantucket, Massachusetts in 2015 and 2016. Values are summed across all stations by year, except Ram Pasture (sampled 2016) is displayed separately, due to unusually high detection rates.

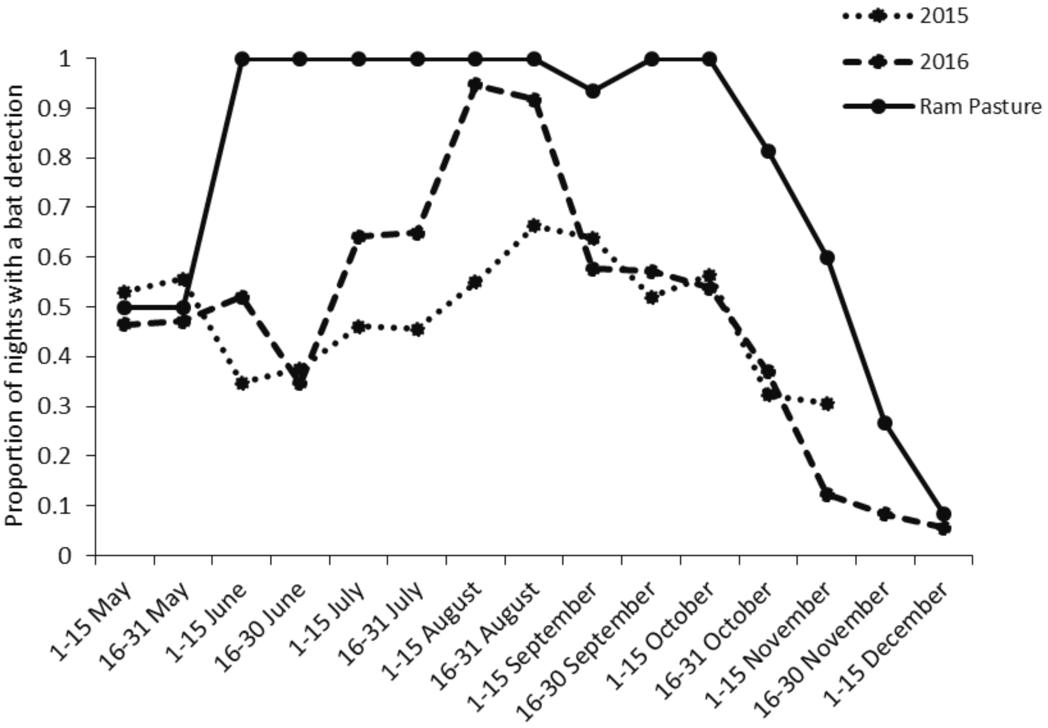


Figure 2.3: Temperature and relative humidity within the crawl space hibernation site during the hibernation period (15 November 2016 – 15 April 2017). Temperature logger failed to collect data after 24 February 2017.

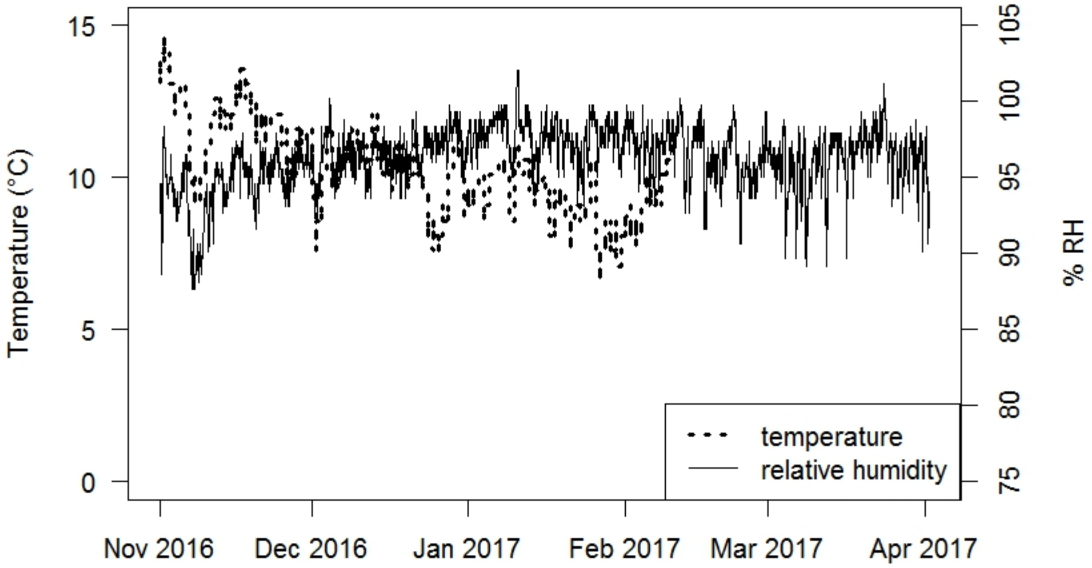


Figure 3.1: Local and regional telemetry stations in the Martha' Vineyard area. The four stations on Martha's Vineyard and Naushon Island were not deployed in 2015; the other stations were present in both years.

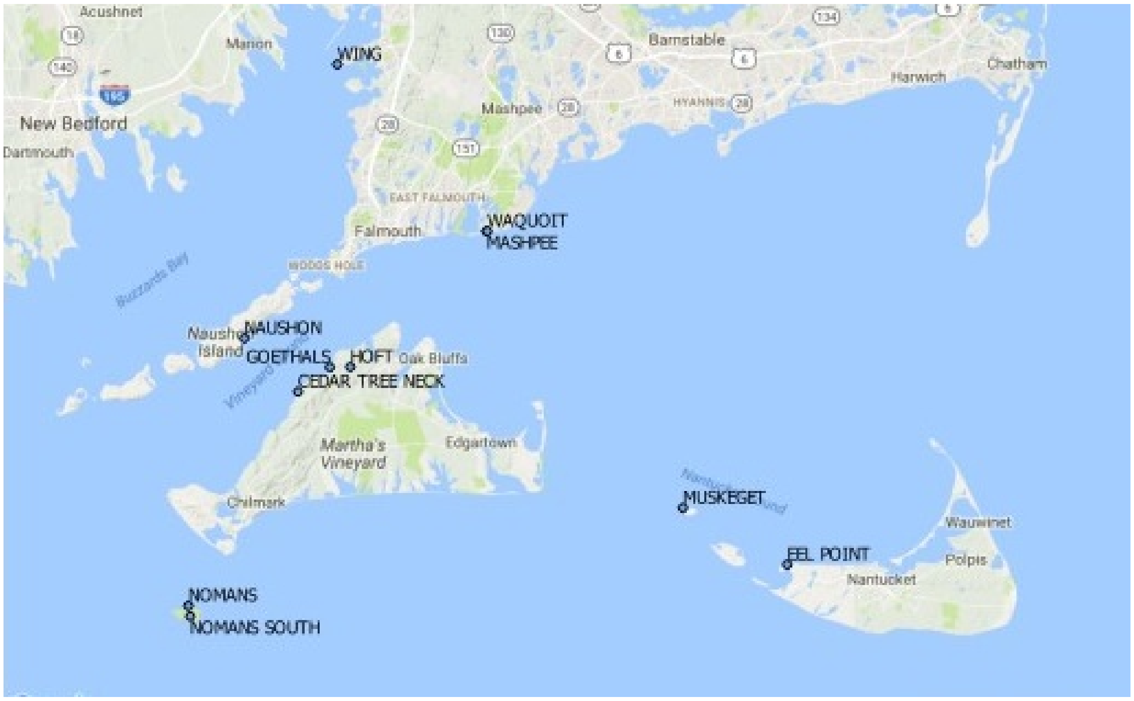


Figure 3.2: The northwest Martha's Vineyard study area, with local telemetry stations, mist-netting sites, and roost sites of northern long-eared bats in the study area in 2016.

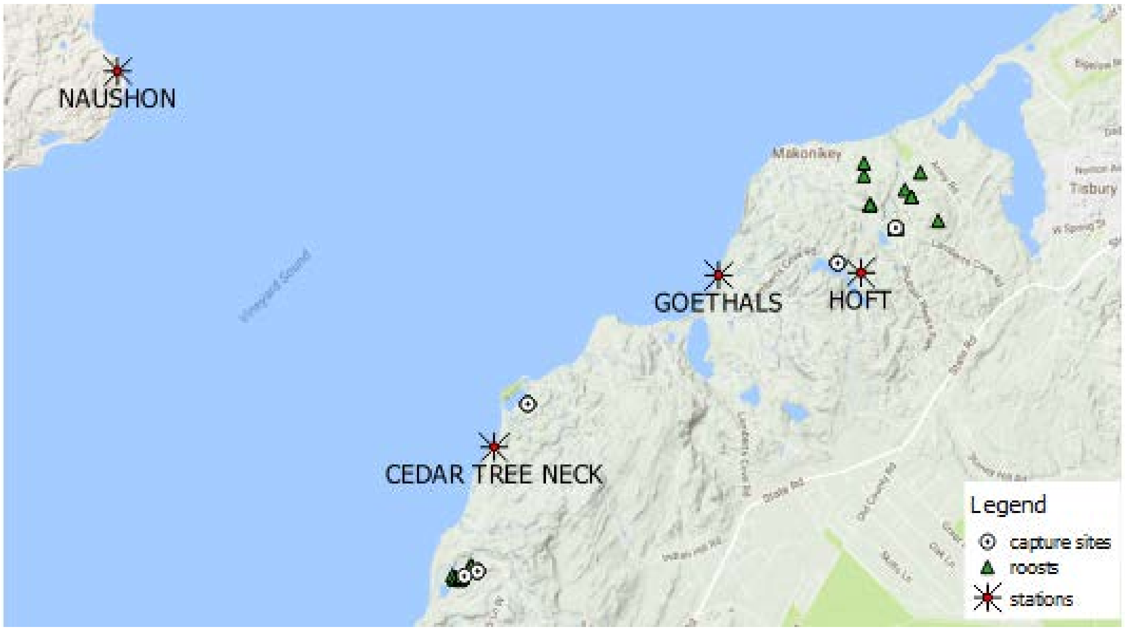
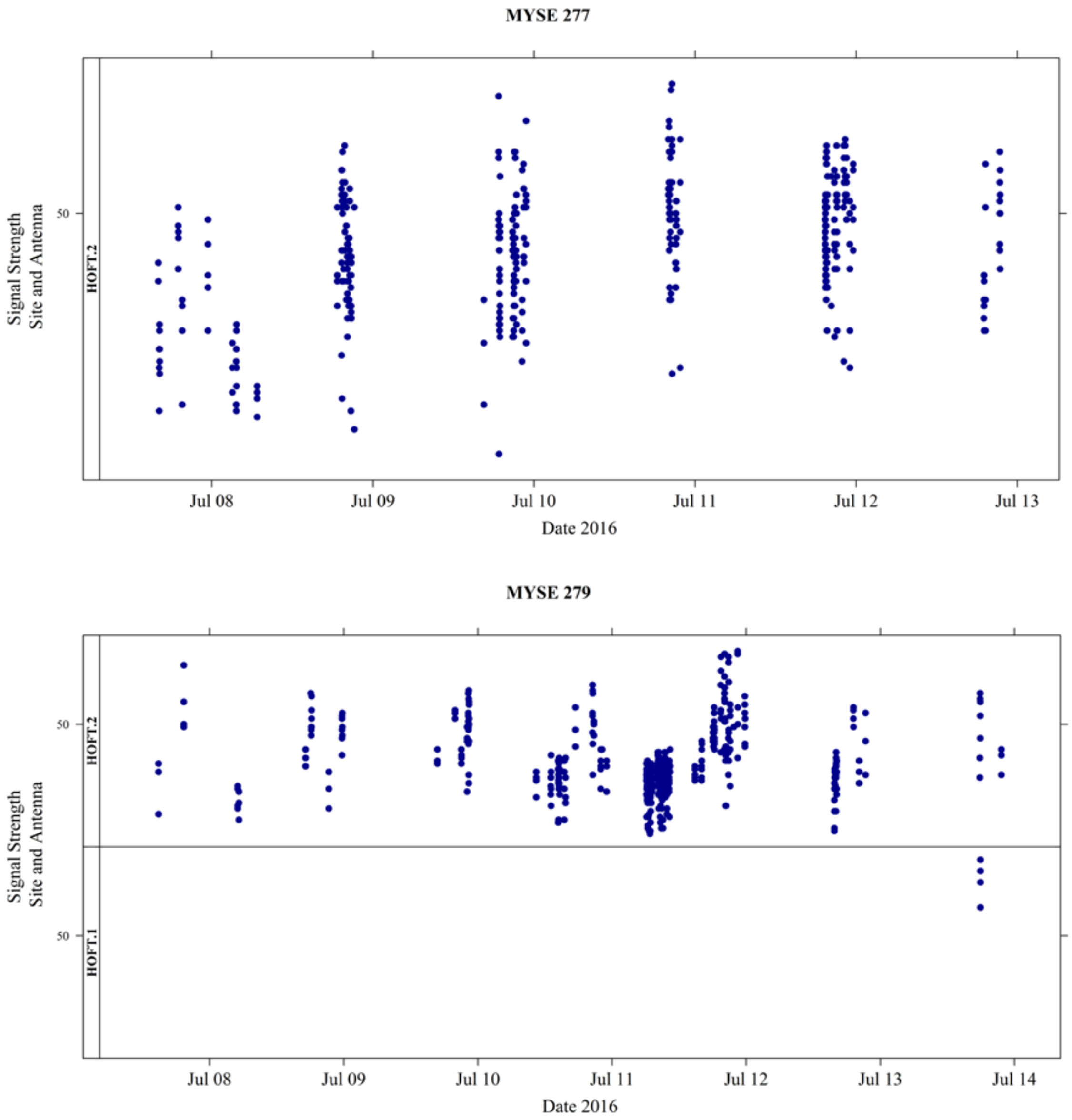
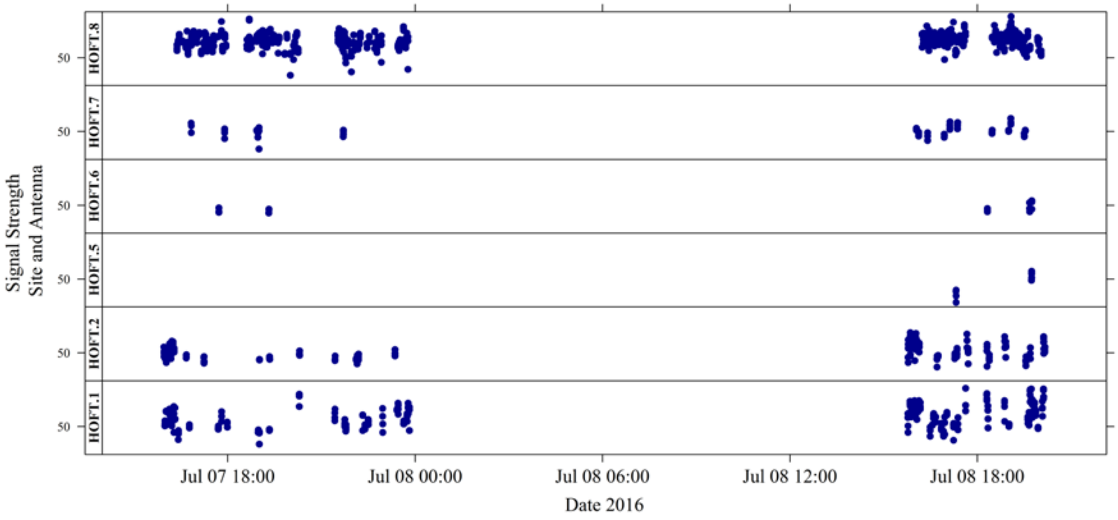


Figure 3.3: Local detection (signal strength versus time) plots for northern long-eared bats recorded by the Hoft telemetry station in July 2016. Three bats primarily foraged in the antenna 2 sector of the Hoft station. No northern long-eared bats were detected by other stations.



MYSE 277

MYSE 279


MYSE 280

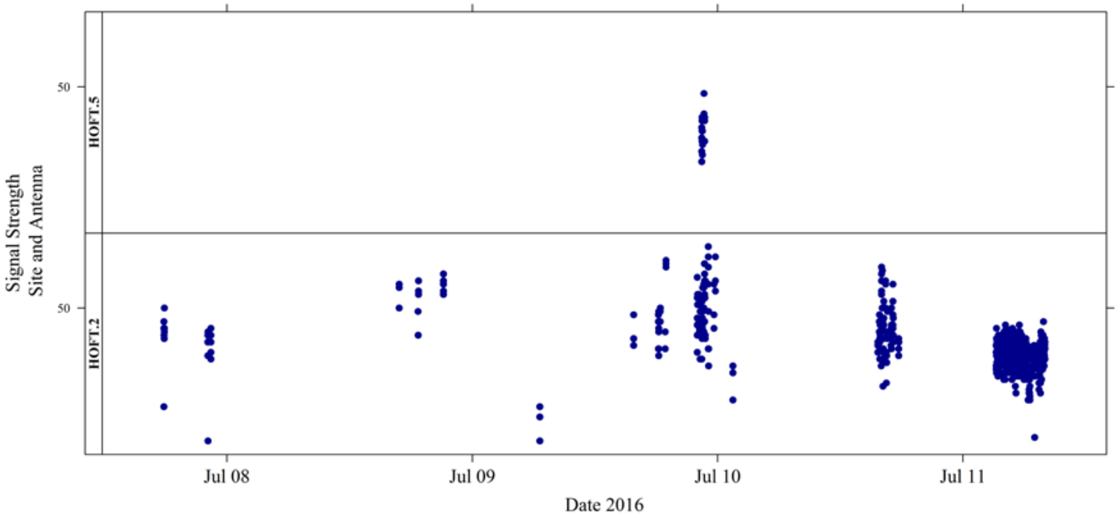
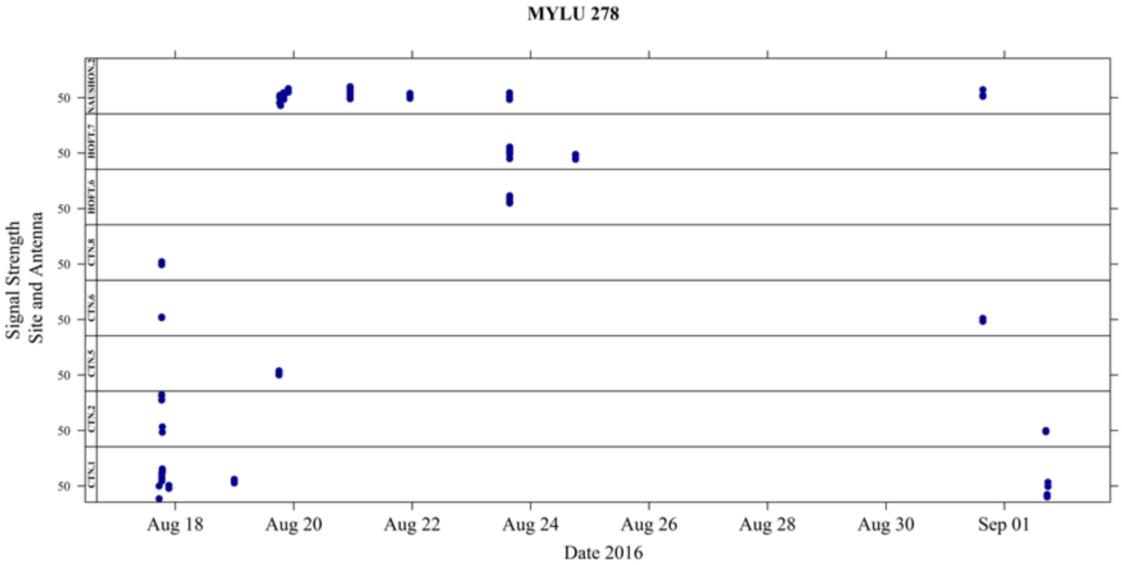

MYSE 284

Figure 3.4: Local detection (signal strength versus time) plots for two little brown bats intermittently recorded by multiple telemetry stations in the northwest Vineyard study area. MYLU 286 migrated off-island and was later recorded by two telemetry stations on Cape Cod.



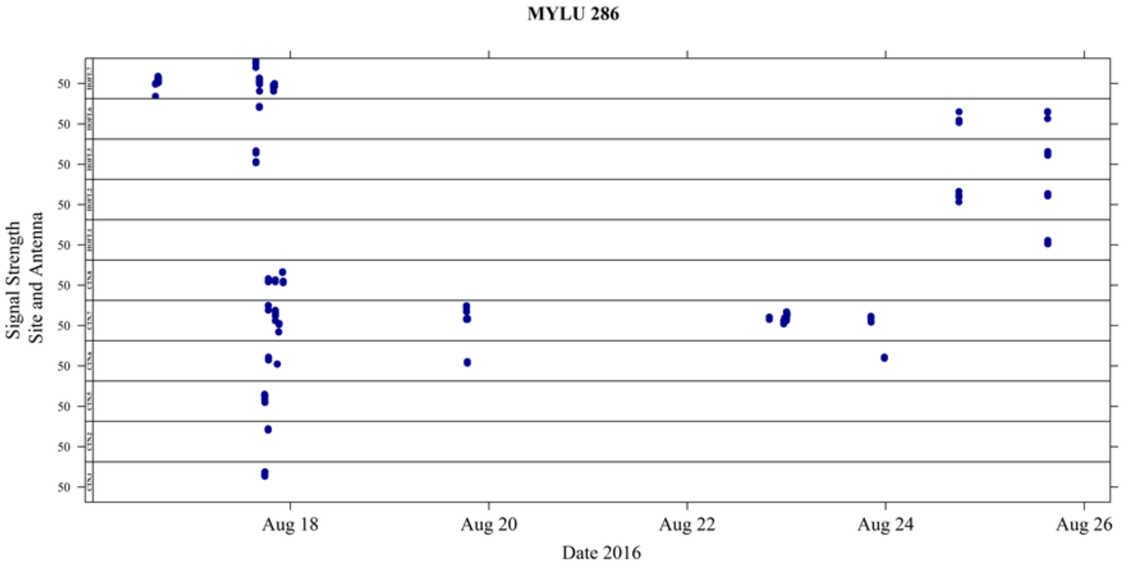


Figure 3.5: Local detection (signal strength versus time) plot for one big brown bat intermittently recorded by multiple telemetry stations in the northwest Vineyard study area. A second big brown bat was recorded briefly by the Hoft station.

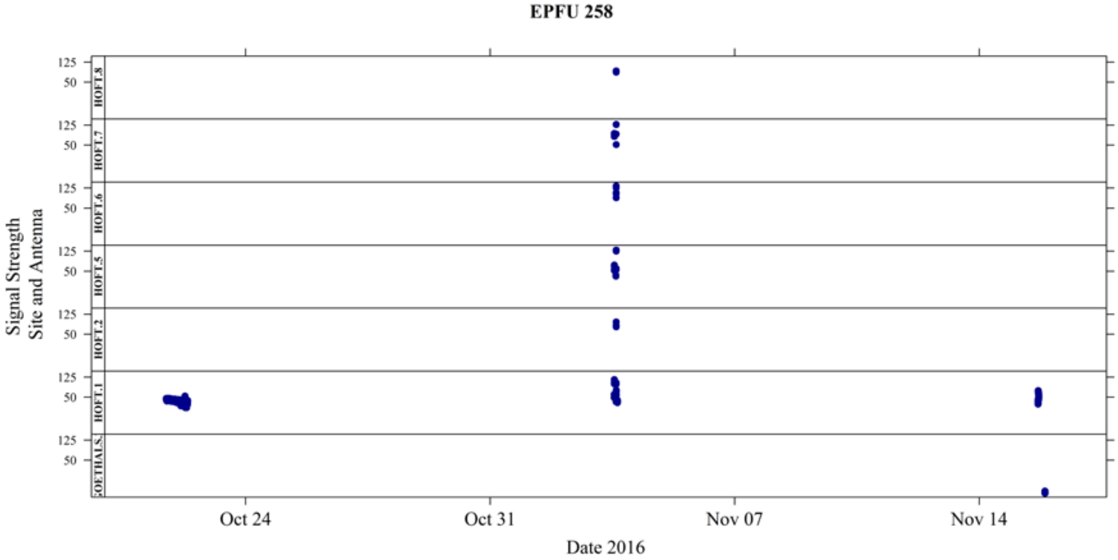


Figure 3.6: Local detection (signal strength versus time) plots for two eastern red bats intermittently recorded by multiple telemetry stations in the northwest Vineyard study area. LABO 473 was also recorded by a local station before migrating off-island on October 19.

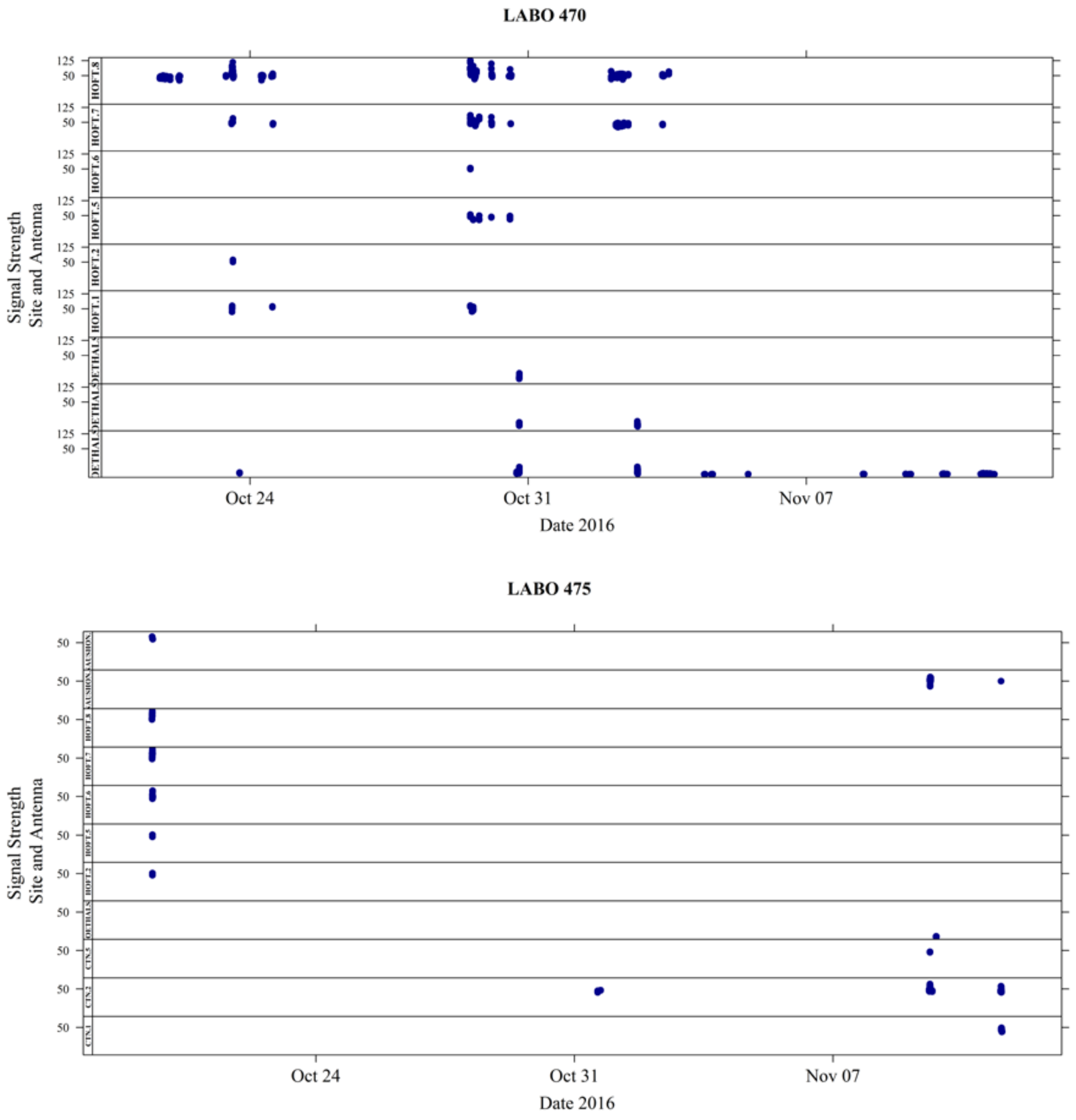


Figure 4.1: Mist-netting locations along the New England coast sampled in this study. Dot in circle indicates successful tagging location.

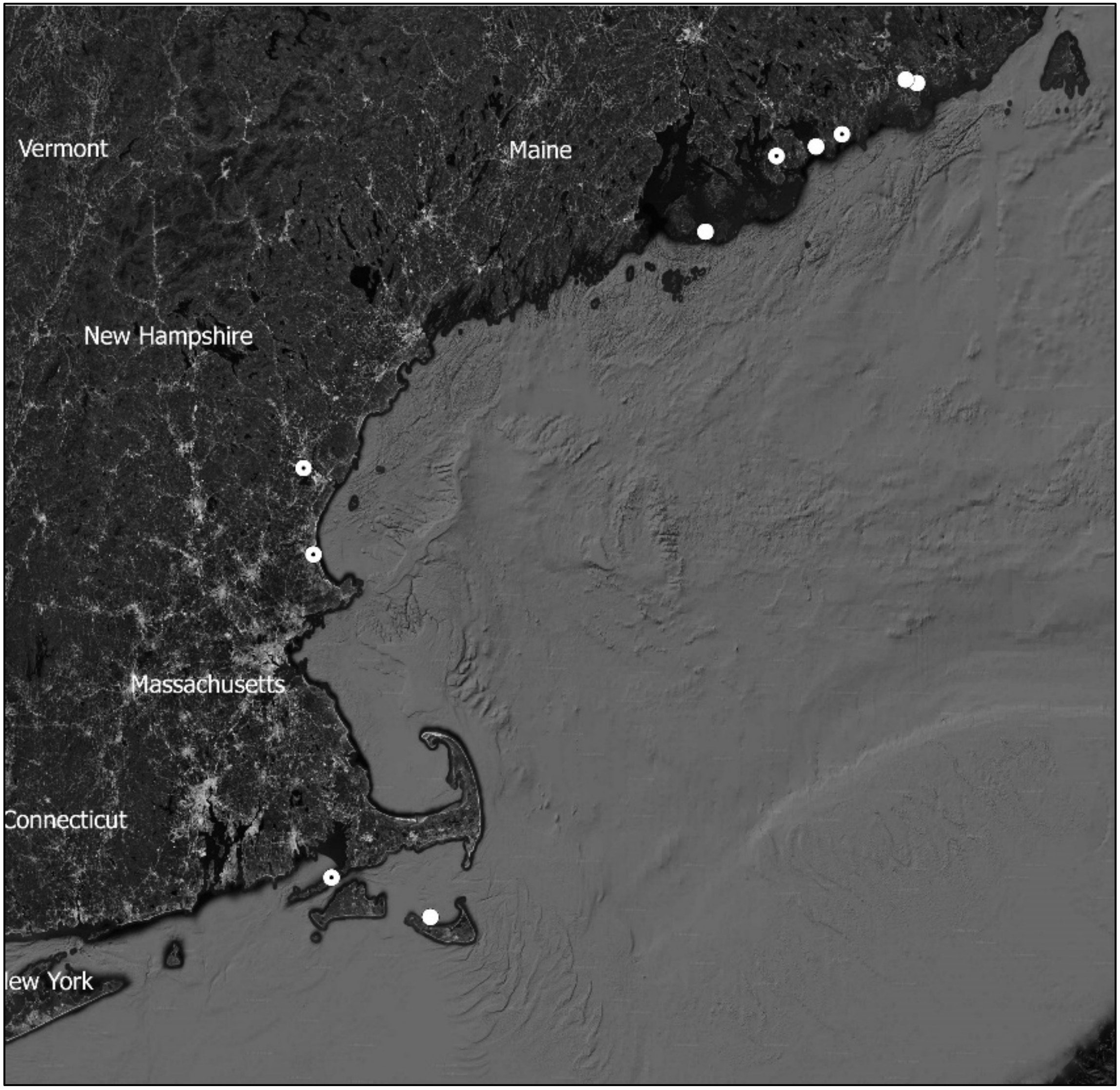
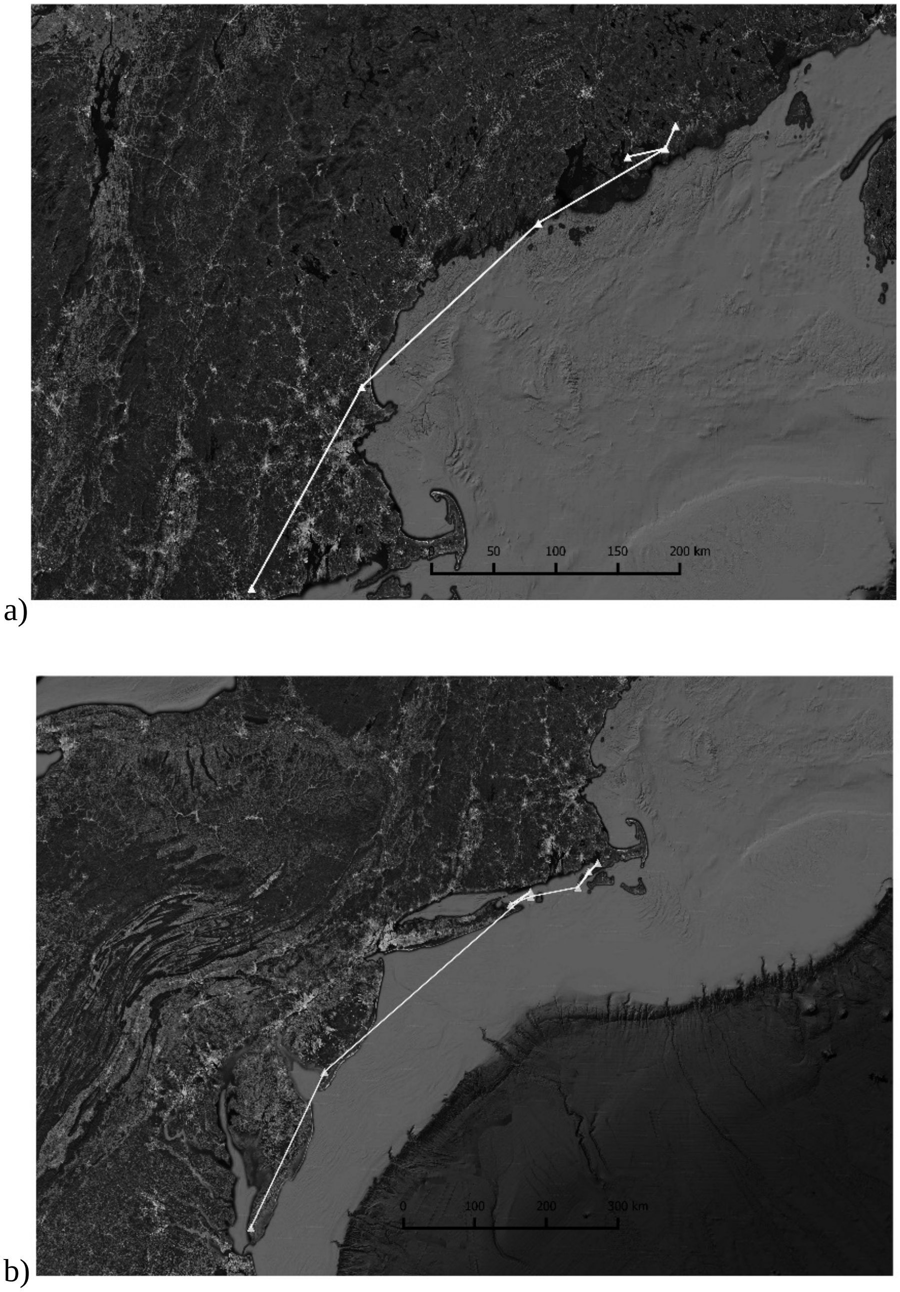


Figure 4.2: Tracking data for a) red bat M373, b) red bat M473, and c) hoary bat F520 along the Atlantic Coast.



c)

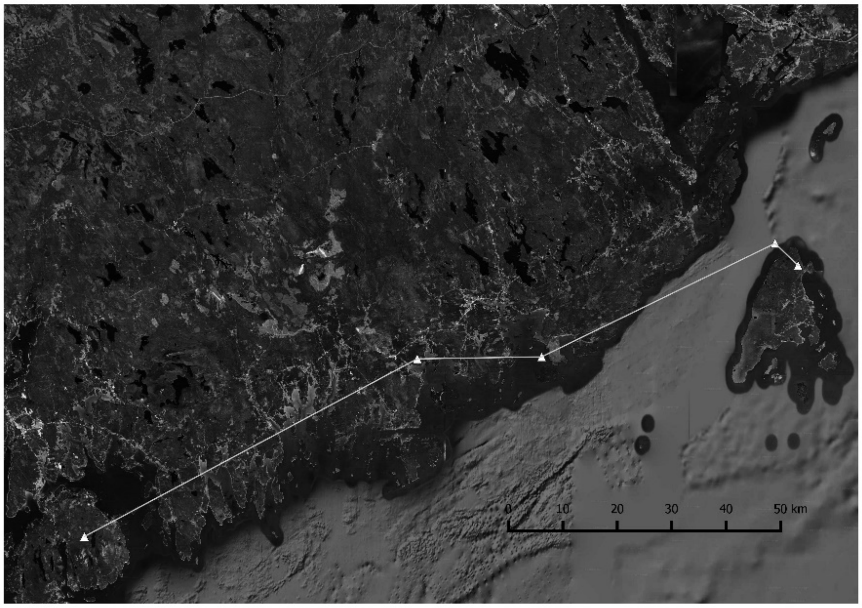
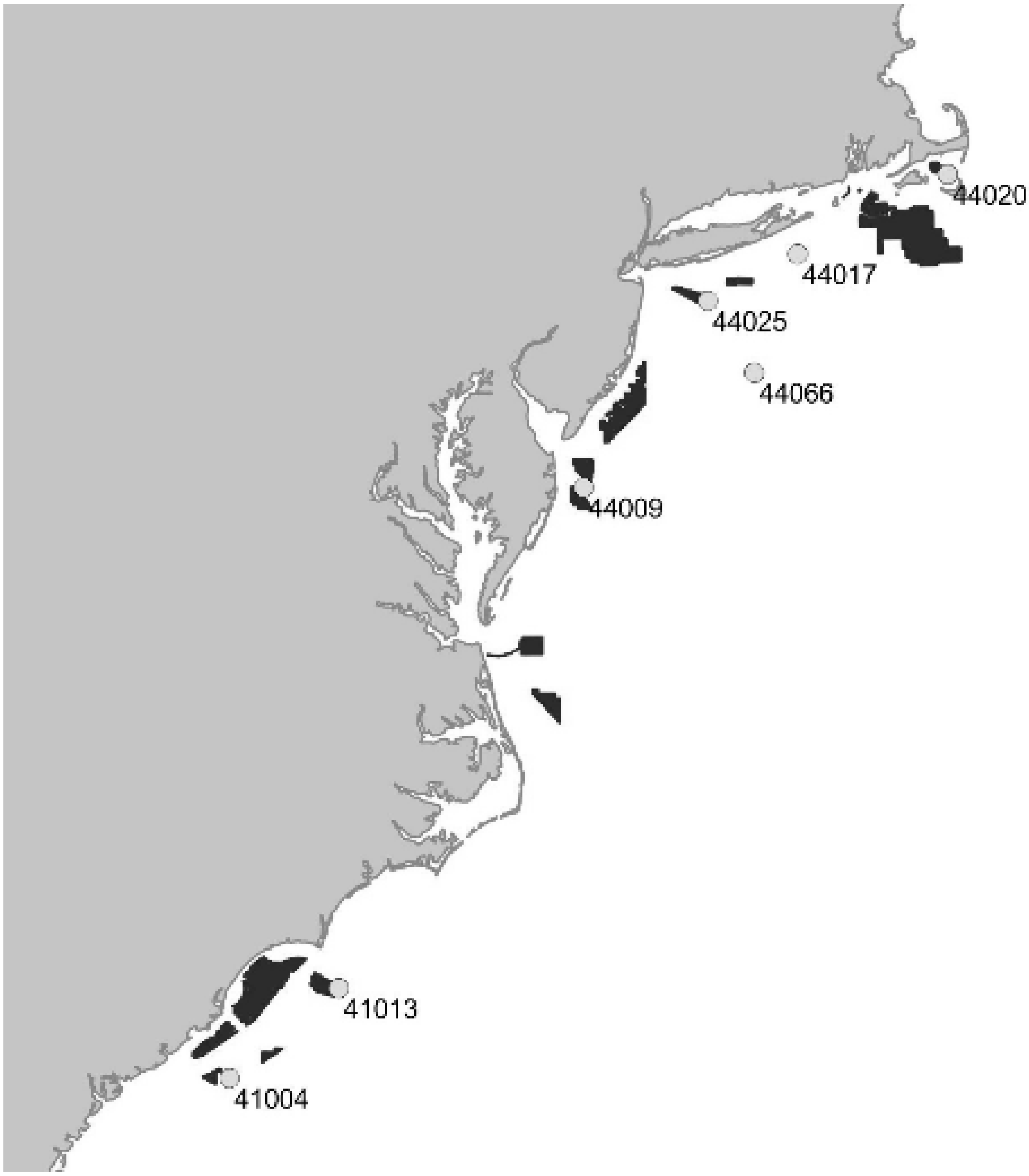


Figure 5.1: Sites of theoretical East Coast offshore wind facilities analyzed in this paper. Circles indicate locations of sampled NOAA data buoy stations (see Table 5.1). Dark shading shows BOEM wind energy lease and planning areas.



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