# UNDERSTANDING WIND ENERGY IMPACTS ON BATS AND TESTING REDUCTION STRATEGIES IN SOUTH TEXAS

by

Sara Patricia Weaver, M.S.

A dissertation submitted to the Graduate Council of
Texas State University in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
with a Major in Aquatic Resources and Integrative Biology
August 2019

Committee Members:

Iván Castro-Arellano, Chair

Cris D. Hein

Amanda M. Hale

Thomas R. Simpson

Michael C. Green

# FAIR USE AND AUTHOR'S PERMISSION STATEMENT

## Fair Use



## Duplication Permission

## DEDICATION

I dedicate this dissertation to my late mother and aunt, Terry Neel and Judy Casebeer, without whom I would not be where I am today, and to the bats we were unable to save.

**ACKNOWLEDGEMENTS**

I wish to acknowledge Tim Hayes, Greg Aldrich, and Duke Energy Renewables for allowing access to their wind energy facility, and for being such amazing partners in an industry and in a state that have often been difficult to make progress. I also want to acknowledge Mr. Nevin Durish with ESE Partners, Dr. Donald Brown at West Virginia University, Mr. Michael Schirmacher with Bat Conservation International, as well as Ms. Manuela Huso and Dr. Dan Dalthorp with U.S. Geologic Survey for their support and technical expertise. I thank my wonderful technicians, crew leaders, and volunteers for their work on this project, namely Ms. Amanda Jones who stuck with me through thick and thin. In addition, I want to thank my lab mates for putting up with me during all the times I couldn't find something in the lab, and for moral support. Your kindness and compassion towards were much appreciated. I further thank my amazing committee for their support, advice, and limitless reviews. Drs. Cris Hein and Amanda Hale were instrumental in the success of this project. I thank Drs. Thomas "Randy" Simpson and Ivan Castro who served as my academic mentors during graduate school and helped mold me into the biologist I am today. I also wish to acknowledge the numerous funding sources and scholarship donors for supporting this project and my academic pursuits. Finally, I thank my amazing husband, Chad Weaver, and my children, Gage and Ashley, for enduring this journey with me. I could not have finished this degree without your understanding, love, and support. I only hope that I can someday repay you.

## TABLE OF CONTENTS

## LIST OF TABLES

**Table** **Page**

## LIST OF FIGURES

**Figure** **Page**

## LIST OF ABBREVIATIONS

| Abbreviation | Description |
|---|---|
| AIC | Akaike Information Criterion |
| AMDEE | Associación Mexicana de Energía Eólica |
| auto ID | Automatic Identification |
| AWEA | American Wind Energy Association |
| AWWI | American Wind Wildlife Institute |
| CI | Confidence Interval |
| dB | Decibels |
| DF | Degrees of Freedom |
| dwa | Density Weighted Area |
| FRQMIN | Frequency Minimum |
| FRQMAX | Frequency Maximum |
| GenEst | Generalized Mortality Estimator |
| GLM | Generalized Linear Model |
| GLMM | Generalized Linear Mixed Model |
| GPS | Global Positioning System |
| GVIF | Genearlized Variance Inflation Factor |
| GW | Gigawatts |
| h | Hour |
| ha | Hectares |
| IACUC | Institutional Animal Care and Use Committee |
| kHz | Kilohertz |
| km | Kilometer |
| LACI | Hoary Bat |
| m | Meter |
| mbar | Millibar |
| MET | Meteorological Tower |
| ms | Millisecond |
| MW | Megawatts |
| NB1 | Negative Binomial Type I |
| NB2 | Negative Binomial Type II |
| NYHU | Evening Bat |
| PGC | Pennsylvania Game Commission |
| SD | Standard Deviation |
| SGCN | Species of Greatest Conservation Need |
| SM | Song Meter |
| spp | Several Species |
| SPUT | Special Purpose Utility Permit |

| | |
|---|---|
| TABR | Brazilian Free-tailed Bat |
| TPWD | Texas Parks and Wildlife Department |
| U.S. | United States |
| USFWS | U.S. Fish and Wildlife Service |
| UV | Ultraviolet |
| WEG | USFWS Land-based Wind Energy Guidelines |
| WNS | White-nose Syndrome |
| WWEA | World Wind Energy Association |

## ABSTRACT

Negative impacts from burning fossil fuels, including climate change, are promoting an increase in development of renewable energy alternatives. In response, wind energy development is expanding at an exponential rate across the globe. However, wind energy development has long been known to directly impact bats, which incur fatalities at wind turbines when struck by moving turbine blades. In the U.S., Texas is the leading producer of wind energy with approximately >13,300 commercially operating wind turbines while also having the greatest diversity of bats. Despite this, research in Texas on this topic is lacking with only a few wind energy facilities producing publicly available or peer-reviewed data. In this dissertation, I conducted one of the first comprehensive studies to understand and reduce wind energy impacts on bats in South Texas. My study site was the Los Vientos Wind Energy Facility with 255 wind turbines encompassing 22,666 ha in Starr County, Texas, part of the Lower Rio Grande Valley region. For my first study I estimated bat fatality rates at Los Vientos using a novel fatality estimator and reported a moderate to high fatality rate, in which Brazilian free-tailed bats (*Tadarida brasiliensis*) were the most impacted species. Based on my results, I recommend bat impact reduction strategies for this location and others in the region experiencing similar impacts. Los Vientos has a similar bat species composition and climate as other regions in the southwestern U.S. and northern Mexico which also lack data on wind energy impacts to bats. My results might provide insights and guidance for these regions as well.

In my second study, I monitored bat acoustic activity at three wind turbines at Los Vientos during late summer to early fall. I investigated relationships between bat activity and bat fatality, weather, and temporal covariates to further our understanding of conditions under which bats are at risk. My results revealed specific climatic (e.g., low wind speeds) and temporal conditions (e.g., hour of the night) during which bats are most active at wind turbines, and showed a positive relationship between activity and fatality, thereby highlighting conditions in which bats are more susceptible to fatality.

In my final study, I tested the efficacy of a novel ultrasonic acoustic deterrent system to reduce bat fatalities at wind turbines. Results of my study indicate this technology is a promising tool for reducing fatalities of Brazilian free-tailed bats and hoary bats (*Lasiurus cinereus*). This was one of the most successful field trials using acoustic deterrents to date. However, my results indicate species-specific responses to deterrents, particularly for yellow bat spp. Therefore, I conclude the technology warrants further studies to increase effectiveness for more species.

Studies investigating wind energy impacts to bats are timely, relevant, and necessary for conservation of imperiled species, informing policy, and guiding responsible wind energy development. Moreover, developing regional and site-specific impact reduction strategies are important for maximizing the generation of renewable energy. Results of my studies can be used to develop such strategies in other data-deficient regions with similar climates and bat species such as the southwestern U.S. and northern Mexico, and with further improvements, the applications of the acoustic deterrent technology I tested are potentially global in reach.

# I. GENERAL INTRODUCTION

Global energy demand is expected to increase 25% by 2040 (International Energy Agency 2018). Climate change (Schlesinger and Mitchell 1987, Inkley et al. 2004; Global Wind Energy Council [GWEC] 2013), and other impacts from burning of fossil fuels, are promoting an increase in development of renewable energy alternatives. In response, wind energy development is expanding across the globe (Bernstein et al. 2006; GWEC 2013). Currently, China has the largest capacity of installed wind energy in the world with more than 200 gigawatts (GW), followed by the United States (U.S.) with nearly 100 GW (World Wind Energy Association [WWEA] 2019). Within the U.S., Texas is the leading producer of wind energy with an installed wind power capacity of nearly 25,000 megawatts (MW) accounting for approximately 24% of the country's total installed capacity (American Wind Energy Association [AWEA] 2019). This output is produced by more than 13,300 wind turbines on the Texas landscape, and is nearly three times the number of turbines in Iowa, the next largest wind energy producing state. Moreover, an additional 8,553 MW of wind generating capacity is either under construction or in advanced development in Texas (AWEA 2019).

Wind energy is an important renewable energy resource necessary to combat climate change (Keith et al. 2004; Owusu and Asumadu-Sarkodie 2016). However, like all energy sources, wind energy has negative effects on certain wildlife populations (Kuvlesky et al. 2007). Wind turbines have long been known to cause bat fatalities (Hall and Richards 1972) due primarily to strikes by turbine blades (Rollins et al. 2012), though it remains unclear as to the potential impacts resulting from barotrauma (Baerwald et al. 2008; Rollins et al. 2012).

Globally, direct impacts of wind turbines on bats have been highest for relatively fast, high flying species during late summer to fall (Kunz et al. 2007; Rydell et al. 2010; Arnett et al. 2016). Most bats are slow to reproduce having only one to two pups per year, and with high fatality rates for some species there is increased concern regarding population level impacts (Barclay and Harder 2003; Frick et al. 2017). The importance of impacted bat species (e.g., *Lasiurus cinereus and Tadarida brasiliensis*) as major insect predators providing a vital ecosystem service and economic assistance in the form of natural pest control to the agricultural industry (Boyles et al. 2011) has spurred several studies focused on understanding the patterns and minimization strategies of wind turbine-caused bat fatalities over the last two decades. The majority of these studies come from Europe and North America, specifically Canada and the U.S. No publicly available data has been forthcoming from China, the world's leading producer of wind energy, and little from India, the fourth largest producer of wind energy (Barclay et al. 2017, WWEA 2019). In North America, Mexico has the highest diversity of bat species (Ceballos 2014), as well as increasing wind energy development, but only one site with a published study (Villegas-Patraca et al. 2012). This leaves a large data gap in our knowledge of impacts on bats, and because most species transcend political boundaries this confounds holistic management across a species range.

Texas has the highest diversity of bats with 68% (n = 32) of all U.S. species (Ammerman et al. 2012), and is part of an important migratory flyway traversed by millions of bats each year (McCracken et al. 1994). Despite this, research on wind energy impacts to bats in Texas is lacking with few facilities producing publicly available or peer-reviewed studies (Hayes 2013; Smallwood 2013). This is an important shortcoming in our knowledge on how wind energy affects various species of bats in the U.S. because of the variability in habitats and species composition across the country (Humphrey 1975). Unfortunately, documented patterns of fatality from regions with available studies are often used to inform wind energy development in other regions where these patterns may not apply (Huso and Dalthorp 2014). Understanding real and potential wind energy impacts to Texas bat populations is relevant for areas across the southwestern U.S and northern Mexico that have similar habitats and species composition. Conducting further research in Texas to refine current recommendations and contribute to optimizing impact reduction strategies is a necessity for bats in this region.

**Study Site**

Duke Energy Renewables owns and operates the Los Vientos III, IV, and V Wind Energy Facilities, extending across approximately 22,666 ha of leased land northeast of Rio Grande City in Starr County, Texas, ranging from approximately 3.8–36.4 km north of the U.S.-Mexico border. These wind energy projects are part of a large five-phase project, with phases I and II occurring in Willacy and Cameron Counties, Texas. Los Vientos III, IV, and V (herein referred to as Los Vientos or the study site) border one another and are thus treated as one site for this study. Los Vientos lies within the Texas-Tamaulipan Thornscrub Level IV ecoregion (Fig. 1.1) portion of the South Texas Plains Level III ecoregion of Texas (Griffith et al. 2007). The thorn woodland and thorn shrubland vegetation is distinctive in this ecoregion, and these Rio Grande Plains are commonly called the “brush country” (Griffith et al. 2007). The vegetation is dominated by drought-tolerant, mostly small-leaved, and often thorn-laden small trees and shrubs, especially legumes. The most important woody species is honey mesquite (*Prosopis* *glandulosa*). Where conditions are suitable, there is a dense understory of smaller trees and shrubs such as brasil (*Condalia hookeri*), colima or lime pricklyash (*Zanthoxylum fagara*), Texas persimmon (*Diospyros texana*), lotebush (*Ziziphus obtusifolia*), granjeno (*Celtis ehrenbergiana*), kidneywood (*Eysenhardtia texana*), coyotillo (*Karwinskia humboldtiana*), Texas paloverde (*Parkinsonia texana*), anacahuita (*Cordia boissieri*), and various species of cacti. Xerophytic brush species, such as blackbrush (*Vachellia rigidula*), guajillo (*Senegalia berlandieri*), and cenizo (*Leucophyllum frutescens*), are typical on the rocky, gravelly ridges and uplands. Mid-and short-grasses are common, including cane bluestem (*Bothriochloa barbinodis*), silver bluestem (*Bothriochloa laguroides*), multi-flowered false rhodesgrass (*Trichloris pluriflora*), sideoats grama (*Bouteloua curtipendula*), pink pappusgrass (*Pappophorum bicolor*), bristlegrasses (*Setaria* spp.), lovegrasses (*Eragrostis* spp.), and tobosa (*Pleuraphis mutica*) (Griffith et al. 2007). All common and scientific names follow nomenclature from the Ladybird Johnson Wildflower Center, Austin, Texas (https://www.wildflower.org).

The bat community in Starr County, Texas is comprised of mostly insectivorous species that include a single member each from family Molossidae and Mormoopidae, and 11 species from the Vespertilionidae family. In addition, there is one nectarivorous species in the family Phyllostomidae. Several of these species have not been document in Starr County, but are thought to occur based on known presence in neighboring counties (Ammerman et al. 2012; Schmidly and Bradley 2016). Table 1.1 provides a list of these species, their foraging behaviors, if they have been documented as a fatality at wind turbines, and their potential for occurrence

My dissertation is organized in three inter-related chapters centered on the interactions of wildlife and wind turbines at the described study site above. First, I quantified the mortality impacts of wind turbines on the suite of bat species occurring at the study site (Chapter II). For Chapter III, I used acoustic detectors and weather variables to quantify factors associated with bat activity at wind turbines and how activity relates to bat fatalities at the study site. Finally, for Chapter IV, I deployed ultrasonic acoustic bat deterrents to evaluate their effectiveness for reducing bat fatalities at wind turbines. Studies investigating wind energy impacts on bats are timely, relevant, and necessary for conservation of bat species, informing policy, and guiding responsible wind energy development, an important renewable energy resource.

**Table 1.1**—Potential bat community assemblage in Starr County, Texas including foraging behaviors, documented fatality status at wind turbines, and potential for occurrence.

| **Common Name**[1] | **Scientific Name**[1] | **Family**[1] | **Foraging Behavior**[1] | **Fatality**[2] | **Potential for Occurrence**[1,3,4] |
|---|---|---|---|---|---|
| Brazilian free-tailed Bat | *Tadarida brasiliensis* | Molossidae | Insectivorous | Yes | High |
| California Myotis | *Myotis californicus* | Verspertilionidae | Insectivorous | Yes | Low |
| Cave Myotis | *Myotis velifer* | Verspertilionidae | Insectivorous | Yes | High |
| Eastern Red Bat | *Lasiurus borealis* | Verspertilionidae | Insectivorous | Yes | High |
| Evening Bat | *Nycticeius humeralis* | Verspertilionidae | Insectivorous | Yes | High |
| Ghost-faced Bat | *Mormoops megalophylla* | Mormoopidae | Insectivorous | Yes | Low |
| Hoary Bat | *Lasiurus cinereus* | Verspertilionidae | Insectivorous | Yes | High |
| Mexican Long-nosed Bat[a] | *Leptonycteris nivalis* | Phyllostomidae | Nectarivorous | No | Low |
| Northern Yellow Bat | *Lasiurus* [*Dasypterus*] *intermedius* | Verspertilionidae | Insectivorous | Yes | High |
| Pallid Bat | *Antrozous pallidus* | Verspertilionidae | Insectivorous | No | Low |
| Silver-haired Bat | *Lasionycteris noctivagans* | Verspertilionidae | Insectivorous | Yes | Low |
| Southern Yellow Bat[b] | *Lasiurus* [*Dasypterus*] *ega* | Verspertilionidae | Insectivorous | Yes | High |
| Tri-colored Bat | *Perimyotis subflavus* | Verspertilionidae | Insectivorous | Yes | Medium |
| Yuma Myotis | *Myotis yumanensis* | Verspertilionidae | Insectivorous | Yes | Low |

[1] Schmidly and Bradley 2016; [2] Barclay et al. 2017; [3] Ammerman et al. 2012; [4] Post-construction monitoring at neighboring wind energy facilities since 2014; [a] federally and state-listed endangered; [b] State-listed threatened.

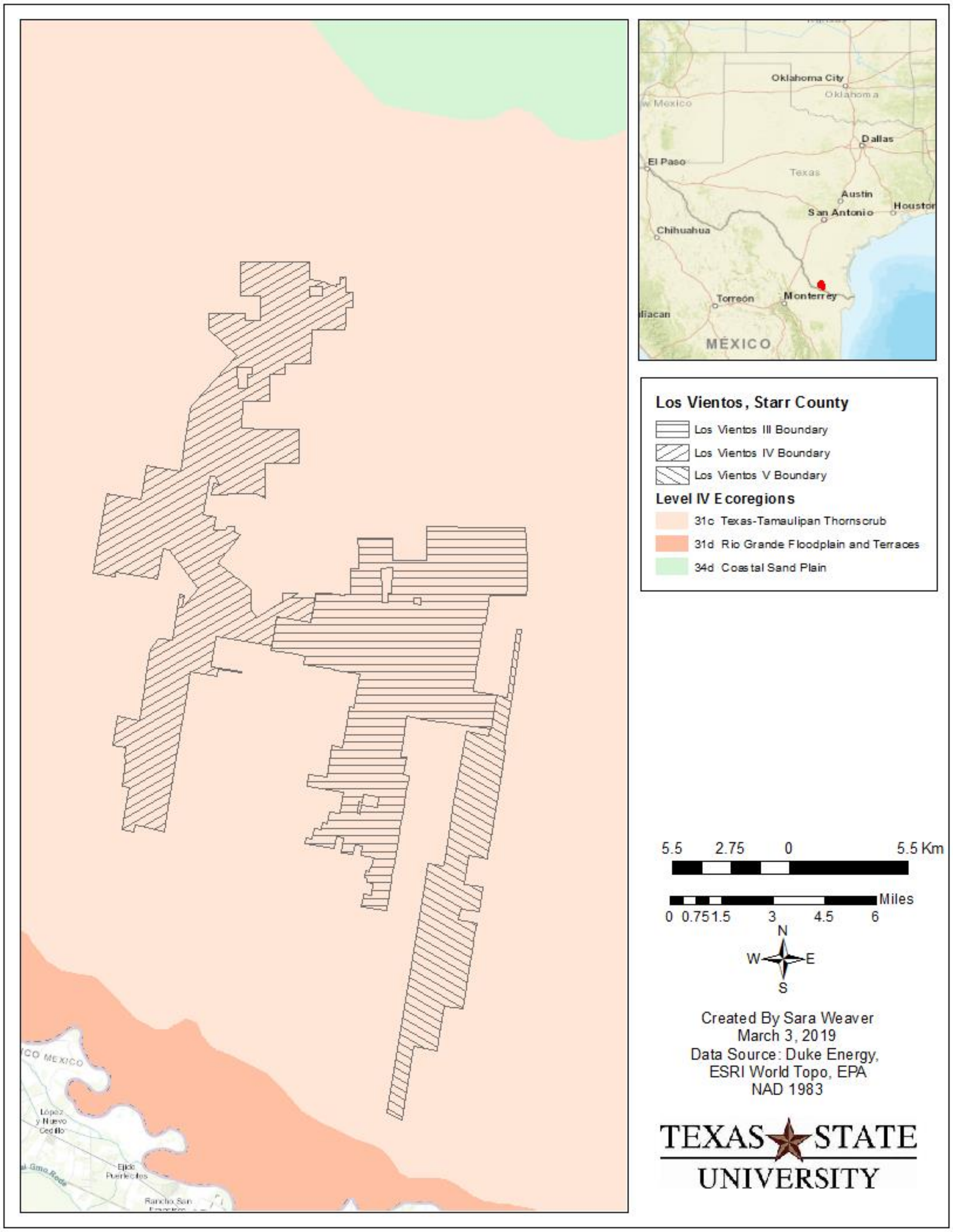



**Fig. 1.1**—Los Vientos III, IV, and V project boundaries and Level IV Ecoregions in Starr County, Texas near the U.S.–Mexico border. Location of project in the inset map is denoted by red color.

## Literature Cited

American Wind Energy Association (AWEA). 2019. Texas Wind Energy. AWEA, Washington, D.C.

Ammerman, L. K., C. L. Hice, and D. J. Schmidly. 2012. Bats of Texas. Texas A&M University Press, College Station, TX.

Arnett, E. B., et al. 2016. Impacts of Wind Energy Development on Bats: A Global Perspective. Pp. 295–323 *in* Bats in the Anthropocene: conservation of bats in a changing world (C. C. Voigt and T. Kingston, eds.). Springer. New York, New York.

Baerwald, E. F., G. H. D'Amours, B. J. Klug, and R. M. R. Barclay. 2008. Barotrauma is a significant cause of bat fatalities at wind turbines. Current Biology 18:R695-R696.

Barclay, R. M. R., and L. D. Harder. 2003. Life histories of bats: life in the slow lane. Pp 209–253 *in* Bat ecology (T. H. Kunz and M. B. Fenton, eds.). University of Chicago Press. Chicago, Illinois.

Barclay, R. M. R., E. F. Baerwald, and J. Rydell. 2017. Bats. Pp 191–221 *in* Wildlife and wind farms, conflicts and solutions. Volume 1 Onshore: potential effects (M. R. Perrow, eds.). Pelagic Publishing. Exeter, United Kingdom.

Bernstein, M. A., J. Griffin, and R. J. Lempert. 2006. Impacts on U.S. energy expenditures of increasing renewable energy use. RAND Corporation, Santa Monica, CA.

Boyles, J. G., P. M. Cryan, G. F. McCracken, and T. H. Kunz. 2011. Economic importance of bats in agriculture. Science 332:41-42.

Ceballos, G. (ed.). 2014. Mammals of Mexico. Johns Hopkins University Press. Baltimore Maryland.

Frick, W. F., et al. 2017. Fatalities at wind turbines may threaten population viability of a migratory bat. Biological Conservation 209:172–177.

Global Wind Energy Council. 2013. 30 years of policies for wind energy. International Renewable Energy Agency, Abu Dhabi, United Arab Emirates.

Griffith, G., S. Bryce, J. Omernik, and A. Rogers. 2007. Ecoregions of Texas. Texas Commission on Environmental Quality, Austin, TX.

Hall, L. S., and G. C. Richards. 1972. Notes on *Tadarida australis*. Australian Mammalogy 1:46–47.

Hayes, M A. 2013. Bats killed in large numbers at United States wind energy facilities. BioScience 63:975–979.

Humphrey, S. R. 1975. Nursery roosts and community diversity of Nearctic bats. Journal of Mammalogy 56:321-346.

Huso, M. M. P., and D. Dalthorp. 2014. A comment on "Bats killed in large numbers at United States wind energy facilities." BioScience 64:546–547.

Inkley, D. B., et al. 2004. Global climate change and wildlife in North America. Wildlife Society Technical Review 04-2. The Wildlife Society, Bethesda, Maryland.

International Energy Agency (IEA). 2018. World energy outlook 2018. IEA Publications. Paris, France.

Keith, D. W., et al. 2004. The influence of large-scale wind power on global climate. PNAS 101:16115-16120.

Kunz, T. H., et al. 2007. Ecological impacts of wind energy development on bats: questions, hypotheses, and research needs. Frontiers in Ecology and the Environment 5:315–324.

Kuvlesky, W. P., L. A. Brennan, M. L. Morrison, K. K. Boydston, B. M. Ballard, and F. C. Bryant. 2007. Wind energy development and wildlife conservation: challenges and opportunities. Journal of Wildlife Management 71:2487-2498.

McCracken, G. F., M. K. McCracken, and A. T. Vawter. 1994. Genetic structure in migratory populations of the bat *Tadarida brasiliensis mexicana*. Journal of Mammalogy 75:500-514.

Owusu, P. A., and S. Asumadu-Sarkodie. 2016. A review of renewable energy sources, sustainability issues and climate change mitigation. Cogent Engineering 3:1167990.

Rollins, K. E., D. K. Meyerholz, G. D. Johnson, A. P. Capparella, and S. S. Loew. 2012. A forensic investigation into the etiology of bat mortality at a wind farm: barotrauma or traumatic injury? 2012. Environmental Pathobiology 49:362-371.

Rydell, J., L. Bach, M.-J. Dubourg-Savage, M. Green, L. Rodrigues, and A. Hedenström. 2010. Bat mortality at wind turbines in Northwestern Europe. Acta Chiropterologica 12:261–274.

Schlesinger, M. E., and J. F. B. Mitchell. 1987. Climate model simulations of the equilibrium climatic response to increased carbon dioxide. Reviews of Geophysics 25:760.

Schmidly, D. J., and R. D. Bradley. 2016. The mammals of Texas. University of Texas Press, Austin.

Smallwood, K. S. 2013. Comparing bird and bat fatality-rate estimates among North American wind-energy projects. Wildlife Society Bulletin 37:19–33.

Villegas-Patraca, R., S. Macías-Sánchez, I. MacGregor-Fors, and C. Muñoz-Robles. 2012. Scavenger removal: bird and bat carcass persistence in a tropical wind farm. Acta Oecologica 43:121–125.

World Wind Energy Association (WWEA). 2019. Wind power capacity worldwide reaches 600 GW, 53.9 GW added in 2018 [Press release]. Retrieved from https://wwindea.org/blog/ 2019/02/25/wind-power-capacity-worldwide-reaches-600-gw-539-gw-added-in-2018/.

## II. ESTIMATING BAT FATALITIES AT A WIND ENERGY FACILITY IN SOUTH TEXAS: IMPLICATIONS TRANSCENDING THE U.S.-MEXICO BORDER[1]

Impacts from burning fossil fuels, including climate change (Schlesinger and Mitchell 1987; Inkley et al. 2004; Global Wind Energy Council [GWEC] 2013), are promoting increased development of renewable energy alternatives. In response, wind energy development is expanding across the globe (Bernstein et al. 2006; GWEC 2013). However, wind energy development has long been known to cause wind turbine-related bat fatalities (Hall and Richards 1972). Currently, wind turbine collisions are considered one of the largest sources of mass mortality events in bats across the world (O'Shea et al. 2016). Although we lack detailed information on population sizes for most bat species, we know they are long-lived mammals that are slow to reproduce. Thus, populations may be unable to recover from large-scale sustained fatality events, such as those attributed to wind energy development (Frick et al. 2017).

Given these concerns, several studies have attempted to enumerate cumulative bat fatality rates in North America at varying temporal and spatial scales (Kunz et al. 2007; Arnett et al. 2008; Arnett and Baerwald 2013; Hayes 2013). One study estimated cumulative bat fatalities ranged from more than 650,000 to approximately 1.3 million in the U.S. and Canada between 2000 and 2011, with an additional 196,190 to 395,886 estimated bat fatalities in 2012 (Arnett and Baerwald 2013). However, others have cautioned estimation of cumulative bat fatality rates based on currently available studies is unlikely to be accurate. This is not only due to differences in methodologies and

[1] Weaver, S. P., A. K. Jones, C. D. Hein, and I. Castro-Arellano. *In Review*. Journal of Mammalogy.

estimators, but also due to bias in where studies have been conducted, with the added problem of certain areas of high wind energy development proving data deficient (Arnett et al. 2008; Huso and Dalthorp 2014a).

Of specific concern is a lack of data from states in the Southwest U.S., specifically Texas, which leads the U.S. in installed wind energy capacity (Smallwood 2013; Huso and Dalthorp 2014a). This is important because Texas also has the highest bat diversity in the nation (Ammerman et al. 2012), and yet has little publicly available or reliable estimates on wind energy impacts (Smallwood 2013). Moreover, studies in North America have been primarily restricted to the U.S. and Canada, with data available from only one facility in Mexico (Villegas-Patraca et al. 2012). The paucity of peer-reviewed and/or publicly available studies from Texas and Mexico is unfortunate, because we cannot accurately assess cumulative impacts to species in North America or determine patterns of fatality in these regions without such data (Hein and Schirmacher 2016). This is particularly important when selecting appropriate impact reduction strategies (Hein and Schirmacher 2016), because species composition (Hall 1981) and fatality patterns are likely to vary strongly among regions.

The primary method for determining bat fatality rates at wind energy facilities is through post-construction fatality monitoring (Huso 2011). Here we provide the first published bat fatality estimates from monitoring efforts in south Texas, and provide additional comments on potential wind energy impacts to bats in northern Mexico, a region with similar species composition (Ammerman et al. 2012; Ceballos 2014) and expanding wind energy development. Our objectives for this study were to 1) conduct one year of post-construction fatality monitoring at the Los Vientos Wind Energy Facility in Starr County, Texas, 2) estimate the total annual bat fatality rate, as well as per MW and per turbine rates, adjusted for bias; 3) describe patterns of fatalities in relationship to species, sex and age ratios, and seasonal timing; and 4) provide recommendations for species conservation and discuss potential implications of impacts and fatality patterns in an international context.

## MATERIALS AND METHODS

*Study site.*—We monitored bat fatalities at the Los Vientos III, IV, and V wind energy facilities near Rio Grande City, Starr County, Texas. The three facilities are adjacent to one another and have the same turbine model, and thus were treated as a single facility for this study (hereafter Los Vientos). Los Vientos encompasses approximately 22,666 hectares and consists of 255 Vestas V-110, 2-megawatt (MW) turbines (Fig. 2.1). All turbines have a nacelle height of 95 m and rotor diameter of 110 m, with a rotor-swept area of 9,503 $m^2$. The site is located in the Texas-Tamaulipan Thornscrub Level IV ecoregion (Griffith et al. 2007), and according to the 2011 National Land Cover Data the habitat is comprised primarily of scrub/shrub (39%), cultivated crops (25%), pasture/hay (24%), developed, open space (5%), grassland/herbaceous (5%), and developed, low intensity (2%) (Homer et al. 2015). The southernmost boundary and wind turbine of Los Vientos are approximately 3.8 km and 10.1 km from the U.S.–Mexico border, respectively (Fig. 2.1).

*Carcass monitoring.*—We randomly selected 100 of the 255 turbines (~39%) for fatality searches. At a subset of 8 randomly selected turbines, we established circular search plots, centered on the turbine and measuring up to 100 m in radius (~200 m diameter from the turbine tower). Some plots contained obstacles such as trees, leading to search plots with a smaller search area. Search plot size ranged from 11,454 to a maximum of 31,405 $m^2$. We established linear transects across the diameter of each plot spaced 5 m apart. Trained biologists searched for bat carcasses by walking all transects searching 2.5 m on both sides for 100% plot coverage. For the remaining 92 turbines we searched only the turbine pad and access road to 100 meters from the turbine. Search area for pad and access road turbines ranged from 685 to a maximum of 2,054 $m^2$. We searched at 7-day intervals during Spring, Summer, and Fall (24 March 2017 through 25 November 2017 and 25 February 2018 through 23 March 2018) and twice monthly during Winter (26 November 2017 through 24 February 2018). We cleared search plots of vegetation by mowing with a tractor biweekly to monthly depending on amount of regrowth.

We assigned a unique identification number to each carcass found during scheduled searches, and recorded date and time found, species, sex and age class (when possible to ascertain), azimuth and distance from the turbine, estimated time of death (previous night, 2–3 days, 4–7, 7–14, >2 weeks, or unknown) based on carcass condition and insect infestation, visibility class (easy or moderate to difficult), and completeness of the carcass (skeleton, partial, or complete). We determined relative age (juveniles or adults) by using a common technique in which we visually inspected wings for epiphyseal-diaphyseal fusion (Brunet-Rossinni and Wilkinson 2009). To improve time of death estimation, we documented decomposition over time for fatalities determined to have occurred the previous night. When calculating age and sex ratios, we only considered fatalities determined to have occurred the previous night. We restricted this assessment due to rapid decomposition of carcasses, which led to uncertainty in our sex and age determinations. In addition, we followed Pennsylvania Game Commission (PGC) protocols (PGC 2007) for determining visibility classes. Only one turbine had difficult visibility confined to a limited area, likely because plots were regularly maintained. Therefore, we treated moderate and difficult as one visibility class (moderate to difficult). In addition, there were no conditions at the site considered to be very difficult visibility.

To assess seasonal timing of fatalities, we removed those carcasses considered to have occurred more than 2 weeks prior to discovery or that were unknown (n=16), and adjusted for all others by assuming maximum estimated time since death (e.g., 2-3 days assumed to have occurred 3 days prior). Furthermore, although we documented carcasses discovered outside the search interval, at non-search turbines, or by personnel not involved in the search effort, these were recorded as incidentals and excluded them from further analyses. This research was conducted in accordance with the Texas State University Institutional Animal Care and Use Committee (IACUC) permit number 20171185494, and Texas Parks and Wildlife Department (TPWD) permit number SPR-0213-023. In addition, we followed guidelines of the American Society of Mammalogists (Sikes et al. 2016).

*Correcting fatality estimates.*—To correct for searcher efficiency bias, we discretely marked and randomly placed previously recovered bat carcasses (trial carcasses) discovered during the study at turbines along the search route (n=183). We assigned to each trial carcass a 0 for undetected, or a 1 for detected on the first search. We left trial carcasses in place (n=69), whenever possible, to test for searcher efficiency on subsequent searches if they went undetected on the first search. We conducted searcher efficiency trials throughout the entire study period and at all sampled turbines. Searchers were unaware of location, number, and timing of trials. Carcasses used in searcher efficiency bias trials were previously frozen and thawed before distribution.

To correct for bias associated with the length of time a carcass remained in the search area until it was scavenged or rendered undetectable by decomposition (hereafter carcass persistence), we left in place searcher efficiency trial carcasses (n=197). We included carcasses scavenged prior to the first search in the carcass persistence data set, but not the searcher efficiency data set (n=14). We checked for carcass presence daily, when possible, and recorded number of days a carcass persisted and only removed them if they persisted at the completion of the study.

*Data analysis.*— We used GenEst (Generalized Mortality Estimator) software version 1.2.1, a newly developed package of modeling and software tools for estimating bird and bat fatality rates for renewable-energy projects (Dalthorp et al. 2018a). The software is designed to accurately estimate fatality rates when there is imperfect detection. Several other estimators for such efforts have been published and used at various degrees (Shoenfeld 2004; Huso 2011; Korner-Nievergelt et al. 2015). However, we selected GenEst due to its flexibility in estimating bias, such as an ability to incorporate a decrease in searcher efficiency when the same carcass is available for detection in multiple searches, as well as model selection using Akaike information criterion with a bias correction term for small sample sizes ($AIC_c$—Simonis et al. 2018). We selected a 95% confidence interval (*CI*) and 1,000 bootstrapping iterations for all analyses in GenEst. The software estimates total annual bat mortality at the site adjusted for searcher efficiency and carcass persistence, and we further calculated mortality per MW and turbine estimates by dividing this estimate by MWs and number of turbines at the site.

GenEst bases fatality estimates upon the following: (i) fraction of turbines sampled, (ii) fraction of carcasses in searched area, (iii) proportion of carcasses persisting, (iv) proportion of carcasses found, and (v) proportion of annual fatality arriving during monitoring period. GenEst models searcher efficiency and carcass persistence with maximum likelihood estimation (Dalthorp et al. 2018b).

GenEst estimates searcher efficiency by modeling two parameters. The first parameter is the probability a carcass is observed in the searched area on the first search following arrival, expressed as *p*. The second parameter is the factor by which searcher efficiency changes for a carcass not detected on the first search that persisted for subsequent searches, expressed as *k*. GenEst has the ability to estimate *k*, or allows for the user to define *k* if trial carcasses were not left for subsequent searches, or no carcasses were detected and it therefore cannot be estimated. Although only 9 trial carcasses persisted long enough for searchers to discover them in successive searches, GenEst was able to estimate *k* for our study. We used GenEst to determine the best covariates for searcher efficiency, including season (winter [November 26–February 24], spring [February 25–May 31], summer [June 1–August 15], and fall [August 16–November 25]) and visibility (easy and moderate to difficult).

GenEst fits four possible distributions to carcass persistence data, including exponential, lognormal, loglogistic, and Weibull. We selected visibility and season as possible covariates influencing location (*l*) and scale (*s*) parameters used to fit the survival curves. In addition to providing median carcass persistence estimates for each level of covariate selected, GenEst reports a series of *r* statistics for 1, 3, 7, 14, and 28-day intervals. These estimates indicate the probability that a carcass will persist until the next search if arriving in the specified time interval. For both searcher efficiency and carcass persistence, we considered the model with the lowest $AIC_c$, as well as models with $\Delta AIC_c < 2$ as competitive models. For further details regarding equations and statistical methods used by GenEst, please refer to the statistical models manual (Dalthorp et al. 2018b).

Research has shown that density of carcasses diminishes with increasing distance from a turbine (Hull and Muir 2010; Huso and Dalthorp 2014b); therefore, simply correcting for survey area without accounting for carcass distribution on the landscape will likely overestimate fatality. Thus, we modeled the density of carcasses as a function of distance from the turbine, known as the density-weighted proportion (dwp). We only used fresh carcasses in easy visibility to eliminate bias associated with searcher efficiency and visibility class. We assumed that carcass persistence and searcher efficiency would be the same for all carcasses within this visibility class. To calculate the dwp, we "binned" carcasses into 1 m rings radiating out from the turbine edge to the maximum plot size (100 m radius). We then calculated the total area of all search plots in the easy visibility class by $m^2$ in each ring and calculated the number of carcasses/$m^2$ in each ring. We modeled density as a conditional cubic polynomial function of distance. We calculated the density weighted area (dwa) of a plot, such that if no proportion of a plot was unsearched then dwa would be 1. We conducted all analyses in R version 3.5.2 (R Development Core Team 2018).

## RESULTS

We found a total of 205 bats comprised of 5 species and 1 species group during standardized carcass searches (Table 2.1). We were unable to identify to species 6 of the

205 bats due to decomposition and lack of identifiable structures. We found an additional 27 incidental bat carcasses comprised of 5 species, all of which were species detected during standardized searches. Most carcasses were Brazilian free-tailed bats (n=156), while yellow bats were the second most discovered (n=32). We grouped yellow bat species for two reasons based on an ongoing study assessing genetic population structure of yellow bats discovered at Los Vientos and a neighboring facility. The first is the confirmed presence of western yellow bats (*L.* [*Dasypterus*] *xanthinus*) from species barcoding of samples taken during this study, which have not been previously documented in south Texas. This species is morphologically identical to a state-listed threatened species, southern yellow bat (*L.* [*Dasypterus*] *ega*), that is known to occur in the county and can only be distinguished via genetic analysis (Ammerman et al. 2012). Second, given the number of morphologically similar species in the study site and difficulty of species identification in the field based on partially decomposed and scavenged remains, all species identifications should be checked using DNA barcoding techniques prior to analysis for species-specific patterns or impacts (Korstian et al. 2016; Jones and Weaver 2019; Amanda M. Hale, Texas Christian University, Fort Worth, Texas, personal communication, March, 2019). We therefore decided to treat these species as a complex and will further refer to them as yellow bats. The remaining bat carcasses were evening bats (*Nycticeius humeralis*; n=5), hoary bats (n=4), and an eastern red bat (*Lasiurus borealis*; n=1). We also discovered a single big free-tailed bat (*Nyctinomops macrotis*), which was the first documented occurrence of this species in the Lower Rio Grande Valley region of Texas (Jones and Weaver 2019).

While we discovered bat carcasses during all seasons, 78% were found during summer and fall (1 June–16 November; n=148). The only species we discovered during standardized searches in winter was the Brazilian free-tailed bat. In fact, Brazilian free-tailed bat fatalities were documented during every month of the study. We found a single yellow bat in April 2017, and the remaining from 28 July–29 September 2017. In addition, discovered hoary bat fatalities occurred from 30 August–8 November 2017, evening bats from 4 May–23 August 2017, and the single eastern red bat was discovered on 23 August 2017 and estimated to have occurred on or near 16 August 2017. The only big free-tailed bat carcass was highly desiccated with only the skeleton remaining (Jones and Weaver 2019). Therefore, we were unable to determine time of death.

Of the 205 bat carcasses discovered, we classified 69 (35%) as having occurred the previous night which we included in sex and age ratio calculations (Korstian et al. 2013). We determined the sex reliably for 64 of the 69 carcasses by examining both external and/or internal morphology, of which 26 were female and 38 were male. We estimated the age for 65 of the 69 carcasses, 61 of which were classified as adults and 4 as juveniles.

*Searcher Efficiency.*— We placed 62 carcasses in moderate to difficult visibility, and 121 in easy visibility to estimate searcher efficiency, of which 120 (66%) were discovered on the first search. Of the 69 carcasses left in place to test for searcher efficiency on subsequent searches, only 9 persisted until a second search, of which one was detected. A single carcass persisted long enough for a third search effort, but was not detected. Based on $\Delta AIC_c$, there were three competing models (Table 2.2). We selected the model with the lowest $AIC_c$ which included season*visibility as a predictor of $p$, and $k$ as a constant with no predictor variables. We selected this model because boxplots best matched the reference model (Supplementary Data SD1). In addition, when visibility was included as a predictor variable for *k* some boxplots had a 0-1 pattern, indicating too many parameters for the number of observations (Dalthorp et al. 2018b). Based on the selected model, median *p* ranged from 0.12 (95% *CI*: 0.03–0.39) during summer in the moderate to difficult visibility class to 0.93 (95% *CI*: 0.63–0.99) during summer in the easy visibility class. Estimated *k* was 0.32 (95% *CI*: 0.03–0.86) and constant for all covariates. (Table 2.3).

*Carcass Persistence.*—We placed 65 carcasses in moderate to difficulty visibility and 132 carcasses in easy visibility to estimate carcass persistence. There were two competing models, and we selected the model with the lowest $AIC_c$ weight of 851.00 (Table 2.4) because there was no clear advantage of the second-best model (1.23 ΔAICc) based on Kaplan-Meier plots (Supplementary Data SD2). The selected model had a Weibull distribution and season + visibility as location covariates, and season as a scale covariate. Based on the selected model, median carcass persistence ranged from 0.96 days during summer in the easy visibility class to 10.82 days during winter in the moderate to difficult visibility class (Table 2.5).

*Bat Fatality Estimates.*—We estimated a median of 8,167 (95% *CI*: 5,956–13,826) bat fatalities per year at the site (Fig. 2.2). This is equivalent to a median of 16 (95% *CI*: 12–27) bat fatalities per MW, or 32 (95% *CI*: 23–54) bat fatalities per turbine. We further estimated bat fatalities by species and by season. Brazilian free-tailed bats had the highest estimated fatality rates, followed by yellow bats (Table 2.6; Supplementary Data SD3). In addition, the highest estimated bat fatality rates occurred during summer, while the lowest estimated bat fatality rates occurred during winter (Table 2.7; Supplementary Data SD4). A complete list of discovered carcasses, including incidentals, and associated data can be found in the Appendix.

## DISCUSSION

We used a novel estimator to calculate bat fatality rates at Los Vientos. GenEst is a new approach that allows for accurate mortality estimates and unbiased comparisons of impacts among facilities (Simonis et al. 2018).We estimated between 5,956–13,826 bat fatalities occurred at Los Vientos during our study. Arnett and Baerwald (2013) estimated bat fatalities in regions of the U.S. and Canada based on available studies from 2000–2011. According to their delineations, Los Vientos is in the Gulf Coast region of Texas (residing <200 km inland) which had no available studies from which to estimate fatalities. We therefore compare fatalities at Los Vientos to the next closest region, the Great Plains (Arnett and Baerwald 2013). Bat fatality at Los Vientos was approximately 2 to 5x higher per MW than mean fatalities in the Great Plains (6.04 [95% *CI*: 3.98–8.10] bats per MW). In fact, Los Vientos had higher average fatalities than 4 of the 5 regions with calculated estimates. The exception being the Southeastern Mixed Forest, which was approximately 2.5x higher (41.17 [95% *CI*: 28.61–53.73] bats per MW) than Los Vientos. Although, data was only available from a single facility for this region (Arnett and Baerwald 2013). In addition, Strickland et al. (2011) summarized data from 66 studies in North America, and found approximately 82% of studies reported less than 10 bat fatalities per MW. We therefore consider bat fatality rates at Los Vientos to be moderate to high. However, we again caution that comparing fatality estimates is confounded by many sources of bias, such as differing methodologies and estimators among studies (Arnett and Baerwald 2013; Huso and Dalthorp 2014a).

Most species discovered during our study were previously reported as fatalities at wind energy facilities in North America, including those in the yellow bat complex (Arnett and Baerwald 2013). Reports of big free-tailed bat carcasses occur in unpublished presentations and reports, but to our knowledge the first published record of a recovered carcass of this species occurred during our study (Jones and Weaver 2019). Brazilian free-tailed bats had the highest estimated fatality, more than 4x that of yellow bats. While tree-roosting species are considered to comprise the highest proportion of fatalities at wind energy facilities in North America (Arnett and Baerwald 2013), a few studies have reported high fatality rates for cave-dwelling Brazilian free-tailed bats. This has been documented in both North America (Miller 2008, Piorkowski and O'Connell 2010) and South America (Barros et al. 2015). Our study supports these findings and provides further evidence of high impacts to this species where its range overlaps with wind energy development.

The lack of publicly available studies in Texas and Mexico, where Brazilian free-tailed bats occur in high abundance (Wilkins 1989), has likely skewed tree-roosting species' representation in previous cumulative calculations for North America (Arnett et al. 2008). Arnett et al. (2016) suggest bats most susceptible to fatalities at wind turbines are not restricted to tree-roosting species, but are more likely those with high wing loading (i.e., long and narrow wings), a characteristic typical of aerial-hawking bats adapted to open-air flight and echolocation. Based on our results and others previously mentioned, we recommend future cumulative assessments of bat impacts in North

America consider using alternative descriptions of the common characteristics for impacted species, such as morphology or by guild (Denzinger and Schnitzler 2013).

Furthermore, when siting wind energy facilities we caution against basing potential impacts to Brazilian free-tailed bats on distance to known colonies alone. Unlike in Miller (2008) and Piorkowski and O'Connell (2010), our site is not in proximity to any known large Brazilian free-tailed bat colony. The closest known colony is in the Camden Street Bridge in San Antonio approximately 300 km to the north, which is estimated at 50,000 bats (Texas Parks and Wildlife Department 2019). Although we have been informed of a potential colony in Falcon Dam approximately 43 km to the west of the closest wind turbine (Nevin D. Durish, ESE Partners, Austin, Texas, personal communication, March, 2019), but this colony nor species have been confirmed. However, due to their high abundance in Texas, affinity for roosting in human-made structures (Wilkins 1989; Ammerman et al. 2012; Schmidly and Bradley 2016), and ability to fly long distances each night (Best and Geluso 2003), it is possible for large colonies of this species to encounter and interact with wind turbines within their range. Therefore, siting decisions should consider the potential for impacts to this species within their known distribution as well as proximity to documented colonies. Where high fatality rates for Brazilian free-tailed bats occur, we encourage wind energy facilities to implement an impact reduction strategy. This species is of high economic importance to the agricultural industry as a prominent predator of crop pests (Cleveland et al. 2006; Federico et al. 2008, Boyles et al. 2011), and high fatality rates could affect regional farmers.

We found a slight male-biased sex ratio for Brazilian free-tailed bats and yellow bats. However, it has been suggested female bats are more likely to be classified as unknowns (Korstian et al. 2013). When we consider the number of unknowns for these two species irrespective of time since death, 74 for Brazilian free-tailed bats and 19 for yellow bats, it is evident molecular techniques are necessary to determine the true sex ratio of fatalities and recommend this approach for future studies.

Our results also indicate a potential age bias, with only 4 out of 65 (6%) carcasses classified as juveniles, of which 1 was a Brazilian free-tailed bat and the remaining 3 yellow bats. This bias is also supported in the literature, with more studies reporting higher fatalities for adults than juveniles (Arnett et al. 2008), and relatively few reporting otherwise (Baerwald and Barclay 2011; Jameson and Willis 2012). However, reasons for age bias in fatalities are not well understood (Hein and Schirmacher 2016). Age determination for juveniles using our method is limited in time to a few months, because joints typically ossify 2 to 3 months after birth (Kunz and Anthony 1982) potentially biasing carcass age determinations (Hein and Schirmacher 2016). Whether or not this is a true pattern of fatality warrants further investigations.

There was a peak in seasonal timing of fatalities during summer and fall, with most fatalities discovered in a one week period during the first week of September (n=17). Most studies in North America also report a seasonal peak in fatalities during summer and fall (Arnett et al. 2008; Baerwald and Barclay 2011). However, peak fatalities during our study occurred over more than 5 months (1 June through 16 November), which is somewhat longer than typically reported (Arnett et al. 2008; Baerwald and Barclay 2011). Studies from Canada and Iowa report peak fatalities occurring in August and September, and in New York from mid-July to mid-August. In Tennessee, majority of fatalities occurred from 1 August to mid-September (Arnett et al. 2008). In addition, we discovered fatalities throughout the entire year, indicating both resident and migratory bats were impacted. The species composition and patterns observed in this study have implications for bat impact reduction strategies. Curtailment, although effective in reducing bat fatalities in the Midwest and Eastern U.S. (Arnett et al. 2013), may not be effective for species in this region. Moreover, the longer period of peak fatality suggests curtailment may not be economically practicable. Thus, alternative strategies, such as acoustic deterrent technology, should be investigated and implemented if proven to be successful. In a concurrent study at Los Vientos, we found Brazilian free-tailed bat and hoary bat fatalities were significantly reduced during testing of a newly developed acoustic deterrent. Such deterrents present a promising impact reduction strategy for these species in this region (Weaver et al. 2019).

Much of the information regarding bat fatalities at wind turbines occurs in unpublished reports not accessible by the public (Rydell et al. 2010). Despite Texas having the highest installed wind energy capacity in the nation, it also has the fewest publicly available reports and/or peer-reviewed studies of any region (Cryan 2011; Hayes 2013). Without access to data regarding bat fatality patterns it is difficult to make informed decisions regarding siting and operations that maximize wind energy production and minimize impacts to bats (Hein and Schirmacher 2016). This highlights the importance of our study, which provides information in a region otherwise devoid of data.

South Texas shares similarities in species composition, climate, and habitat with northern Mexico (Ammerman et al. 2012; Ceballos 2014). Therefore, patterns of fatality at Los Vientos may be representative of those at wind energy facilities in northern Mexico States of Tamaulipas (which borders Starr County to the south), Nuevo Leon, and Coahuila. Currently, Mexico has 1.14 GW of installed wind energy capacity in these states, but projections of 4.5 GW of wind energy are expected by 2024 for this region (Mexican Association of Wind Energy [Spanish translation—Associación Mexicana de Energía Eólica; AMDEE] 2019). Moreover, the farther south from the Texas border a wind facility is located, comparisons to our results will be further complicated as other bat species, not present in the USA, will interact with these facilities. Similar to Texas, there is a paucity of data regarding the impacts of bats in Mexico, with only one study available (Villegas-Patraca et al. 2012). Given the rapid expansion of wind energy in the cross-border region and the results of our study, a greater understanding of the impacts of wind energy on these under-reported species is warranted. Moreover, research to assess the cost-effectiveness of impact reduction strategies should continue with an emphasis on Brazilian free-tailed bats and yellow bats.

## ACKNOWLEDGMENTS

This study was made possible through support from Duke Energy, Bat Conservation International, Houston Safari Club and Texas State University. We thank N. Durish and M. Schirmacher for their technical expertise, and M. Huso, and D. Dalthorp for their assistance with GenEst. We also thank the technicians and volunteers who assisted with fieldwork, and D. Dalthorp and anonymous reviewers who improved the quality of this manuscript.

**Table 2.1.**—Species composition and sex determination based on external and/or internal morphology of bat carcasses discovered during standardized searches for post-construction fatality monitoring at the Los Vientos Wind Energy Facility in Starr County, Texas from 24 March 2017 through 23 March 2018. Due to identification uncertainties yellow bats (*Lasiurus* [*Dasypterus*]) were pooled together (see text for details).

| | | Sex[a] | | |
|---|---|---|---|---|
| Species | n | Male | Female | Unknown |
| *Tadarida brasiliensis* | 156 | 31 | 18 | 3 |
| *Lasiurus* [*Dasypterus*] | 32 | 6 | 4 | 1 |
| Unidentified | 6 | - | - | 1 |
| *Nycticeius humeralis* | 5 | - | 2 | - |
| *Lasiurus cinereus* | 4 | 1 | 2 | - |
| *Lasiurus borealis* | 1 | - | - | - |
| *Nyctinomops macrotis* | 1 | - | - | - |
| Total | 205 | 38 | 26 | 5 |

[a] We only report sex determination for 69 bat carcasses estimated to have occurred the previous night to avoid potential bias associated with desiccation. These data were used for the sex ratio calculations.

**Table 2.2—** Top searcher efficiency models for post-construction bat fatality monitoring conducted at Los Vientos Wind Energy Facility in Starr County, Texas from 24 March 2017 through 23 March 2018.

| *p* formula | *k* formula | $AIC_c$ | $\Delta AIC_c$ |
|---|---|---|---|
| *p* ~ season*visibility | *k* ~ constant | 216.95 | 0 |
| *p* ~ season*visibility | *k* ~ visibility | 218.53 | 1.58 |
| *p* ~ visibility | *k* ~ constant | 218.81 | 1.86 |

**Table 2.3.—**Searcher efficiency estimates and 95% confidence intervals (*CI*) of *p* and *k* for each covariate level for the selected model (n=number of trial carcasses placed in each combination of covariates to estimate searcher efficiency). Searcher efficiency trials were conducted during post-construction bat fatality monitoring at Los Vientos Wind Energy facility in Starr County, Texas from 24 March 2017 through 23 March 2018.

| Season | Visibility | n | Median *p* | 95% | Median *k* | 95% *CI* |
|---|---|---|---|---|---|---|
| Fall | Easy | 43 | 0.79 | 0.64– | 0.32 | 0.03–0.86 |
| Spring | Easy | 47 | 0.83 | 0.70– | 0.32 | 0.03–0.86 |
| Summer | Easy | 14 | 0.93 | 0.63– | 0.32 | 0.03–0.86 |
| Winter | Easy | 17 | 0.58 | 0.35– | 0.32 | 0.03–0.86 |
| Fall | Moderate to difficult | 17 | 0.58 | 0.35– | 0.32 | 0.03–0.86 |
| Spring | Moderate to difficult | 20 | 0.37 | 0.20– | 0.32 | 0.03–0.86 |
| Summer | Moderate to difficult | 15 | 0.12 | 0.03– | 0.32 | 0.03–0.86 |
| Winter | Moderate to difficult | 10 | 0.50 | 0.23– | 0.32 | 0.03–0.86 |

**Table 2.4.—** Top carcass persistence models for post-construction bat fatality monitoring conducted at Los Vientos Wind Energy Facility in Starr County, Texas from 24 March 2017 through 23 March 2018.

| Location formula | Scale formula | $AIC_c$ | $\Delta AIC_c$ |
|---|---|---|---|
| *l* ~ season + visibility | *s* ~ season | 216.95 | 0 |
| *l* ~ season + visibility | *s* ~ season + | 218.53 | 1.58 |

**Table 2.5.—** Carcass persistence estimates and 95% confidence intervals (*CI*) of location (*l*) and scale (*s*) parameters, as well as median carcass persistence (CP) time in days and *r* statistics for each covariate level of the selected model (n=number of trial carcasses placed in each combination of covariates to estimate CP). Carcass persistence trials were conducted during post-construction bat fatality monitoring at Los Vientos Wind Energy facility in Starr County, Texas from 24 March 2017 through 23 March 2018.

| Season | Visibility | n | Median *l* | 95% *CI* | Median *s* | 95% *CI* | Median CP | *r*1 | *r*3 | *r*7 | *r*14 | *r*28 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fall | Easy | 52 | 0.73 | 0.45–1.02 | 1.034 | 0.84–1.28 | 1.42 | 0.79 | 0.53 | 0.29 | 0.15 | 0.08 |
| Spring | Easy | 47 | 1.65 | 1.27–2.03 | 1.377 | 1.07–1.77 | 3.13 | 0.84 | 0.69 | 0.52 | 0.36 | 0.21 |
| Summer | Easy | 16 | 0.76 | -0.10–1.62 | 2.186 | 1.50–3.19 | 0.96 | 0.62 | 0.47 | 0.33 | 0.23 | 0.15 |
| Winter | Easy | 17 | 2.31 | 1.84–2.78 | 1.095 | 0.76–1.58 | 6.72 | 0.94 | 0.84 | 0.70 | 0.53 | 0.34 |
| Fall | Moderate to difficult | 18 | 1.21 | 0.82–1.60 | 1.034 | 0.84–1.28 | 2.29 | 0.86 | 0.65 | 0.42 | 0.24 | 0.12 |
| Spring | Moderate to difficult | 19 | 2.12 | 1.66–2.59 | 1.377 | 1.07–1.77 | 5.04 | 0.88 | 0.77 | 0.62 | 0.47 | 0.31 |
| Summer | Moderate to difficult | 18 | 1.24 | 0.38–2.09 | 2.186 | 1.50–3.19 | 1.54 | 0.68 | 0.54 | 0.41 | 0.30 | 0.20 |
| Winter | Moderate to difficult | 10 | 2.78 | 2.27–3.30 | 1.095 | 0.76–1.58 | 10.82 | 0.96 | 0.90 | 0.79 | 0.65 | 0.47 |

**Table 2.6.**—Annual species-specific bat fatality estimates and 95% confidence intervals (*CI*) at Los Vientos Wind Energy facility in Starr County, Texas. Estimates obtained using GenEst software and empirical data (n = discovered bat carcasses) collected during post-construction bat fatality monitoring from 24 March 2017 through 23 March 2018.

| Species | n | Estimate | 95% *CI* |
|---|---|---|---|
| *Tadarida brasiliensis* | 156 | 6,090 | 4,390–10,590 |
| *Lasiurus* [*Dasypterus*] | 32 | 1,453 | 839–3,005 |
| *Nycticeius humeralis* | 5 | 197 | 44–415 |
| *Lasiurus cinereus* | 4 | 143 | 4–379 |
| Unknown | 6 | 127 | 20–308 |
| *Lasiurus borealis* | 1 | 63 | 1–257 |
| *Nyctinomops macrotis* | 1 | 23 | 1–86 |

**Table 2.7.**—Seasonal bat fatality estimates and 95% confidence intervals (*CI*) at Los Vientos Wind Energy facility in Starr County, Texas. Estimates obtained using GenEst software and empirical data (n = discovered bat carcasses) collected during post-construction bat fatality monitoring from 24 March 2017 through 23 March 2018.

| Season | n | Estimate | 95% *CI* |
|---|---|---|---|
| Summer | 82 | 4,299 | 2,332–9,901 |
| Fall | 75 | 2,653 | 1,749–3,912 |
| Spring | 42 | 964 | 633–1,394 |
| Winter | 6 | 179 | 37–421 |

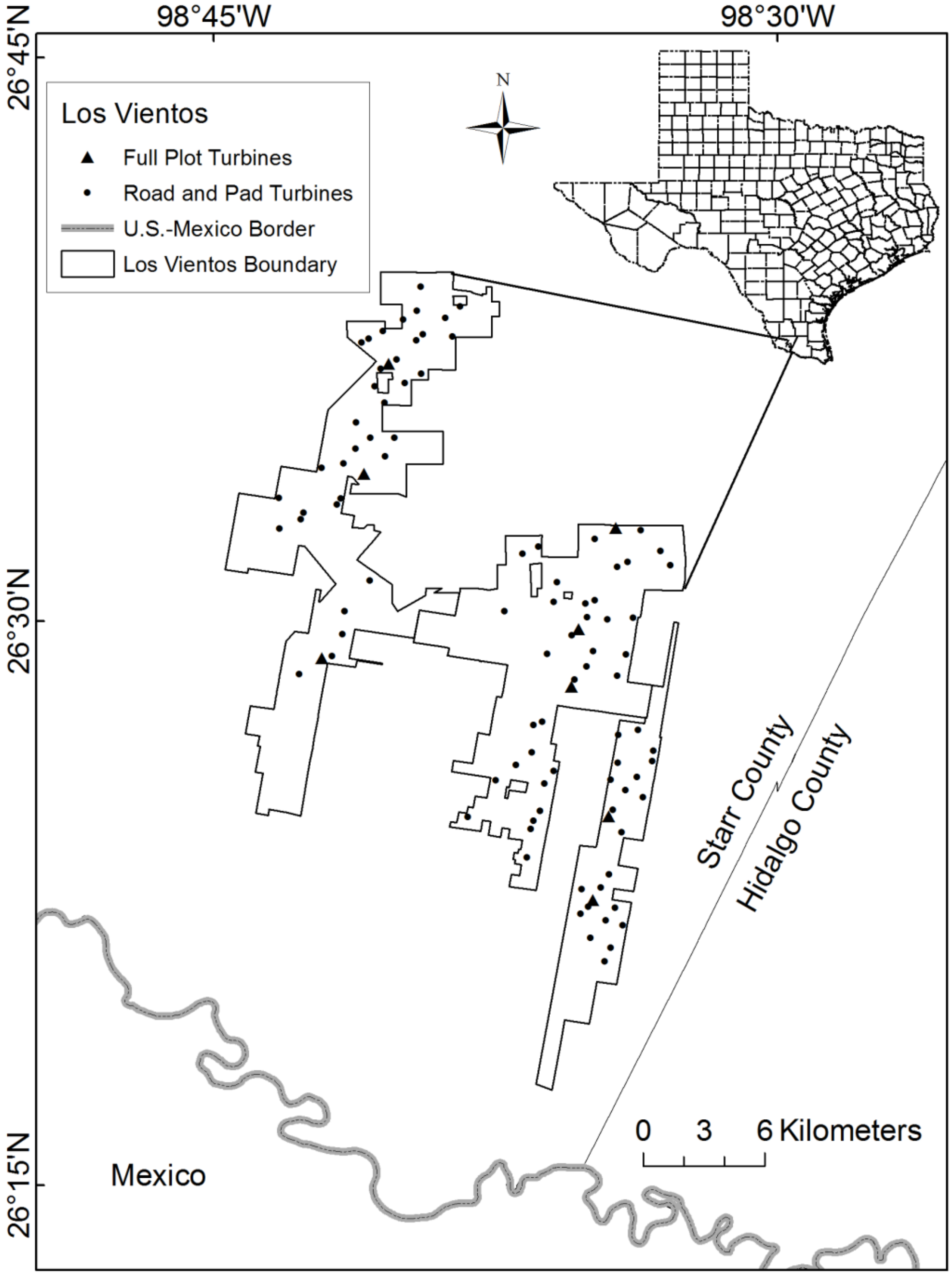



**Fig. 2.1.**—Site map of the Los Vientos Wind Energy Facility in Starr County, Texas. Insert map of Texas counties denotes the location of Starr County within Texas. Point locations on the map represent spatial distribution of all searched turbines during post-construction bat fatality monitoring from 24 March 2017 through 23 March 2018. Triangles represent turbines with full plots up to a maximum of 100 m radius (31,405 $m^2$), and circles represent turbines in which only roads and pads were searched to a maximum of 100 m radius (2,054 $m^2$).

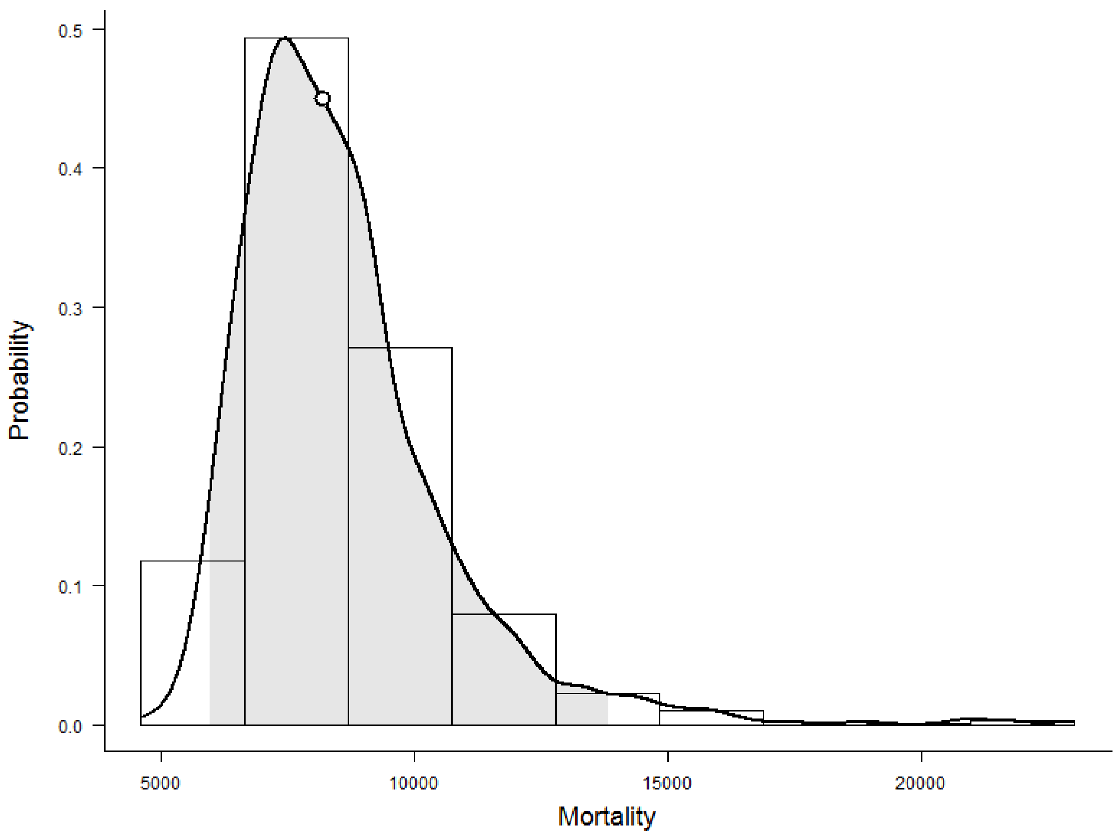
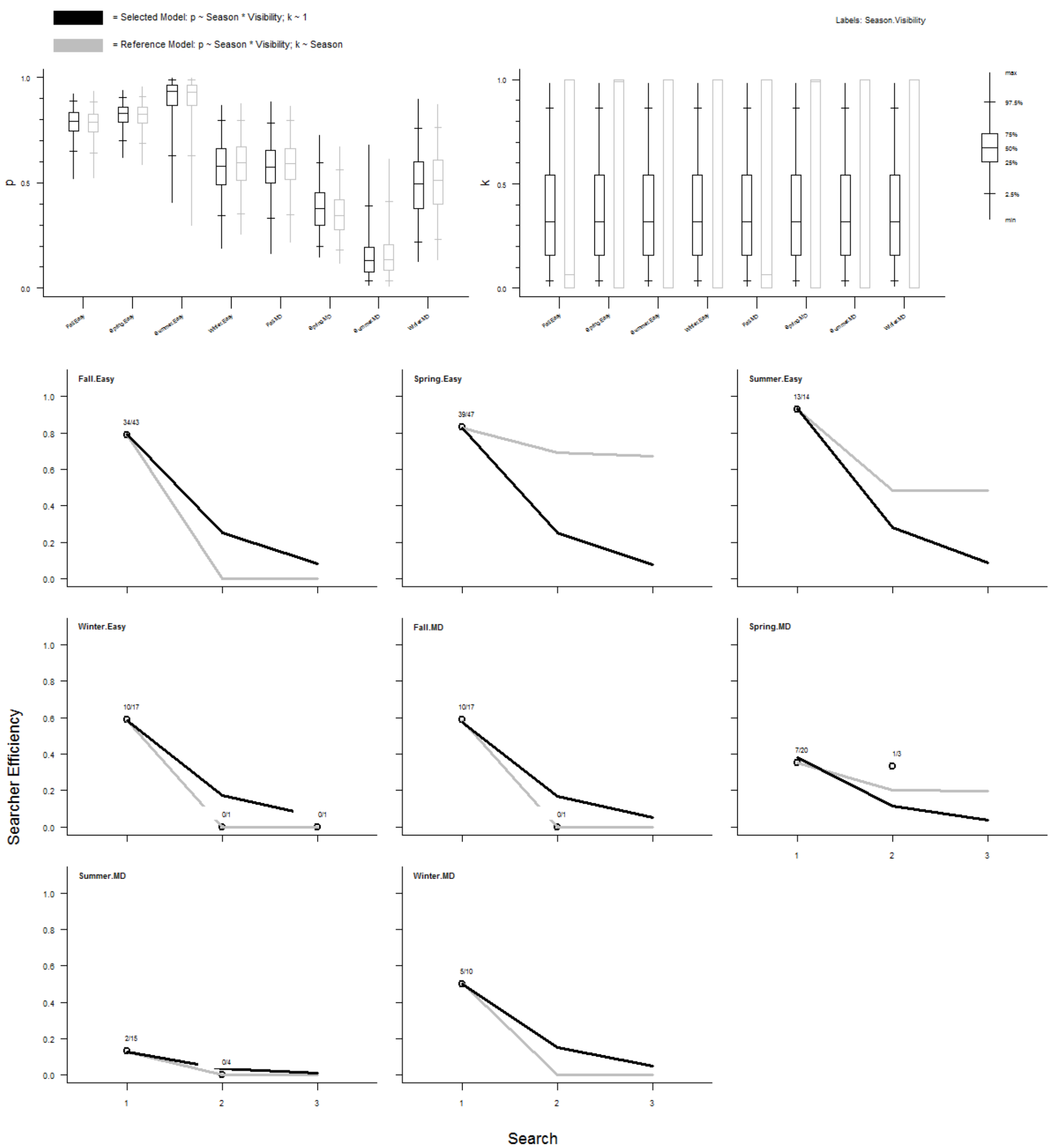


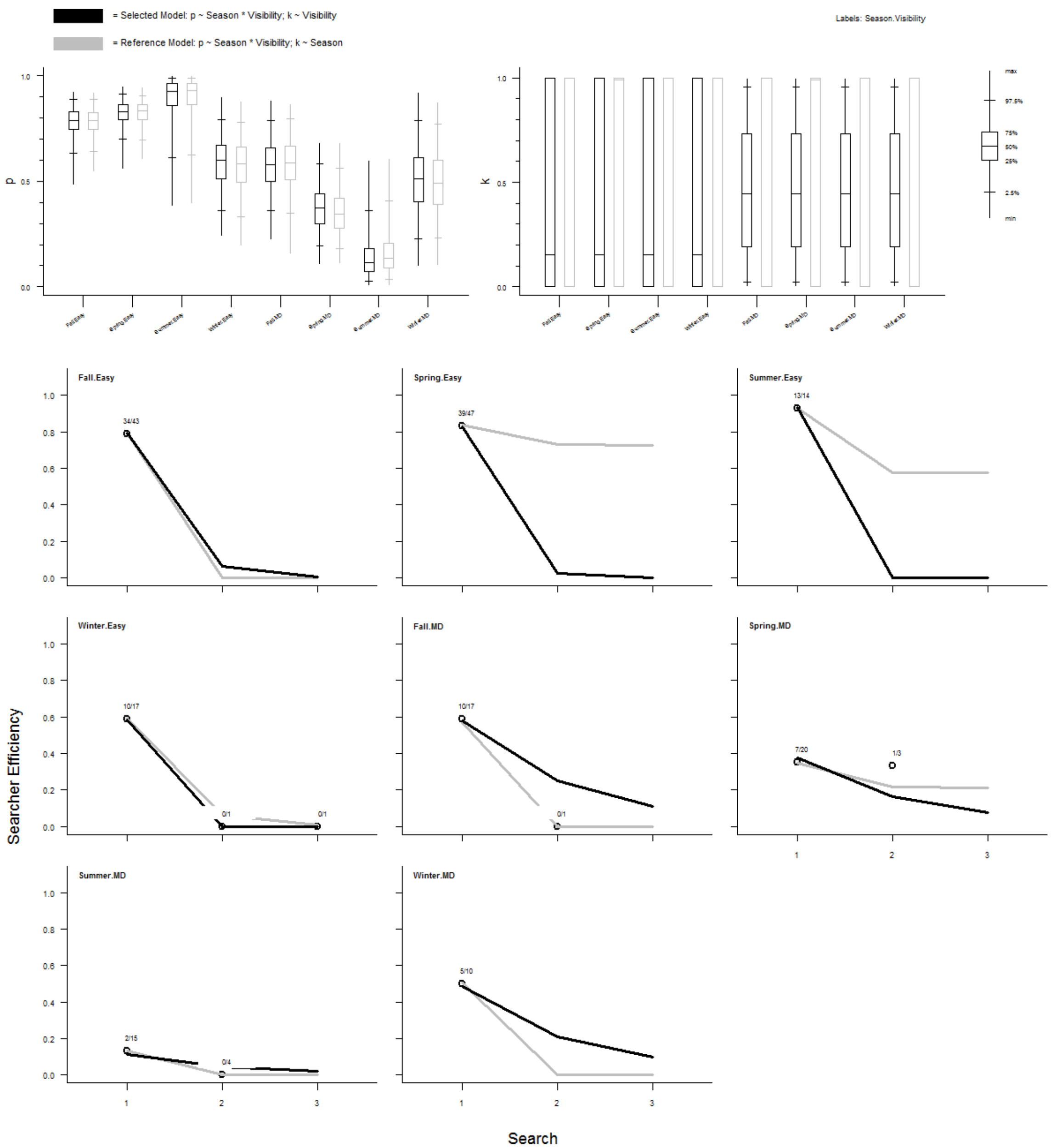

**Fig. 2.2.**—Estimated total yearly bat mortality and 95% confidence interval (*CI*) (8,167 bats per year; 95% *CI*: 5,956–13,826) for all species at Los Vientos Wind Energy Facility in Starr County, Texas. Estimates obtained using GenEst software and data collected during post-construction bat fatality monitoring from 24 March 2017 through 23 March 2018.

**Supplementary Data SD1.—**Search event plots of estimated and observed searcher efficiency for bias trials conducted during post-construction fatality monitoring at the Los Vientos Wind Energy Facility in Starr County, Texas from 24 March 2017 through 23 March 2018. Initial figures (a) represent the selected model, followed by the two competing models with $\Delta AIC_c$ 1.58 (b) and 1.86 (c), respectively. Dark lines represent the selected model, gray lines represent the most complex model, or reference model. Box plots represent estimated *p* and *k* for the selected searcher efficiency model (black lines) versus the reference model (grey lines).

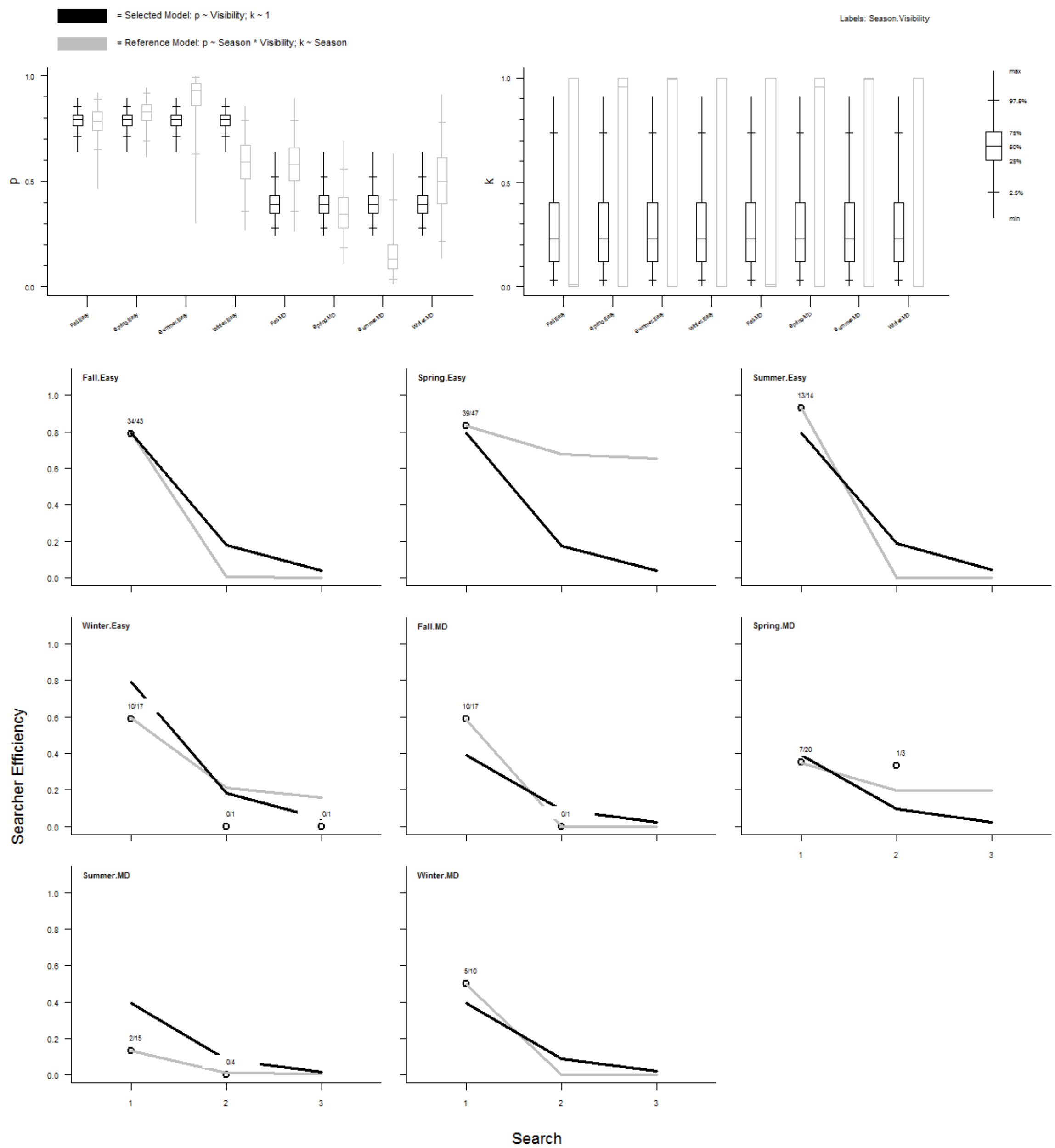
a)



b)

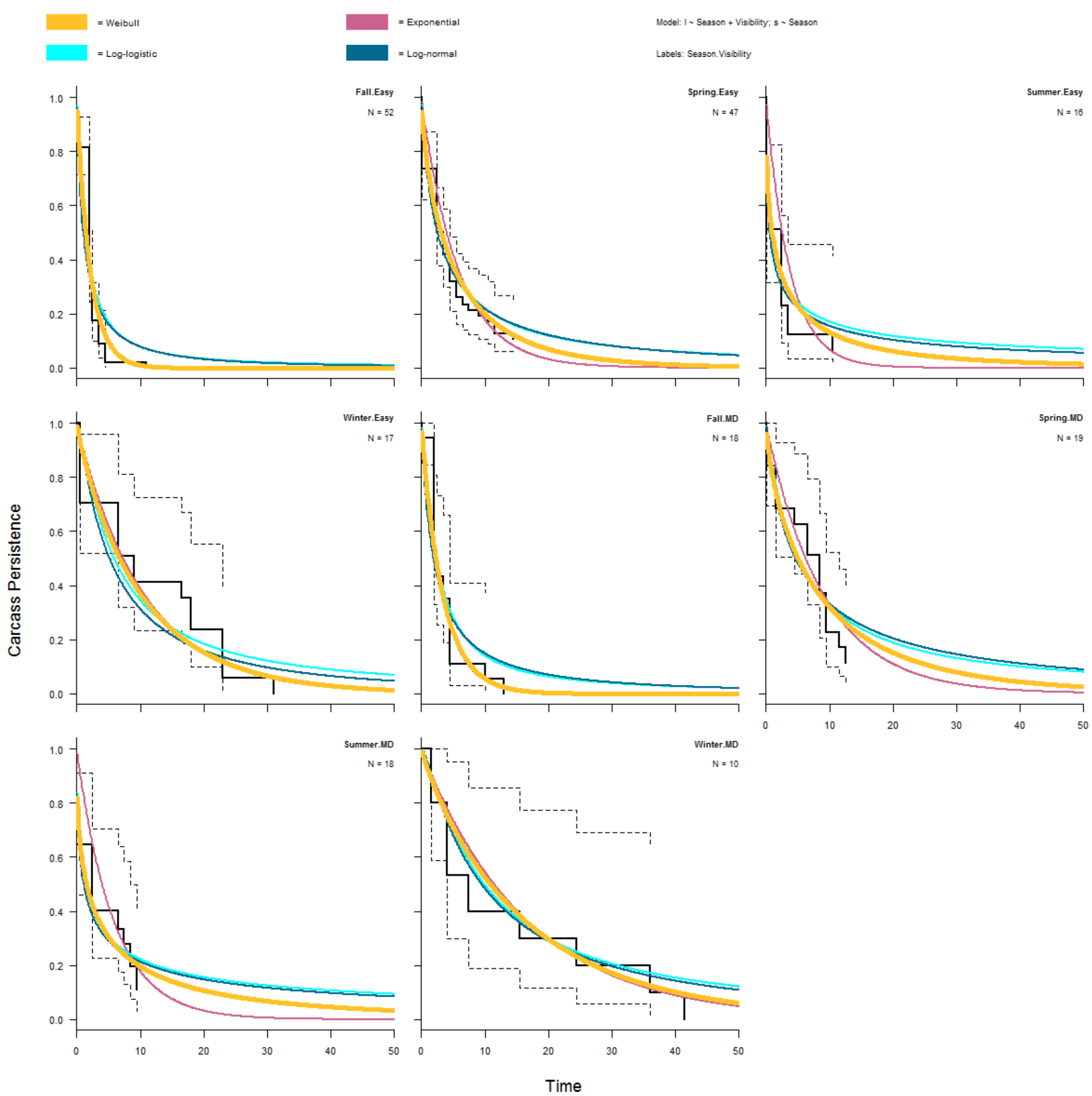

= Selected Model: p ~ Season * Visibility; k ~ Visibility
= Reference Model: p ~ Season * Visibility; k ~ Season
Labels: Season.Visibility
p
k
Fall.Easy
Spring.Easy
Summer.Easy
Winter.Easy
Fall.MD
Spring.MD
Summer.MD
Winter.MD
Searcher Efficiency
Search

c)

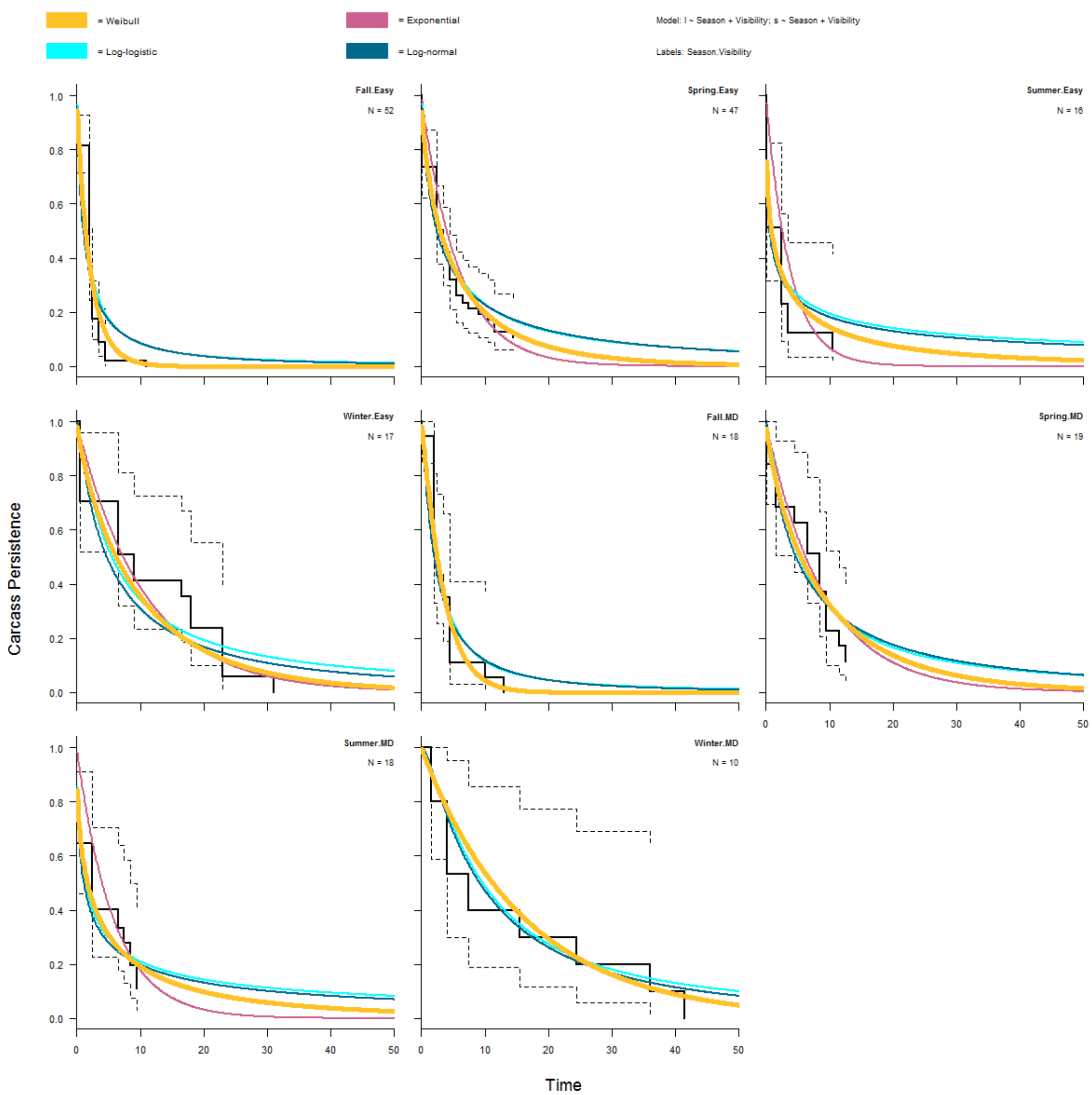

= Selected Model: p ~ Visibility; k ~ 1
= Reference Model: p ~ Season * Visibility; k ~ Season
Labels: Season.Visibility
p
k
Fall.Easy
34/43
Spring.Easy
39/47
Summer.Easy
13/14
Winter.Easy
10/17
0/1
0/1
Fall.MD
10/17
0/1
Spring.MD
7/20
1/3
Summer.MD
2/15
0/4
Winter.MD
5/10
Searcher Efficiency
Search

**Supplementary Data SD2.**—Kaplan-Meier plots of observed data (stair-step solid lines) and empirical confidence limits (stair-step dashed lines) of observed carcass persistence by time and combination of predictor variables (season and visibility) for Weibull (orange), loglogistic (light blue), exponential (mauve), and lognormal (dark blue) distriubutions. Data collected for bias trials during post-construction fatality monitoring at the Los Vientos Wind Energy facility in Starr County, Texas from 24 March 2017 through 23 March 2018. Initial plots represent the selected model (a), followed by the competing model with $\Delta AIC_c$ 1.58 (b).

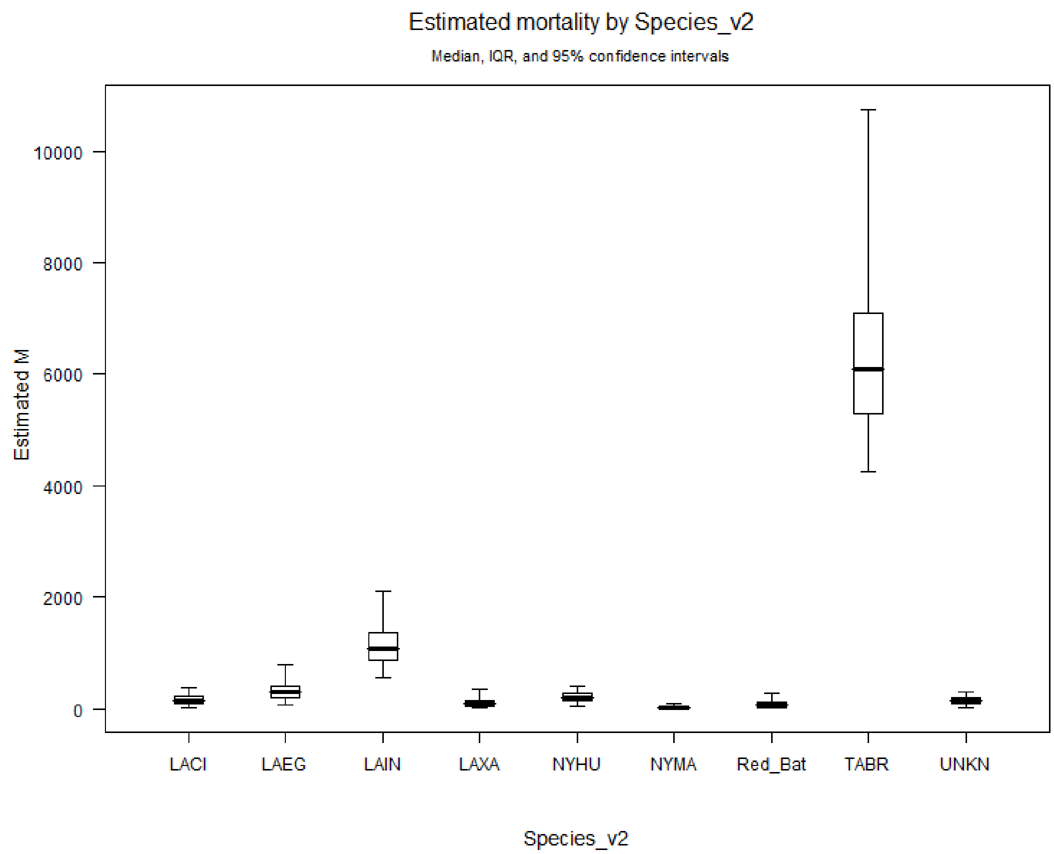
a)



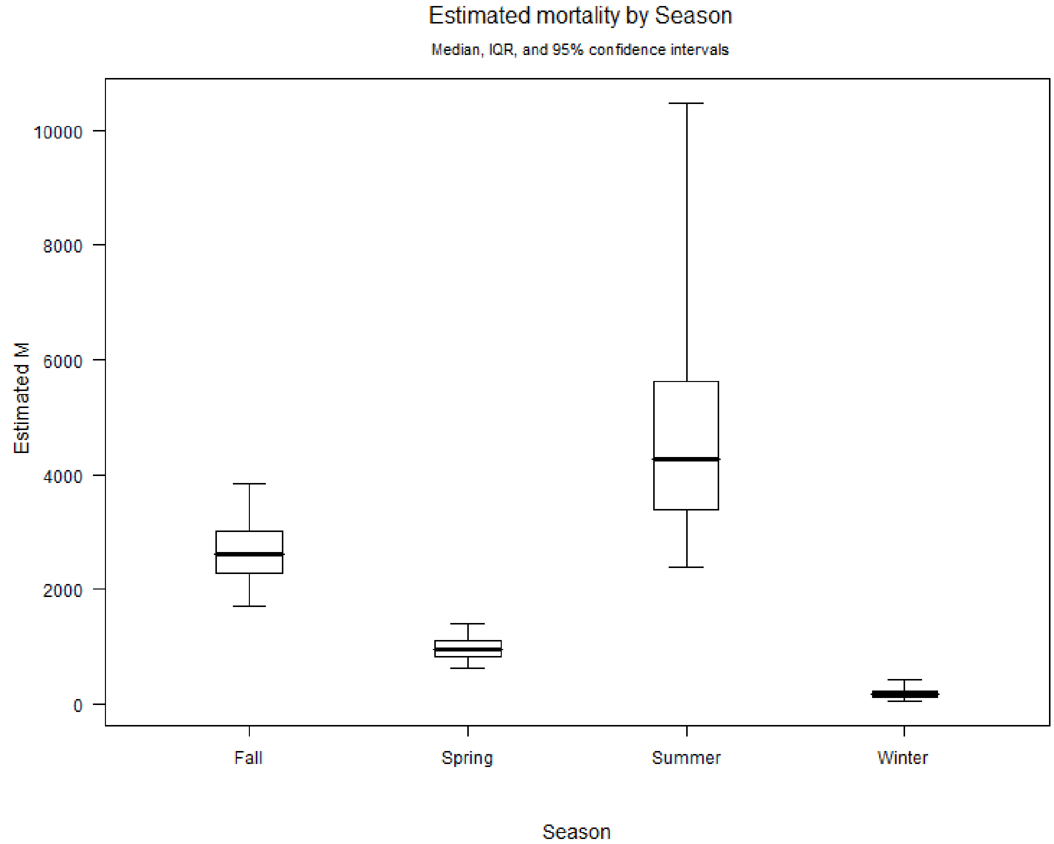
b)


= Weibull
= Exponential
Model: l ~ Season + Visibility; s ~ Season + Visibility
= Log-logistic
= Log-normal
Labels: Season.Visibility
Fall.Easy
N = 52
Spring.Easy
N = 47
Summer.Easy
N = 16
Winter.Easy
N = 17
Fall.MD
N = 18
Spring.MD
N = 19
Summer.MD
N = 18
Winter.MD
N = 10
Carcass Persistence
Time

**Supplementary Data SD3.**—Box plots and 95% confidence intervals of estimated bat mortality by species from post-construction fatality monitoring at the Los Vientos Wind Energy facility in Starr County, Texas from 24 March 2017 through 23 March 2018 (LA_Complex=yellow bats), LABO=*Lasiurus borealis*, LACI=*Lasiurus cinereus*, NYHU=*Nycteceius humeralis*, NYMA=*Nyctinomops macrotis*, TABR=*Tadarida brasiliensis*, UNKN=Unknown spp.



**Supplementary Data SD4.**—Box plots and 95% confidence intervals of estimated bat mortality by season from post-construction fatality monitoring at the Los Vientos Wind Energy facility in Starr County, Texas from 24 March 2017 through 23 March 2018.



## Literature Cited

AMDEE. 2018. Wind in numbers. www.amdee.org. Accessed 10 April 2019.

Ammerman, L. K., C. L. Hice, and D. J. Schmidly. 2012. Bats of Texas. Texas A&M University Press, College Station, TX.

Arnett, E. B., and E. F. Baerwald. 2013. Impacts of wind energy development on bats: implications for conservation. Pp 435–456 *in* Bat evolution, ecology, and conservation (R. A. Adams and S. C. Pedersen, eds.). Springer, New York, New York.

Arnett, E. B., et al. 2016. Impacts of Wind Energy Development on Bats: A Global Perspective. Pp. 295–323 *in* Bats in the Anthropocene: conservation of bats in a changing world (C. C. Voigt and T. Kingston, eds.). Springer. New York, New York.

Arnett, E. B., et al. 2008. Patterns of bat fatalities at wind energy facilities in North America. Journal of Wildlife Management 72:61–78.

Arnett, E. B., C. D. Hein, M. R. Schirmacher, M. M. P. Huso, and J. M. Szewczak. 2013. Evaluating the Effectiveness of an Ultrasonic Acoustic Deterrent for Reducing Bat Fatalities at Wind Turbines. PLoS ONE 8:1–11.

Arnett, E. B., M. M. P. Huso, M. R. Schirmacher, and J. P. Hayes. 2011. Changing wind turbine cut-in speed reduces bat fatalities at wind facilities. Frontiers in Ecology and the Environment 9:209–214.

Baerwald, E. F., and R. M. Barclay. 2011. Patterns of activity and fatality of migratory bats at a wind energy facility in Alberta, Canada, Journal of Wildlife Management 75:1103–1114.

Barros, M. A. S., R. Gastal de Magalhães, and A. M. Rui. 2015. Species composition and mortality of bats at the Osório Wind Farm, southern Brazil. Studies on Neotropical Fauna and Environment 50:31–39.

Bernstein, M. A., J. Griffin, and R. J. Lempert. 2006. Impacts on U.S. energy expenditures of increasing renewable energy use. RAND Corporation, Santa Monica, CA.

Best, T. L., and K. N. Geluso. 2003. Summer foraging range of Mexican free-tailed bats (*Tadarida brasiliensis mexicana*) from Carlsbad Cavern, New Mexico. Southwestern Naturalist 48:590-596.

Boyles, J. G., P. M. Cryan, G. F. McCracken, and T. H. Kunz. 2011. Economic importance of bats in agriculture. Science 332:41-42.

Brunet-Rossinni, A. K., and G. S. Wilkinson. 2009. Methods for age estimation and the study of senescence in bats. Pp. 315–328 in Ecological and behavioral methods for the study of bats (T. H. Kunz and S. Parsons, eds.). Johns Hopkins University Press. Baltimore, Maryland.

Ceballos, G. (ed.). 2014. Mammals of Mexico. Johns Hopkins University Press. Baltimore Maryland

Cleveland, C. J., M. Betke, P. Federico, J. D. Frank, T. G. Hallam, J. Horn, J. D. Lopez, G. F. McCracken, R. A. Medellin, A. Moreno-Valdez, C. G. Sansone, J. K. Westbrook, and T. H. Kunz. 2006. Economic value of the pest control service provided by Brazilian free-tailed bats in south-central Texas. Frontiers in Ecology and the Environment 4:238–243.

Cryan, P. M. 2011. Wind turbines as landscape impediments to the migratory connectivity of bats. Environmental Law 41:355–370.

Dalthorp, D., et al. 2018a. GenEst: Generalized mortality estimator. R package version 1.2.1.

Dalthorp, D., L. Madsen, M. Huso, P. Rabie, R. Wolpert, J. Studyvin, J. Simonis, and J. Mintz. 2018b. GenEst statistical models—A generalized estimator of mortality: U.S. Geological Survey Techniques and Methods, book 7, chap. A2, 13 p.

Denzinger, A., and H. U. Schnitzler. 2013. Bat guilds, a concept to classify the highly diverse foraging and echolocation behaviors of microchiropteran bats. Frontiers in Physiology 4:1-15.

Federico, P., T. G. Hallam, G. F. McCracken, S. T. Purucker, W. E. Grant, A. N. Correa-Sandoval, J. K. Westbrook, R. A. Medellin, C. J. Cleveland, C. G. Sanson, J. D. Lopez, M. Betke, A. Moreno-Valdez, and T. H. Kunz. 2008. Brazilian free-tailed bats as insect pest regulators in transgenic and conventional cotton crops. Ecological Applications 18:826–837.

Frick, W. F., E. F. Baerwald, J. F. Pollock, R. M. R. Barclay, J. A. Szymanski, T. J. Weller, A. L. Russell, S. C. Loeb, R. A. Medellin, and L. P. McGuire. 2017. Fatalities at wind turbines may threaten population viability of a migratory bat. Biological Conservation 209:172–177.

Global Wind Energy Council. 2013. 30 years of policies for wind energy. International Renewable Energy Agency, Abu Dhabi, United Arab Emirates.

Griffith, G., S. Bryce, J. Omernik, and A. Rogers. 2007. Ecoregions of Texas. Texas Commission on Environmental Quality, Austin, TX.

Hall, L. S., and G. C. Richards. 1972. Notes on *Tadarida australis*. Australian Mammalogy 1:46–47.

Hall, E. R. 1981. The mammals of North America. 2nd ed. John Wiley & Sons, Inc. New York 1:1–600 + 90.

Hayes, M A. 2013. Bats killed in large numbers at United States wind energy facilities. BioScience 63:975–979.

Hein, C. D., and M. R. Schirmacher. 2016. Impact of wind energy on bats: A summary of our current knowledge Impact of wind energy on bats: a summary of our current knowledge. Human-Wildlife Interactions 10:19–27.

Homer, C. G., et al. 2015. Completion of the 2011 National Land Cover Database for the conterminous United States – representing a decade of land cover change information. Photogrammetric Engineering and Remote Sensing 81:345–354.

Hull, C., and S. Muir. 2010. Search area for monitoring bird and bat carcasses at wind farms using a Monte-Carlo model. Australian Journal of Environmental Management 17:77-87.

Huso, M. M. P. 2011. An estimator of wildlife fatality from observed carcasses. Environmetrics 22:318–329.

Huso, M. M. P., and D. Dalthorp. 2014a. A comment on "Bats killed in large numbers at United States wind energy facilities." BioScience 64:546–547.

Huso, M. M. P., and D. Dalthorp. 2014b. Accounting for unsearched areas in estimating wind turbine-caused fatality. Journal of Wildlife Management 78:347-358.

Inkley, D. B., M. G. Anderson, A. R. Blaustein, V. R. Burkett, B. Felzer, B. Griffith, J. Price, and T. L. Root. 2004. Global climate change and wildlife in North America. Wildlife Society Technical Review 04-2. The Wildlife Society, Bethesda, Maryland.

Jameson, J. W., and C. K. R. Willis. 2012. Bat mortality at a wind power facility in central Canada. Northwestern Naturalist 93:194-202.

Jones, A. K., and S. P. Weaver. 2019. Big free-tailed bat (*Nyctinomops macrotis*) discovered at a wind energy facility in the Lower Rio Grande Valley, Texas. Southwestern Naturalist 63:75–76.

Korner-Nievergelt, F. et al. 2015. Mortality estimation from carcass searches using the R-package carcass—A tutorial. Wildlife Biology 21:30-43.

Korstian, J. M., A. M. Hale, V. J. Bennett, and D. A. Williams. 2013. Advances in sex determination in bats and its utility in wind-wildlife studies. Molecular Ecology Resources 13:776–780.

Korstian, J. M., A. M. Hale, V. J. Bennett, and D. A. Williams. 2016. Using DNA barcoding to improve bat carcass identification at wind farms in the United States. Conservation Genetics Resources 8:27–34.

Kunz, T. H., and E. L. P. Anthony. 1982. Age estimation and post-natal growth in the bat *Myotis lucifugus*. Journal of Mammalogy 63:23-32.

Kunz, T. H., et al. 2007. Ecological impacts of wind energy development on bats: questions, hypotheses, and research needs. Frontiers in Ecology and the Environment 5:315–324.

Miller, A. 2008. Patterns of avian and bat mortality at a utility-scaled wind farm on the southern High Plains. M.S. thesis, Texas Tech University, Lubbock, Texas.

O'Shea, T. J., P. M. Cryan, D. T. S. Hayman, R. K. Plowright, and D. G. Streicker. 2016. Multiple mortality events in bats: a global review. Mammal Review 46: 175–190. DOI: 10.1111/mam.12064

Pennsylvania Game Commission (PGC). 2007. Wind energy voluntary cooperation agreement. Pennsylvania Game Commission, Harrisburg, PA.

Piorkowski, M. D., and T. J. O'Connell. 2010. Spatial pattern of summer bat mortality from collisions with wind turbines in mixed-grass prairie. American Midland Naturalist 164:260–269.

R Development Core Team. 2018. R: a language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria. www.R-project.org/.

Rydell, J., L. Bach, M.-J. Dubourg-Savage, M. Green, L. Rodrigues, and A. Hedenström. 2010. Bat mortality at wind turbines in Northwestern Europe. Source: Acta Chiropterologica 12:261–274.

Schlesinger, M. E., and J. F. B. Mitchell. 1987. Climate model simulations of the equilibrium climatic response to increased carbon dioxide. Reviews of Geophysics 25:760.

Schmidly, D. J., and R. D. Bradley. 2016. The mammals of Texas. University of Texas Press, Austin.

Shoenfeld, P. 2004. Suggestions regarding avian mortality extrapolation. FPL Energy, West Virginia Highlands Conservancy, Davis.

Sikes, R. S., and the Animal Care and Use Committee of the American Society of Mammalogists. 2016. 2016 guidelines of the American Society of Mammalogists for the use of wild mammals in research and education. Journal of Mammalogy 97:663–688.

Simonis, J., D. Dalthorp, M. Huso, J. Mintz, P. Rabie, and J. Studyvin. 2018. GenEst user guide—Software for a generalized estimator of mortality. U.S. Geological Survey, Techniques and Methods, book 7, chap C19, 72 p.

Smallwood, K. S. 2013. Comparing bird and bat fatality-rate estimates among North American wind-energy projects. Wildlife Society Bulletin 37:19–33.

Strickland, M. D., E. B. Arnett, W. P. Erickson, D. Johnson, M. L. Morrison, J. Shaffer, and W. Warren-Hicks. 2011. Comprehensive guide to studying wind energy/wildlife interactions. Prepared for the National Wind coordinating Collaborative, Washington, D.C.

Texas Parks and Wildlife Department. 2019. Bat-watching sites of Texas. www.tpwd.texas.gov/huntwild/wild/species/bats/bat-watching-sites. Accessed 2 April 2019.

Villegas-Patraca, R., S. Macías-Sánchez, I. MacGregor-Fors, and C. Muñoz-Robles. 2012. Scavenger removal: bird and bat carcass persistence in a tropical wind farm. Acta Oecologica 43:121–125.

Weaver, S. P., C. D. Hein, I. Castro-Arellano, and T. R. Simpson. 2019. Testing ultrasonic acoustic deterrents for reducing bat fatalities at wind turbines in south Texas. Pp. 101–104 in Proceedings of the Wind-Wildlife Research Meeting XII, St. Paul, Minnesota, 28–30 November 2018 (S. S. Schwartz, ed.). American Wind Wildlife Institute, Washington, DC.

Wilkins, K. T. 1989. *Tadarida brasiliensis*. Mammalian Species 331:1–10.

## III. BAT ACOUSTIC ACTIVITY AT WIND TURBINES IN SOUTH TEXAS[2]

Wind turbine collisions are considered one of the largest sources of mass bat mortality events across the world (O'Shea et al. 2016). Many hypotheses have been proposed concerning ultimate causes of bat fatalities from wind energy development, with evidence of bat attraction to wind turbines presumably increasing their susceptibility to fatalities (Cryan and Barclay 2009; Cryan et al. 2014). Historically, studying bat behavior and activity at wind turbines has been difficult due to their nocturnal habits, small size, and flight ability (Kunz et al. 2007; Cryan and Barclay 2009). However, bat acoustic detector technology has allowed researchers to study bat behavior and activity during both siting and operational phases of a project (Cryan et al. 2014).

All insectivorous bats use echolocation by emitting high frequency vocalizations and interpreting the reflected echoes from nearby objects. This rare sensory capability is used primarily for foraging, but also for navigation, communication, roost site selection, and water resource detection (Jones and Teeling 2006). There are species and situational variations to call types that echolocating bats emit (Schnitzler et al. 2003; Jones and Holderied 2007), but they are generally classified as broadband, narrowband, and long constant frequency with Doppler-shift compensation (Schnitzler et al. 2003). This method of vocalization allows for qualitative and quantitative assessments of activity using technologies such as acoustic detectors (Clement et al. 2014), which is useful in assessing the conditions under which bats interact with wind turbines. Details of bat acoustic activity at wind turbines provides information not obtained in post-construction fatality

[2] Weaver, S. P., D. Cordani, N. D. Durish, and I. Castro-Arellano. Publication: Journal of Mammalogy *in preparation*.

monitoring efforts, because detectors provide a time stamp of presence which can then be used to relate activity to weather, temporal, and operational correlates (Reynolds 2006). Moreover, acoustic monitoring can allow investigations of echolocation behavior at wind turbines, such as occurrence of feeding buzzes or social calls, which can inform on whether or not bats forage or interact with each other at wind turbines (Reynolds 2006; Reimer et al. 2018). Such information could have implications for designing impact reduction strategies, assuming the type of activity at wind turbines correlates to fatalities (Hayes et al. 2019).

Currently, information on bat behaviors at wind turbines is lacking for several understudied species of bats in South Texas, including yellow bats (*Lasiurus* [*Dasypterus*] spp.) and Brazilian free-tailed bats (*Tadarida brasiliensis*) which have incurred high fatality rates at wind energy facilities (Miller 2008; Piorkowski and O'Connell 2010, Weaver et al. 2019b). Acoustic studies at wind turbines will aid in understanding conditions under which bats are more active and perceivably at higher risk of fatalities, and inform decisions on reducing risk (Hein 2017).

My research objectives were to 1) document bat acoustic activity patterns at wind turbines at the Los Vientos Wind Energy Facility in Starr County, Texas, 2) assess potential weather and temporal parameters associated with bat activity at wind turbines in south Texas, and 3) determine if there is a relationship between bat activity and bat fatality at the site.

## MATERIALS AND METHODS

The study site for this research was the Los Vientos III, IV, and IV Wind Energy Facilities in Starr County, Texas. The three facilities (herein referred to as Los Vientos or the study site) are adjacent to one another and have the same turbine model. Thus, I treated all as a single facility for this study. Los Vientos encompasses approximately 22,666 ha and consists of 255 Vestas V-110, 2-megawatt (MW) turbines. All turbines have a nacelle height of 95 m and rotor diameter of 110 m, with a rotor-swept area of 9,503 $m^2$. I deployed a single acoustic detector (Song Meter [SM] 3 BAT, Wildlife Acoustics) in the nacelle of three wind turbines programmed to operate from 30 minutes before sunset to 30 minutes after sunrise from 14 August to 19 October 2017. Distance between wind turbines fitted with acoustic detectors ranged from 9 to 15 km. Each detector had two SMM-U1 ultrasonic microphones and recorded in full-spectrum WAV format. Microphones were positioned outside the nacelle similar to those in Gorresen et al. (2015). I set minimum recording frequency (FRQMIN) to 16 kilohertz (kHz), maximum frequency (FRQMAX) to 96 kHz, and the sampling rate to 192 kHz, which gives a recording frequency range that overlaps with all bat species known to occupy the region around the study site. Memory SD cards were removed and replaced for downloading every two to three weeks for the duration of the study. Also, the date of each recorded bat pass was adjusted to reflect effective date, as the detector was programmed to operate only within the night and twilight. For example, if a bat pass was recorded on the morning of 15 August 2017, it was listed as occurring between 30 minutes before sunset to 30 minutes after sunrise on the night of 14 August 2017.

Habitat surrounding the selected turbines was primarily shrub/scrub (4-96 and 3-08) and pasture/hay at 4-60 (Fig. 3.1). Turbines selected were full-plot turbines as part of a concurrent post-construction monitoring effort conducted to estimate bat fatality rates at the study site (see Chapter II). These turbines were selected to compare bat activity with discovered bat carcasses. However, too few fresh carcasses that could be confirmed as occurring the previous night, to compare with nightly activity were found at these turbines during the study, possibly due to length of sampling search interval (7 days), scavenger removal, or searcher efficiency (Weaver et al. 2019b). Therefore, I compared bat activity at these three full-plot turbines with number of fresh bat carcasses discovered during a parallel study centered on assessing the effectiveness of an ultrasonic acoustic deterrent in reducing fatalities. Testing was conducted during the same time frame in 2017 at the study site (Weaver et al. 2019a). For this parallel study, a set of 16 turbines were affixed with acoustic deterrents that were either on (treatment) or off (controls) each night. Although these turbines were not originally a part of the present study, they were searched daily during concurrent acoustic deterrent testing and are representative of fatality patterns during my study period when bat activity at turbines was recorded. I adjusted the date a bat carcass was discovered during deterrent testing to the effective night of fatality occurrence. For example, if a fresh bat carcass was found on the morning of 5 September 2017, it was assumed to have occurred on the night of 4 September 2017. Turbines selected for testing acoustic deterrents were originally considered for being included in the present study. However, due to turbine manufacturer warranty concerns I was unable to pair these technologies (Fig. 3.1).

I analyzed acoustic data using Kaleidoscope Pro 5 Auto ID Analysis Software (Wildlife Acoustics, Inc.), and used the Bats of North America 5.1.0 classifiers for Texas with a balanced (neutral) sensitivity setting and selected the following species for automatic identification (auto ID): eastern red bat (*Lasiurus borealis*), hoary bat (*L. cinereus*), southern yellow bat (*L. ega*), northern yellow bat (*L. intermedius*), cave myotis (*Myotis velifer*), evening bat (*Nycticeius humeralis*), tricolored bat (*Perimyotis subflavus*), and Brazilian free-tailed bat. I based auto ID species selection on species range maps (Ammerman et al. 2012; Schmidly and Bradley 2016), and carcasses found during post-construction fatality monitoring at the site, as well as at other South Texas facilities in Cameron , Hidalgo, Starr,  and Willacy counties. I selected 8–120 kHz for minimum and maximum frequency range detection, 2–500 ms minimum and maximum length of detected pulses, 500 ms maximum inter-syllable gap, and a minimum of 2 pulses for signal detection parameters. Nevin Durish (ESE Partners), a bat acoustic expert assisted me in manually reviewing all bat files, including those labeled as "noise", to eliminate false positives and negatives and confirm species ID. Only search phase calls were used to determine species identification. When insufficient search phase pulses were available for identification, or quality of a file was too low to determine species identification, bat files were placed into a low or high frequency group (low *f* and high *f*), with the lowest characteristic frequency of 35 kHz as the dividing point (Table 3.1).

Acoustic recordings cannot identify number of bats or bat abundance because multiple bat passes could be from the same individual. Therefore, I quantified bat activity as bat passes per detector-night and used this to standardize activity measures, and related overall bat activity patterns by turbine, month, and hour of night, both for all bats and by species or species group. I calculated a detector-night as the total bat passes divided by the number of recording microphones (n=6) per night, and not individual detector units (n=3) because the microphone is considered the individual sampling unit.

I obtained hourly measurements of temperature, relative humidity, wind speed, and barometric pressure from weather instruments on a meteorological tower (MET) located at the facility (MET 36: 98°32'45.68"W, 26°31'21.81"N). Recording instruments were mounted 90–95 m from the ground, which corresponds with turbine nacelle heights (95 m). I converted relative humidity to absolute humidity ($g/m^3$) using the recorded temperature and relative humidity data (Vaisala, http://www.vaisala.com/Vaisala%20Documents/Application%20notes/ Humidity_ Conversion_Formulas_B210973EN-F.pdf). I used absolute humidity instead of relative humidity because absolute humidity is independent of temperature and a better measure of air moisture than relative humidity (Colloff 2009; Hillman et al. 2009). I obtained nightly fraction of moon illumination from the U.S. Naval Observatory's Astronomical Applications Department website (https://aa.usno.navy.mil/data/docs/MoonFraction.php).

To determine if there was a relationship between bat fatality and bat activity, I performed a generalized linear model (GLM) with total nightly bat carcasses as the response variable and total bat passes per night as the predictor variable. The data were overdispersed, and thus I modeled with a negative binomial distribution using function "glm.nb" with package "MASS" version 7.3-51.4 (Venables and Ripley 2002) in R version 3.5.3 (R Development Core Team 2019). In addition, I assessed the relationship of weather and temporal covariates on bat activity using a negative binomial GLM with stepwise selection using the "step" function in R, and selected the model with lowest

Akaike information criterion (AIC). I modeled total bat passes per hour as the response variable, temperature (°C), and hourly absolute humidity ($g/m^3$), wind speed (m/s), pressure (mbar), Δ 24-hour pressure, and fraction of moon illuminated as predictor variables, as well as Julian date and hour of night since recording began (1–11) as a quadratic polynomials. I modeled the last two variables as quadratic polynomials after viewing scatterplots and determining there was a non-linear relationship. I scaled covariates by subtracting the mean and dividing by the standard deviation (SD). Prior to modeling, I assessed collinearity of variables using function "vif" in package "car" version 3.0-3 (Fox and Weisberg 2019) and dropped a covariate if the generalized variance inflation factor (GVIF^(1/2*DF)) was >3.0 (Zuur et al. 2010). I restricted analysis from 08:00 PM to 06:00 AM despite detectors recording outside this time frame due to few detected recordings of bat passes (<0.1%) during these hours (n=53). This is likely because bats had not yet emerged and become active earlier in the evening, and had ceased activity by the mid-morning. It is important to note that hourly bat activity was modeled based only on the hour and not by minute. For example, if a bat pass was detected at 06:58 AM I classified it as occurring during the 06:00 AM hour, or 10 hours after recording began.

## RESULTS

Detectors recorded at all three turbines continuously between 14 August 2017 and 19 October 2017 for 67 nights each, or 402 total detector-nights. I documented 61,186 total bat passes across all microphones for an average of 152 ± 16.9 bat passes/detector-night. Activity ranged from 0.8 bat passes/night to 669 bat passes/night. I was unable to classify to species many files due to low file quality or lack of distinguishing call characteristics.

Therefore, the low *f* species group comprised the majority (44%) of all bat passes (n=26,733), for an average of 67 bat passes/detector-night (Table 3.2). Brazilian free-tailed bats comprised the majority (27%) of bat passes (n=16,521) of those I was able to identify to species, for an average of 41 bat passes/detector-night. Additionally, after I had processed the data by Kaleidoscope and manually reviewed all files, I discovered that western yellow bats (*L. xanthinus*) and western red bats (*L. blossevellii*) were genetically confirmed to occur at the site during a concurrent study (Amanda M. Hale, Texas Christian University, Fort Worth, Texas, personal communication, March, 2019). Distinguishing among the various yellow and red bat species acoustically is difficult given the overlap in echolocation characteristics. Therefore, I grouped all yellow bat species into one yellow bat group, and red bat species into a red bat group. Yellow bats comprised the next most commonly detected group at 23% (n=14,192), for an average of 35 bat passes/detector-night. The remaining species or groups combined accounted for only 6% of detections (n=3,740).

All low frequency species and species groups exhibited a nightly unimodal activity pattern. Low *f* and yellow bat activity was highest at 0000, or 12:00 AM (midnight). Brazilian free-tailed bat activity peaked at 0200 (02:00 AM). Hoary bat activity was highest at 2300 (11:00 PM) and stayed fairly consisted from 2300 to 0400 (11:00 PM to 04:00AM) ranging from 1.01 to 1.20 bat passes/detector-night (Fig. 3.2).

Evening bats displayed a bimodal nightly activity pattern that was highest at 2000 (08:00 PM) and peaked again at 0200 (02:00 AM). Red bats had intermittent increased activity throughout the night and peaked at 0600 (06:00 AM). Cave myotis had a mostly unimodal activity pattern with a pronounced peak at 0000 (12:00 AM), and bats in the high *f* group had periodic peaks with the highest activity occurring between 4 and 5 hours after recording (11:00 PM to 12:00 AM; Fig. 3.3). Although cautioned should be maintained when interpreting the acoustic activity patterns for the high frequency species and group described above due to low sample size (n=181).

September showed the highest bat activity at 181 bat passes/detector-night, followed by October with 159 bat passes/detector-night, and August with 97 bat passes/detector-night. Turbines 3-08 and 4-96 had similar bat activity rates averaging 58 bat passes/detector-night and 56 bat passes/detector-night, respectively. Turbine 4-60 was somewhat lower averaging 38 bat passes/detector-night. The night of the highest recorded activity was the night beginning on 4 September 2017 with 669 bat passes/detector-night followed by 1 September 2017 with 531 bat passes/detector-night, while 7 September 2017 was the lowest at 0.8 bat passes/detector-night (Fig. 3.4). The two nights with the highest activity also corresponded to nights with the highest documented fatalities with 31 bat carcasses discovered on 1 September 2017 and 30 bat carcasses discovered 4 September 2017. Generalized linear model results ($\beta = 0.007$, SE = 0.001, Z = 11.42, $p < 0.001$) of bat fatalities versus bat activity indicate a significant positive relationship between the two variables (Fig. 3.5).

The top model with the lowest AIC (6836.7) from stepwise selection assessing the relationship between bat activity and weather and temporal covariates included absolute humidity, temperature, wind speed, Julian date, and hour of night (Table 3.3). However, there were three competing models ($< 2.0\ \Delta$ AIC) that added either the 24-hour change in pressure, moon illumination, or pressure. I selected the top model because it was the most parsimonious and because the covariates in the competing models were not significant predictors of bat activity.

Results of the selected model indicate a significant non-linear relationship between bat activity and hour of night (Fig. 3.6A) and Julian date (Fig. 3.6B), a significant negative relationship with wind speed (Fig. 3.6C) and temperature (Fig. 3.6D), and a significant positive relationship with absolute humidity (Fig. 3.6E; Table 3.4). Across the study, the range in nightly hourly temperature was 16.6°C to 35.6°, pressure from 980.2 to 999.6 mbars, wind speed from 0.5 to 12.7 m/s, and absolute humidity from 6.7 to 23.4 g/m$^3$.

## DISCUSSION

To my knowledge, this is the first study to assess bat acoustic activity at wind turbines in south Texas. Fern et al. (2018) studied summer bat acoustic activity patterns for cave myotis, eastern red bats, evening bats, and Brazilian free-tailed bats at a nearby ranch in Jim Hogg and Starr counties from June through September 2017. The activity patterns I recorded at rotor height were similar to patterns observed by Fern et al. (2018).
They found evening bats displaying a bimodal pattern, eastern red bats a sporadic pattern with multiple peaks, and cave myotis and Brazilian free-tailed bats a unimodal pattern and the nightly timing of peak activity for Brazilian free-tailed bats, eastern red bats, and evening bats mirrored that in my study. However, cave myotis had a later peak in activity around 0300 (03:00 AM) (Fern et al. 2018). Unlike Fern et al. (2018), I did not distinguish between eastern red and western red bats and instead formed a red bat group. Their decision to not consider western red bats is likely because they were unaware of their confirmed presence in south Texas. Nevertheless, there are striking similarities between our two studies. However, Brazilian free-tailed bats were the least detected species during their study (Fern et al. 2018). This could be due to differences in recording

heights of microphones. My microphones were positioned at approximately 95 m above ground, while those in their study varied but were never more than 7.62 m above ground due to cable length constraints (Fern et al. 2018). Brazilian free-tailed bats are considered to be high altitude flyers often exhibiting more activity above ground than at ground level (McCracken et al. 2008). My results and those of Fern et al. (2018) demonstrate the importance of assessing nightly bat activity patterns by individual species when considering operational mitigation approaches at wind energy facilities, particularly if there is a specific target species of concern.

Based on my results, the most active species, and most susceptible to fatality, at the study site is the Brazilian free-tailed bat. This is further supported by fatality monitoring data at the study site in which this species comprised 76% of discovered carcasses (Weaver et al. 2019b). Given these mortality results, it is probable Brazilian free-tailed bats comprise the majority of bat passes classified in the low *f* group, and were underrepresented in this assessment using only the recordings classified to species level.

I consider bat activity at Los Vientos to be relatively high for the study period when compared to other wind energy facilities. Baerwald and Barclay (2009) reported activity from various sites, with a highest average of 14.8 bat passes/detector-night. Jain et al. (2011) reported an average of 36.6 bat passes/detector-night (Jain et al. 2011). Activity rates of these studies were 10.3 to 4.2 times lower than my study, respectively. One study conducted in north Texas monitored bat activity both at wind turbine nacelle height and ground level at two wind turbines in relationship to foraging behaviors from 2011 to 2016 (Foo et al. 2017). While they did not distinguish bat passes per detector-night, nor did they identify number of passes recorded at ground-level versus nacelle height (likely due to differences in objectives), they did report a total of 3,606 bat passes from 284 nights of surveys across 5 years (Foo et al. 2017). This is 94% fewer calls than I recorded in 67 nights in 2017 only.

The high level of bat activity at Los Vientos is not unexpected based on pre-construction acoustic detector data for the study site. During pre-construction monitoring, two Remote Bat Acoustic Technology (ReBAT®) systems were mounted on two MET towers at Los Vientos, each with a microphone at 30 m and 6 m. Detectors recorded nightly from 1 September 2014 to 1 September 2015. Average annual activity was 315 bat passes/detector-night, more than 2x that of my study (Normandeau Associates, Inc. 2016). The difference between pre- and post-construction acoustic activity could be due to differences in methodology, timing, equipment, interannual variation, weather, placement on the landscape and of microphones, etc. Despite these differences, both studies confirm bat activity was very high at Los Vientos during both sampling periods. Due to a high volume of data, Normandeau Associates, Inc. (2016) was only able to assign species identifications to a subsample of bat passes (3.5%, n=15,291), in which Brazilian free-tailed bats comprised the majority of identified species. However, composition of the remaining species and species groups differed somewhat from my study primarily because they included more species in auto ID analysis due to a lack of knowledge pertaining to species composition for the region (Normandeau Associates, Inc. 2016).

Low wind speed, moderate temperatures, and high absolute humidity were important weather covariates associated with increased bat activity. Others have reported similar results for wind speed and humidity (Amorim et al. 2012, Lang et al. 2006).

Temperature is also a known predictor of bat activity, although typically there is a positive relationship (Anthony et al. 1981; Amorim et al. 2012; Müller et al. 2012; Bender and Hartman 2015). The negative relationship of bat activity with temperature is potentially due to the limited recording period, during which temperatures remained high enough for bat activity for the duration of my study. Had recording taken place during other seasons, such as winter, this relationship would most likely be different. While these weather covariates are associated with and can be used to predict increasing bat activity, it is important to note that they do not imply cause and effect. Some bats display an attraction to wind turbines (Cryan et al. 2014), and this behavior increases interactions as well as risk which cannot be accounted for by weather covariates alone.

Pressure and pressure changes were not important predictors of bat activity. The results are heterogeneous regarding the relationship between pressure and bat activity with results from some research reporting a positive relationship with increasing pressure (Berkova and Zukal 2010; Bender and Hartman 2015), and others reporting a negative relationship (Paige 1995; Turbill 2008). Moreover, fraction of moon illuminated was also not an important variable associated with nightly bat activity. Research results indicate some species display decreased activity with increased moon illumination (Lang et al. 2006), while others exhibit the opposite behavior (Cryan et al. 2014). The lack of importance of these covariates in my model may be due to grouping bat activity for all species, but might prove to be important on a species-specific level. Furthermore, it is possible that bats respond to pressure changes on a different scale, and night time activity could be influenced by changes less than 24 hours in advance.

Results of my study can help inform operational minimization, or curtailment, strategies in south Texas for wind energy operators interested in these methods (Baerwald et al. 2009; Arnett et al. 2011; Martin et al. 2017). During operational minimization the turbine blades are feathered and the cut-in speed (i.e., the wind speed at which the turbine begins generating electricity) is raised, resulting in little to no rotation of the blades at relatively low wind speeds (Martin et al. 2017). At Los Vientos the manufacturer’s cut-in speed is 3.5 m/s. Raising cut-in speeds to 5.0 m/s or higher (previously termed curtailment) has demonstrated effectiveness for reducing bat fatalities because this speed corresponds with peak fatality (Baerwald et al. 2009; Arnett et al. 2011. However, there is a paucity of data indicating whether this strategy is effective for Brazilian free-tailed bats. Moreover, this method results in lowered energy production and reduced profits for facilities. Therefore, efforts have increased to further refine this strategy and account for other influential weather variables on bat activity, such as temperature, in order to reduce the necessary curtailment time to effectively reduce fatalities (Martin et al. 2017). This method is sometimes referred to as smart curtailment. My results indicate such efforts will be most effective if focused during nights of low wind speed, high absolute humidity, and moderate temperatures. The level of fatality reduction desired, as well as species of interest, will dictate threshold recommendations for each of these climatic variables. Temporal covariates associated with nightly bat activity included hour of night and Julian date, both of which are well-documented in the literature as important factors influencing bat activity (Kunz 1973; Brooks 2009).

Based on beta values, the influence of each variable in order of importance is hour of night, Julian date, wind speed, absolute humidity, and finally temperature. However, nightly timing of impact reduction strategies should consider target species. For example, if Brazilian free-tailed bats are the species of concern then efforts to reduce fatalities should be concentrated from 2100 to 0500 (09:00 PM to 05:00 AM), which corresponds with 99% of activity, and from 2200 to 0400 (10:00PM to 04:00AM) with 91% of activity. This will vary for other species, such as evening bats, that were most active earlier in the evening. When considering Julian date, my monitoring period was restricted to 67 nights during late summer to early fall. Based on results of Chapter II and Chapter IV, the current study might not be sufficient for determining seasonal timing of reduction strategies. Furthermore, because I only conducted a single season of acoustic monitoring, there is likely to be interannual variation in daily bat activity patterns, as is demonstrated in Chapter IV.

The relationship between bat acoustic activity and bat fatalities indicates a smart curtailment strategy using acoustic detectors, such as the Turbine Integrated Mortality Reduction (TIMR) system, might be effective at reducing bat fatalities in this region (Hayes et al. 2019). However, this system still results in power loss and may be considered an unacceptable method by wind energy operators. The current strategy of TIMR is to curtail turbines if wind speed averages <8.0 m/s and ≥1 bat call is detected in a 10-minute period (Hayes et al. 2019). Given the high level of bat activity at Los Vientos, under the currently reported methods this system could result in curtailing turbines for a majority of the night. Higher thresholds for decision making could reduce curtailment times to an acceptable level if this strategy is deployed. Furthermore, it has not been tested on the suite of species at Los Vientos and will require validation testing. If this strategy is not a viable option, I recommend exploring other potential impact reduction strategies, such as ultrasonic acoustic deterrents which have been proven effective for Brazilian free-tailed bats and hoary bats at the study site (Weaver et al. 2019a).

It is possible other weather variables, such as precipitation and cloud cover, are associated with bat activity and could further refine smart curtailment strategies. However, I was unable to account for these parameters because they were not measured by MET tower instruments. Data from the closest weather station that collected hourly precipitation (Rio Grande City, TX US; COOP:417622) was more than 14 kilometers south of the nearest wind turbine and showed no rainfall on days that I observed rainfall at the study site. Localized weather events confined to the study site commonly occurred, which were confirmed on the ground and via radar on cell phone based weather apps. Therefore, I am not confident in data collected by weather stations outside the study site reflect actual on site conditions and chose not to use them in our analyses.

Future analyses of these data include quantifying potential foraging activity by assessing feeding buzzes and pairing acoustic data with thermal imaging camera data recorded concurrently at the same turbines. Pairing these observations will allow for further behavioral analyses and refinement of impact reduction strategy recommendations. Data analysis for this effort will begin in fall of 2019.

## ACKNOWLEDGMENTS

This study was made possible through support from Duke Energy and Texas Parks and Wildlife Department. I thank the crew leaders, technicians, and volunteers who assisted with fieldwork, and N. Durish, C. Hein and M. Schirmacher for their technical expertise. I also thank D. Cordani for her assistance with data analysis.

**Table 3.1. —**Range of echolocation call characteristics spanning the mean and standard deviation for species known to occur at Los Vientos Wind Energy Facility in Starr County, Texas.

| Species | $f_c$ | hi *f* | lo *f* | *f* maxE | Duration | Group |
|---|---|---|---|---|---|---|
| Cave Myotis[1] | 38–42 | 65–110 | 32–38 | 41–49 | 5–7 | High *f* |
| Tri-colored Bat[2] | 41–44 | 48–67 | 40–43 | 42–46 | 5.8–8.4 | High *f* |
| Eastern Red Bat[2] | 37–44 | 54–81 | 37–43 | 39–49 | 4.6–9.1 | High *f* |
| Evening Bat[2] | 36–40 | 48–78 | 34–38 | 37–43 | 3.8–9.4 | High *f* |
| Northern Yellow Bat[2] | 27–30 | 38–53 | 26–29 | 27–32 | 8.3–13 | Low *f* |
| Southern Yellow Bat[3,4] | 27–34 | 34–52 | 29–34 | 30–38 | 3.9–9.3 | Low *f* |
| Brazilian free-tailed Bat[2] | 23–38 | 25–39 | 22–26 | 25–31 | 9.5–14 | Low *f* |
| Hoary Bat[2] | 18–22 | 21–21 | 18–22 | 18–23 | 7–15 | Low *f* |

$f_c$: characteristic frequency, or frequency at the lowest slope; hi *f*: highest frequency (kHz); lo *f*: lowest frequency (kHz); *f*maxE: the frequency with the most power; Duration: duration in milliseconds of the call from beginning to end; Group: based on $f_c$ above (High *f*) or below (Low *f*) 35 kHz. [1]-Szewczak et al. 2008 [2]-Szewczak et al. 2011. [3]-Rydell et al. 2002. [4]-O'Farrell et al. 1999.

**Table 3.2. —**Number and composition of acoustically detected bat passes by species and species group identified at Los Vientos Wind Energy Facility between 14 August and 19 October 2017. Low *f* includes Brazilian free-tailed bats, yellow bats, and hoary bats. High *f* includes red bats, evening bats, and cave myotis.

| **Species** | **Total Bat Passes** | **Bat Passes/Detector-night** | **Composition (%)** |
|---|---|---|---|
| Low *f* | 26,733 | 66.50 | 43.69 |
| Brazilian free-tailed bat | 16,521 | 41.10 | 27.00 |
| Yellow Bats | 14,192 | 35.30 | 23.19 |
| Hoary Bats | 3,559 | 8.85 | 5.82 |
| Red Bats | 78 | 0.19 | 0.13 |
| Evening Bats | 63 | 0.16 | 0.10 |
| High *f* | 21 | 0.05 | 0.03 |
| Cave Myotis | 19 | 0.05 | 0.03 |
| Total | 61,186 | 152.2 | 100 |

**Table 3.3. —**Model results from stepwise selection using Akaike information criterion (AIC) and ΔAIC for generalized linear models of bat acoustic activity related to weather and temporal covariates at Los Vientos Wind Energy Facility in Starr County, Texas from 14 August through 19 October 2017. The most parsimonious model is the top model followed by stepwise elimination or addition of covariates from the "step" function in R.

| Model | Df | Deviance | AIC | ΔAIC |
|---|---|---|---|---|
| AbsHum+Temp+Wind Spd+ JD^5+Hour^2 | - | 857.5 | 6836.7 | 0.0 |
| +Press.Change | 1 | 856.9 | 6838.1 | 1.4 |
| +MoonIll | 1 | 857.1 | 6838.3 | 1.6 |
| +Pressure | 1 | 857.4 | 6838.6 | 1.9 |
| -Temp | 1 | 867.6 | 6844.8 | 8.1 |
| -AbsHum | 1 | 885.7 | 6862.9 | 26.2 |
| -WindSpd | 1 | 902.4 | 6879.7 | 43.0 |
| - JD^2 | 5 | 955.9 | 6925.1 | 88.4 |
| -Hour^2 | 2 | 1237.7 | 7212.9 | 376.2 |

MoonIll=fraction of moon illumination; AbsHum=absolute humidity ($g/m^3$); Temp=temperature (°C); Wind Spd=wind speed (m/s); JD^2=squared Julian date; hour^2=squared hour since recording.

**Table 3.4**. **—**Results of the top generalized linear model for bat acoustic activity and weather parameters at Los Vientos Wind Energy Facility in Starr County, Texas from 14 August through 19 October, 2017. Parameter estimates, standard error (SE), *Z* values, and *P* values. All variables were statistically significant.

| **Variable** | **Estimate** | **SE** | ***Z* value** | ***P* value** |
|---|---|---|---|---|
| Intercept | 3.75 | 0.05 | 70.99 | <0.001 |
| Temp | -0.28 | 0.08 | -3.34 | <0.001 |
| AbsHum | 0.42 | 0.07 | 5.85 | <0.001 |
| Wind Spd | -0.48 | 0.06 | -7.05 | <0.001 |
| JulianDate1 | 10.03 | 1.79 | 5.60 | <0.001 |
| JulianDate2 | -10.32 | 1.48 | -6.98 | <0.001 |
| JulianDate3 | 6.02 | 1.82 | 3.32 | <0.001 |
| JulianDate4 | -10.77 | 1.58 | -6.81 | <0.001 |
| JulianDate5 | 6.05 | 1.48 | 4.08 | <0.001 |
| Hour1 | -19.47 | 1.94 | -10.01 | <0.001 |
| Hour2 | -32.70 | 1.48 | -22.04 | <0.001 |

Temp=temperature (°C); AbsHum=absolute humidity ($g/m^3$); Press.Change= 24-hour Δ pressure change ($m/g^3$); Wind Spd=wind speed (m/s)

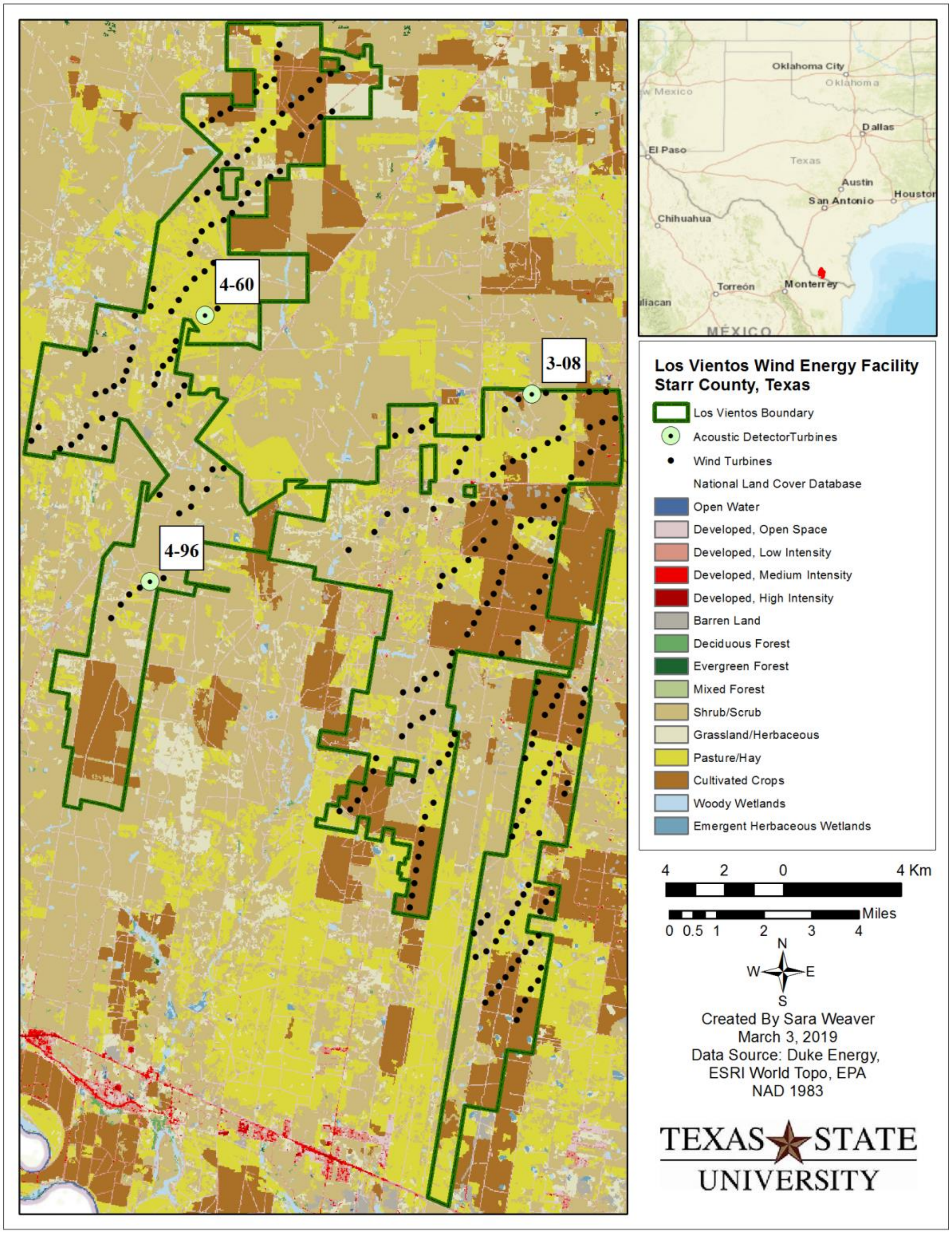



**Fig. 3.1.—**Study site location in Starr County, Texas part of the Lower Rio Grande Valley, including site boundary, turbine locations, and 2011 National Land Cover Database cover types. Inset map shows the location of study site within Texas.

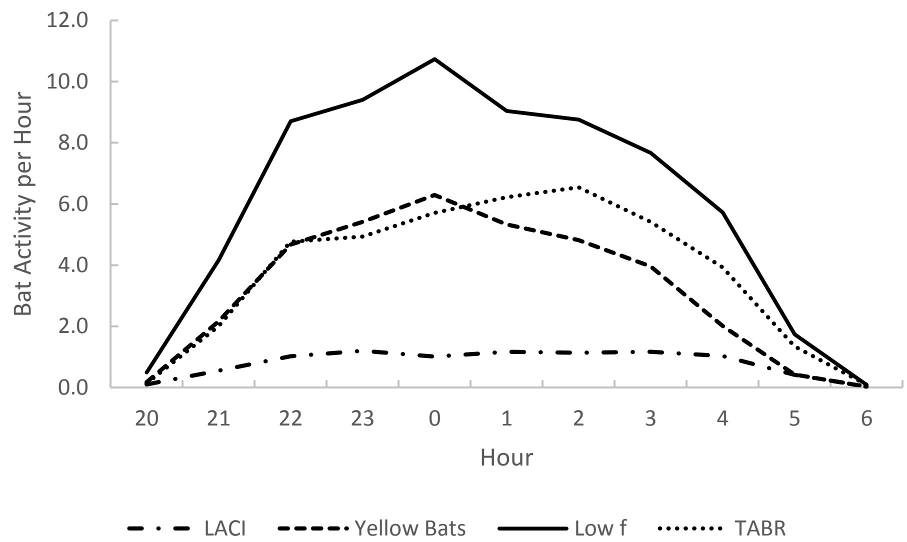



**Fig. 3.2.—**Low frequency species and species group's nightly bat acoustic activity by hour (2000–0600 or 08:00 PM–06:00 AM) for each species and species group at Los Vientos Wind Energy Facility in Starr County, Texas recorded from 14 August to 19 October 2017. LACI=hoary bat (*Lasiurus cinereus*); Yellow Bats=northern, southern, and western yellow bats (*L.* [*Dasypterus*] *intermedius/ega*/*xanthinus*); Low f=all bat passes in which species identification was not possible and classified as low frequency species group; TABR=Brazilian free-tailed bat (*Tadarida brasiliensis*).

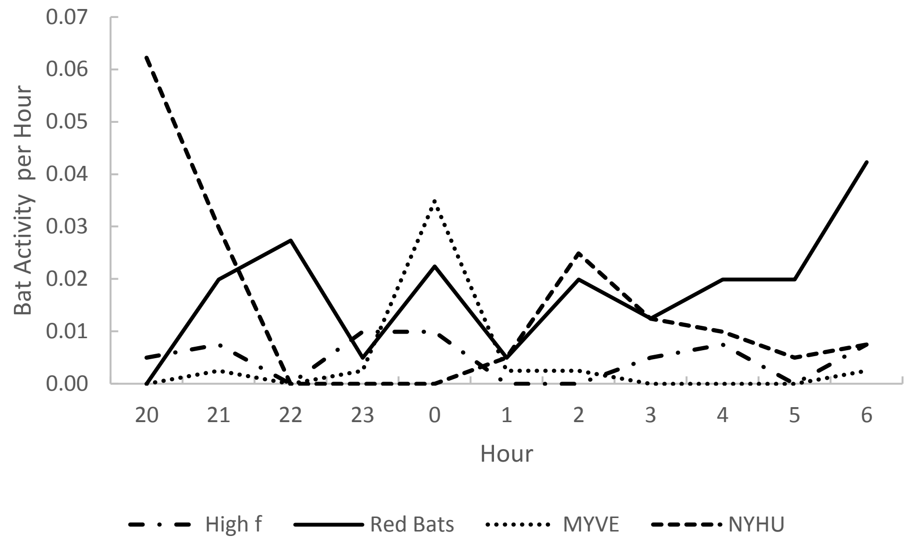



**Fig. 3.3. —**High frequency species and species group's nightly bat acoustic activity by hour (2000–0600 or 08:00 PM–06:00 AM) for each species and species group at Los Vientos Wind Energy Facility in Starr County, Texas recorded from 14 August to 19 October 2017. High f=all bat passes in which species identification was not possible and classified as high frequency species group; Red Bats= eastern and western red bats (*Lasiurus borealis/blossevillii*); MYVE=cave myotis (*Myotis velifer*); NYHU=evening bat (*Nycticeius humeralis*).

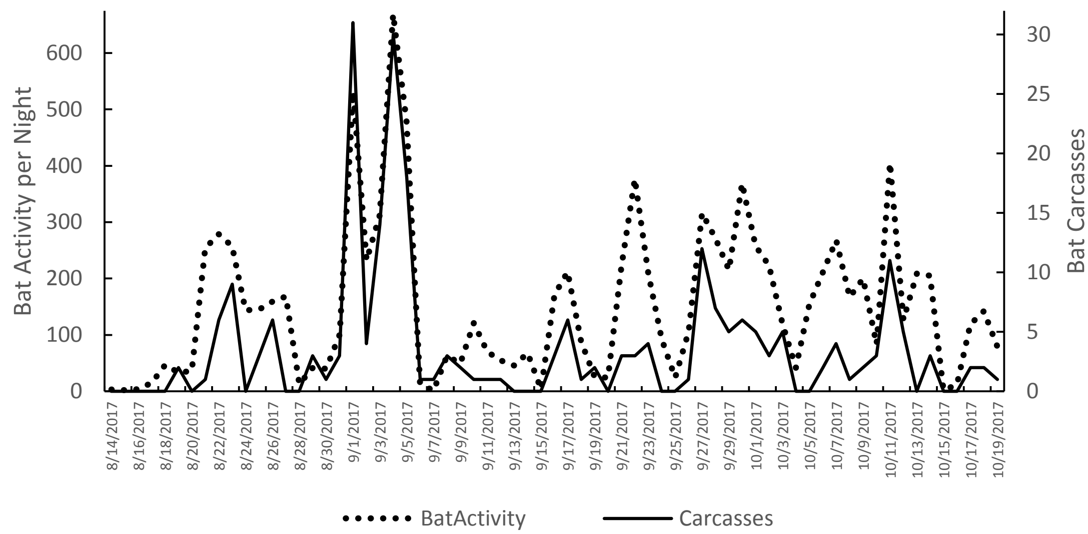



**Fig. 3.4.—**Daily bat acoustic activity and detected bat carcasses discovered during deterrent testing (Chapter IV) at the Los Vientos Wind Energy Facility in Starr County, Texas from 14 August to 19 October 2017.

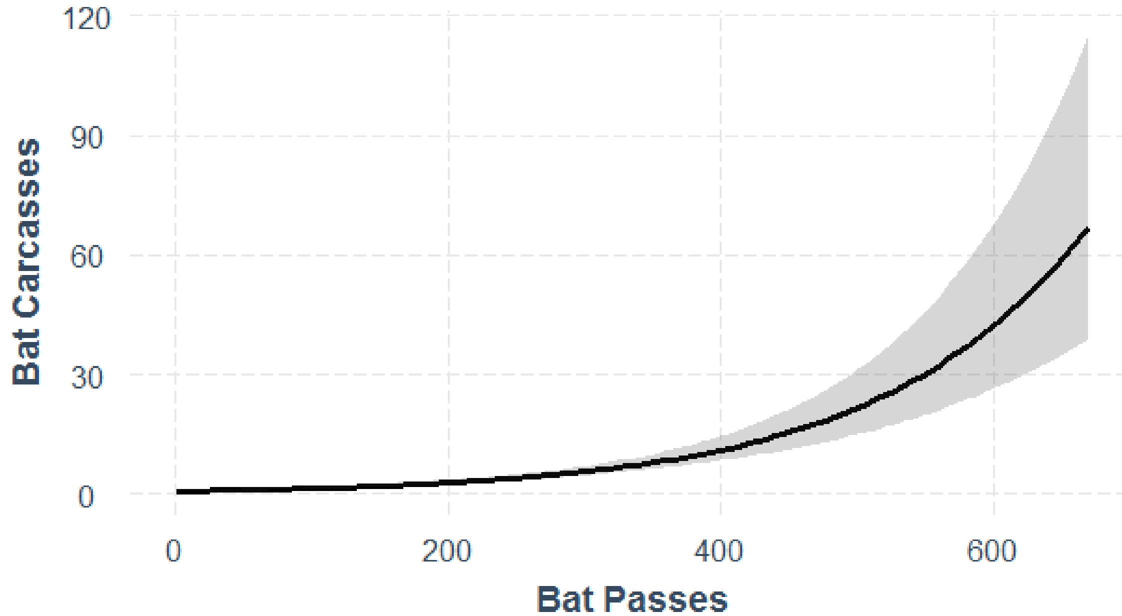



**Fig. 3.5.—**Effect plot of relationship between bat passes per night and bat fatality (black line) with 95% confidence intervals (gray) at Los Vientos Wind Energy Facility in Starr County, Texas from 14 August through 19 October 2017.

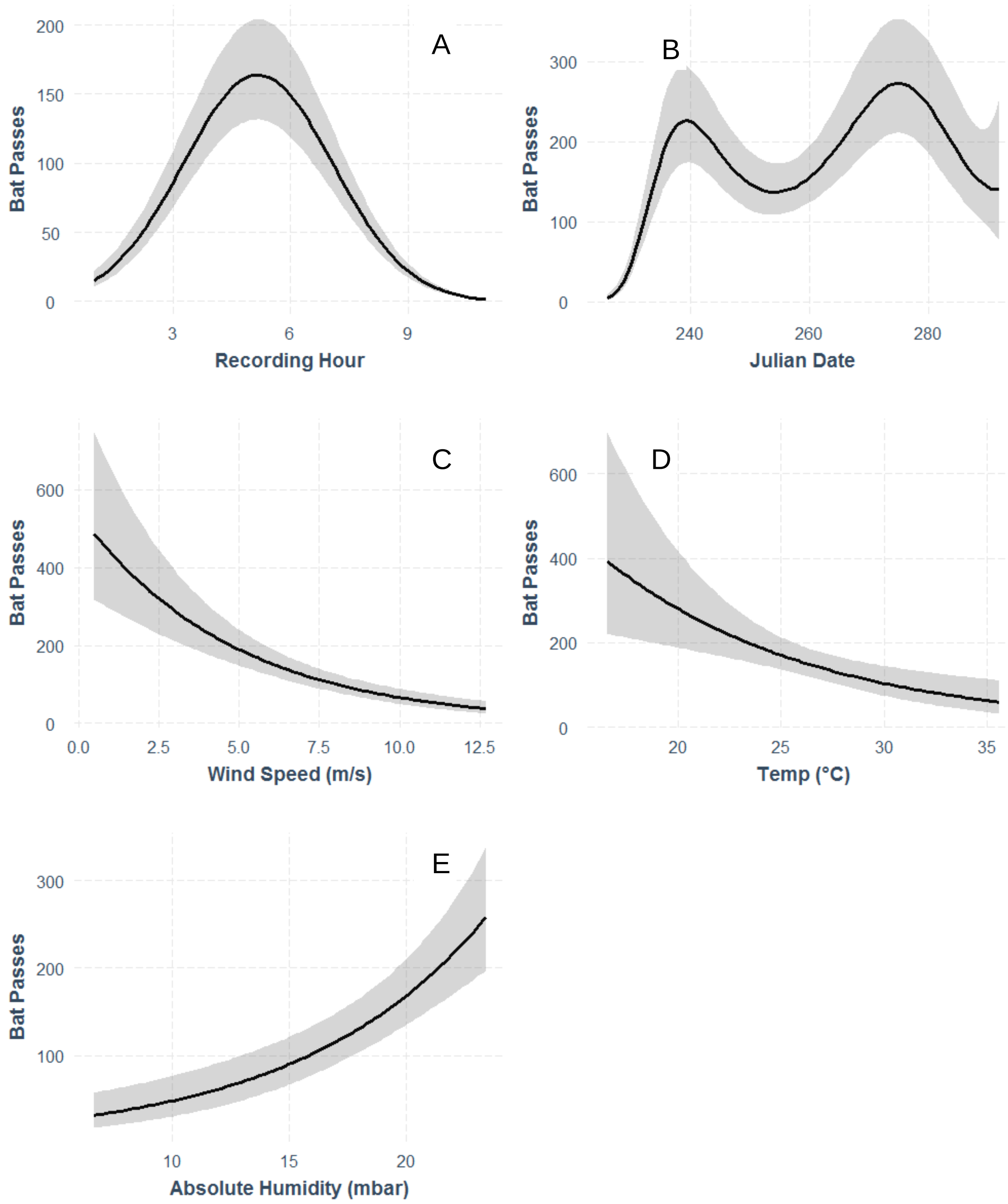



**Fig. 3.6. —** Effect plot of relationship between bat passes per hour and significant predictor variables of hour since recording began (A), Julian date (B), wind speed (C), temperature (D), and absolute humidity (E), with 95% confidence intervals (gray) at Los Vientos Wind Energy Facility in Starr County, Texas from 14 August to 19 October 2017.

# LITERATURE CITED


Amorim, F., H. Rebelo, and L. Rodrigues. 2012. Factors influencing bat activity and mortality at a wind farm in the Mediterranean region. Acta Chiropterologica 14:439-457.

Anthony, E. L. P., M. H. Stack, and T. H. Kunz. 1981. Night roosting and the nocturnal time budget of the little brown bat, *Myotis lucifugus*: effects of reproductive status, prey density, and environmental conditions. Oecologia 51:151–156.

Arnett, E. B., M. M. P. Huso, M. R. Schirmacher, and J. P. Hayes. 2011. Altering turbine speed reduces bat mortality at wind-energy facilities. Frontiers in Ecology and the Environment 9:209-214.

Baerwald, E. F., and R. M. R. Barclay. 2009. Geographic variation in activity and fatality of migratory bats at wind energy facilities. Journal of Mammalogy 90:1341-1349.

Baerwald, E. F., J. E. Edworthy, M. Holder, and R. M. R. Barclay. 2009. A large-scale mitigation experiment to reduce bat fatalities at wind energy facilities. Journal of Wildlife Management 73:1077–1081.

Bender, M. J., and G. D. Hartman. 2015. Bat activity increases with barometric pressure and temperature during autumn in central Georgia. Southeastern Naturalist 14:231–242.

Berkova, H., and J. Zukal. 2010. Cave visitation by temperate-zone bats: effects of climatic factors. Journal of Zoology 280:387–395.

Brooks, R. T. 2009. Habitat-associated and temporal patterns of bat activity in a diverse forest landscape of southern New England, USA. Biodiversity and Conservation 18:529-545.

Clement, M. J., K. L. Murray, D. I. Solic, and J. C. Gruver. 2014. The effect of call libraries and acoustic filters on the identification of bat echolocation. Ecology and Evolution 4:3482–3493.

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

Cryan, P. M., P. M. Gorresen, C. D. Hein, M. R. Schirmacher, R. H. Diehl, M. M. Huso, D. T. S. Hayman, P. D. Fricker, F. J. Bonaccorso, D. H. Johnson, K. Heist, and D. C. Dalton. 2014. Behavior of bats at wind turbines. Proceedings of the National Academy of Sciences of the United States of America 111:15126–15131.

Fern, R. R., H. T. Davis, J. A. Baumgardt, M. L. Morrison, and T. A. Campbell. 2018. Summer activity patterns of four resident south Texas bat species. Global Ecology and Conservation e00500.

Foo, C. F., V. J. Bennett, A. M. Hale, and J. M Korstian, A. J. Schildt, and D. A. Williams. 2017. Increasing evidence that bats actively forage at wind turbines. PeerJ 5:e3985.

Fox, J., and S. Weisberg. 2019. An R companion to applied regression. Third edition. Springer, Thousand Oaks, CA.

Gorresen, P. M, et al. 2015. Behavior of the Hawaiian hoary bat (*Lasiurus cinereus semotus*) at wind turbines and its distribution across the northern Ko’olau Mountains, O’ahu. Technical Report HCSU-064. University of Hawaii at Hilo, Hilo, HI.

Hayes, M. A., L. A. Hooton, K. L. Gilland, C. Grandgent, R. L. Smith, S. R. Lindsay, J. D. Collins, S. M. Schumacher, P. A Rabie, J. C. Gruver, and J. Goodrich-Mahoney. 2019. A smart curtailment approach for reducing bat fatalities and curtailment time at wind energy facilities. Ecological Applications e01881.

Hein, C. D. 2017. Monitoring Bats. Pages 31–56 *in* M. R. Perrow, editor. Wildlife and Wind Farms, Conflicts and Solutions. Volume 2 Onshore: Monitoring and Mitigation. Pelagic Publishing, Exeter, UK.

Jones, G., and M. W. Holderied. 2007. Bat echolocation calls: adaptation and convergent evolution. Proceedings of the Royal Society of London B 274:905–912.

Jones, G., and E. C. Teeling. 2006. The evolution of echolocation in bats. Trends in Ecology and Evolution 21:149-156.

Jain, A. A., R. R. Koford, A. W. Hancock, and G. G. Zenner. 2011. Bat mortality and activity at a northern Iowa wind resource area. American Midland Naturalist 165:185-200.

Kunz, T. H. 1973. Resource utilization: temporal and spatial components of bat activity in central Iowa. Journal of Mammalogy 54:14-32.

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

Lang, A. B., E. K. V. Kalko, H. Römer, C. Bockholdt, and D. K. N. Dechmann. 2006. Activity levels of bats and katydids in relation to the lunar cycle. Oecologia 146:659–666.

Martin, C. M., E. B. Arnett, R. D. Stevens, and M. C. Wallace. 2017. Reducing bat fatalities at wind facilities while improving the economic efficiency of operational mitigation. Journal of Mammalogy 98:378-385.

McCracken, G. F., E. H. Gillam, J. K. Westbrook, Y. Lee, M. L. Jensen, and B. B. Balsley. 2008. Brazilian free-tailed bats (*Tadarida brasiliensis*: Molossidae, Chiroptera) at high altitude: links to migratory insect populations. Integrative and Comparative Biology 48:107-118.

Müller, J., M. et al. 2012. Aggregative response in bats: prey abundance versus habitat. Oecologia 169:673–684.

Normandeau Associates, Inc. 2016. Bat monitoring final report for the Los Vientos III Wind Resource Area. Unpublished report. Gainesville, FL.

O'Farrell, M. J., B. W. Miller, and W. L. Gannon. 1999. Qualitative identification of free-flying bats using the Anabat detector. Journal of Mammalogy 80:11–23.

Paige, K. N. 1995. Bats and barometric pressure: conserving limited energy and tracking insects from the roost. Functional Ecology 9:463-467.

Reimer, J. P, E. F. Baerwald, and R. M. R. Barclay. 2018. Echolocation activity of migratory bats at a wind energy facility: testing the feeding-attraction hypothesis to explain fatalities. Journal of Mammalogy 99:1472–1477.

Reynolds, D. S. 2006. Monitoring the potential impact of a wind development site on bats in the northeast. Journal of Wildlife Management 70:1219–1227.

Rydell, J., H. T. Arita, M. Santos, and J. Granados. 2002. Acoustic identification of insectivorous bats (order Chiroptera) of Yucatan, Mexico. Journal of Zoology 257: 27–36.

Schnitzler, H. U., C. F. Moss, and A. Denzinger. 2003. From spatial orientation to food acquisition in echolocating bats. Trends in Ecology and Evolution 18:386–394.

Szewczak, J.M., A. Corcoran, J. Kennedy, T. J. Weller, and P. C. Ormsbee. 2008. Echolocation call characteristics of Arizona bats. Humboldt State University, Arcata, California. Retrieved from http://www.sonobat.com/download/AZ_Acoustic_Table-Mar08.pdf.

Szewczak, J.M., A. Corcoran, J. Kennedy, P. C. Ormsbee, and T. J. Weller. 2011. Echolocation call characteristics of eastern U.S. bats. Humboldt State University, Arcata, California. Retrieved from http://www.sonobat.com/download/EasternUS_Acoustic_Table_Mar2011.pdf.

Turbill, C. 2008. Winter activity of Australian tree-roosting bats: influence of temperature and climatic patterns. Journal of Zoology 276:285–290.

Venables, W. N., and B. D. Ripley. 2002. Modern applied statistics with S. Fourth edition. Springer, New York, NY

Weaver, S. P., I. Castro-Arellano, T. R. Simpson, and C. D. Hein. 2019a. Testing ultrasonic acoustic deterrents for reducing bat fatalities at wind turbines in south Texas. Pp 101-104 in Proceedings of the Wind-Wildlife Research Meeting XII. St. Paul, MN November 28-30, 2018. Prepared for the Wildlife Workgroup of the National Wind Coordinating Collaborative by the American Wind Wildlife Institute. Washington, DC, Susan Savitt Schwarz, ed. 148 pp.

Weaver, S. P., A. K. Jones, C. D. Hein, and I. Castro-Arellano. 2019b. Estimating bat fatalities at a wind energy facility in south Texas: implications transcending the U.S.-Mexico border. Journal of Mammalogy in review.

Zuur, A. F., E. N. Leno, and C. S. Elphick. 2010. A protocol for data exploration to avoid common statistical problems. Methods in Ecology and Evolution 1:3-10.

# IV. ULTRASONIC ACOUSTIC DETERRENTS SIGNIFICANTLY REDUCE *TADARIDA BRASILIENSIS* AND *LASIURUS CINEREUS* FATALITIES AT WIND TURBINES IN SOUTH TEXAS[1]

## INTRODUCTION

Wind energy development has long been known to cause wind turbine-related bat fatalities (Hall & Richards, 1972), and is currently considered the largest sources of mass bat mortality in the world (O'Shea et al., 2016). Since bats are long-lived, slow reproducing mammals, populations may be unable to recover from large-scale sustained fatality events such as those attributed to wind turbines (Frick et al., 2017). As global wind energy development expands to meet energy demands (Bernstein et al., 2006), this issue will require practicable solutions to conserve bat populations worldwide.

Currently, the only proven method of reducing bat fatalities caused by wind turbines is curtailment (i.e., feathering wind turbines and raising cut-in speeds approximately 1.5 to 3.0 m/s above the manufacturer's cut-in speed at night during late summer and early autumn). Although effective, curtailment is cost-prohibitive in many circumstances and limits power generated from each turbine (Baerwald et al., 2009; Arnett et al., 2011). Recent efforts to refine this strategy, referred to as smart curtailment, show promise in reducing annual production losses (Martin et al., 2017), and decreasing fatality rates for more species (Hayes et al., 2019). However, additional studies are warranted to ensure the strategy meets both conservation and economic goals. Alternative technologies that allow for uninterrupted power generation represent a mutually

[1] Weaver, S. P., C. D. Hein, T. R. Simpson, J. W. Evans, and I. Castro-Arellano. Publication: Conservation Letters *in preparation*.

beneficial solution for conservationists and energy producers and may be necessary in certain situations, such as lower wind regions where smart curtailment is not practicable (Arnett et al., 2013; Hayes et al., 2019).

Insectivorous bat species emit ultrasonic (>20 kilohertz [kHz]) vocalizations known as echolocation. They use the returning echoes of these vocalizations reflected from nearby objects as a means of sensory perception during foraging and navigation (Jones and Teeling 2006). There are species and situational variation to the type of calls echolocating bats emit (Schnitzler et al., 2003, Jones & Holderied, 2007), but they are generally classified as either broadband, narrowband, or long constant frequency with Doppler-shift compensation (Schnitzler et al., 2003). Some insect prey have coevolved mechanisms to deter bat predation by emitting their own ultrasound, effectively "jamming" or masking an approaching bats ability to receive and/or decipher its own echolocation, thereby reducing capture success (Corcoran et al., 2009, Corcoran & Conner, 2012). In addition, some bat species are capable of adaptively jamming conspecifics when in competition for food resources (Corcoran & Conner, 2014). Thus, investigating the use of sound to dissuade or discourage bats from approaching wind turbines as a practicable impact reduction strategy is warranted.

Between 2009 and 2010, the first experimental test of ultrasonic acoustic deterrents (hereafter deterrents) was conducted at an operational wind energy facility in Pennsylvania (Arnett et al., 2013).  Despite numerous challenges with the devices (e.g., water entry and overheating), there was a 21–51% reduction in bat fatalities in 2009, and an 18–62% reduction in 2010, and significant reductions for low-frequency calling species, including *Lasiurus cinereus* and *Lasionycteris noctivagans* . In subsequent years, unpublished ground-based testing (e.g., preliminary field tests in areas of concentrated bat activity, such as ponds) continued to show depressed bat activity in the presence of deterrents (C. Hein, personal communication, August 2016), but studies testing reduction in fatalities at wind energy facilities were limited and not publicly available.

My objectives were to 1) assess overall and species-specific effectiveness of a new deterrent technology for reducing bat fatalities at an operational wind energy facility located in south Texas, and 2) determine functionality of the deterrents to meet mechanical expectations in the south Texas environment. Overall, I evaluated this technology's viability in reducing fatality for certain species of bats, and reliability or mechanical performance in an environment with extreme conditions (e.g., temperature).

## METHODS

I conducted the following study in accordance with the Texas State University Institutional Animal Care and Use Committee (protocol 20171185494), Texas Parks and Wildlife Department (TPWD) permit number SPR-0213-023, and USFWS Migratory Bird Special Purpose Utility Permit number MB13574C-0.

### *Study Site*

I tested deterrents at the Los Vientos III, IV, and V wind energy facilities near Rio Grande City, Starr County, Texas. The three facilities are adjacent to one another and have the same turbine model, and thus were treated as a single facility for this study (hereafter Los Vientos). Los Vientos encompasses approximately 22,666 ha and consists of 255 Vestas V-110, 2-megawatt (MW) turbines. All turbines have a nacelle height of 95 m and rotor diameter of 110 m, with a rotor-swept area of 9,503 $m^2$. The site is located in the Texas-Tamaulipan Thornscrub Level IV ecoregion (Griffith et al., 2007), and according to the 2011 National Land Cover Data the habitat is comprised primarily of scrub/shrub (39%), cultivated crops (25%), pasture/hay (24%), developed, open space (5%), grassland/herbaceous (5%), and developed, low intensity (2%) (Homer et al., 2015). The southernmost boundary and wind turbine of Los Vientos are approximately 3.8 km and 10.1 km from the U.S.–Mexico border, respectively. Turbines at the site were feathered up to the manufacturer's cut-in speed of 3.5 m/s.

***Turbine selection, deterrent installation, and treatment schedule***

I conducted my study from 31 July to 30 October 2017 and 2018. I randomly selected 16 turbines for testing deterrents. I reviewed turbine selection to ensure these were distributed across the study site, and that they were a representative sample of the entire facility (e.g., turbines positions were a combination of within a turbine string and at the end of a turbine string). I also considered other factors in the final turbine selection, including nearby obstacles with potential to prevent bat fatality searches, landowner access issues, and site safety issues (i.e. remoteness, areas of past vandalism, etc.).

The deterrents in this study were manufactured by NRG Systems (Hinesburg, VT). Each deterrent array consisted of a waterproof box with 6 sub arrays, or speakers. Each sub array emits a continuous high frequency sound at one of the following predetermined frequencies kHz: 20, 26, 32, 38, 44, and 50. Therefore, each full array emits a frequency range from 20–50 kHz. This frequency range overlaps with the characteristic frequency of all bats known to occur in the region around the study site. At a distance of 1 m, the sound pressure level averages 122 decibels (dB).

In 2017, I equipped each of the 16 turbines with 6 deterrent arrays mounted on the nacelle. I selected the configuration of deterrents based on prior behavioral research indicating most bats approach wind turbines from the leeward (downwind) side and investigate the nacelle region behind the rotor swept area (Cryan et al., 2014). I therefore positioned the deterrents so that the sound was projected on the leeward side of the wind turbines. This rationale was based on the assumption that encountering deterrent sound upon first approach would cause bats to change course and leave the entire airspace around a wind turbine. However, a concurrent bat behavioral study at wind turbines with the same model of deterrents at a different facility demonstrated that bats may just alter activity centers away from the nacelle and toward the rotor swept area, instead of avoiding wind turbines altogether (B. Morton, personal communication, March 2018). Thus, in 2018 I opted to change the deterrent configuration on all 16 turbines and removed a unit positioned on the back of the nacelle such that there were only 5 deterrents per turbine, as well as reoriented three deterrents to face towards the rotor swept area. Figures depicting the location and orientation of deterrents on the nacelle during both years can be seen in the Appendix (Appendix, Figures 1–5).

Each night during the study, I randomly assigned 8 turbines as controls (deterrents off) and 8 as treatments (deterrents on). The treatment schedule was originally balanced every 16 nights to ensure each turbine received treatment and control conditions equally throughout the study period. However, technical difficulties resulted in 7 nights in 2017 in which 1–2 turbines were incorrectly assigned leading to an unbalanced design. This did not occur in 2018, and the treatment schedule was balanced.

***Bat fatality surveys***

I established circular search plots measuring 100 m in radius at each of the 16 turbines. I centered plots on the turbine and established linear transects across the diameter of each plot spaced 5 m apart and oriented north-south. Field technicians trained in established search techniques and proper identification of local bat species conducted carcass searches when possible at all 16 turbines each day following a treatment night. Reasons for abandoned searches included unsafe weather (e.g., lightening) and site conditions (e.g., flooded roads).  Searches began 15 minutes after sunrise and technicians walked each of these transects at a rate of approximately 60 m/min, searching 2.5 m on each side of the transect line for 100% plot coverage. Carcasses discovered outside of plots, or found prior to or after a scheduled search are considered incidental finds and were not used in this study. Moreover, in subsequent analyses I included only carcasses determined to be killed the night before that could be assigned to a treatment group from the previous night. The identification of fresh carcasses was based on several factors, including insect load, pliability of wings, presence of fluid in the eyes, and odor. I cleared search plots of vegetation by mowing with a tractor biweekly to monthly depending on amount of regrowth to allow for highest possible detection of carcasses.

I grouped *L.* [*Dasypterus*] *ega* and *L.* [*Dasypterus*] *xanthinus*, as well as *L. borealis* and *L. blossevillii* based on an ongoing bat genetics study analyzing samples from my research. Results of the genetics study have confirmed presence of *L.* [*Dasypterus*] *xanthinus* and *L. blossevillii* from species barcoding of samples taken at Los Vientos and a neighboring facility. These species have not been previously documented in south Texas. *Lasiurus* [*Dasypterus*] *xanthinus* is morphologically identical to *L.*

[*Dasypterus*] *ega*, a state-listed threatened species that is known to occur in the county and can only be distinguished via genetic analysis (Ammerman et al., 2012). Moreover, the potential for *L. blossevillii* to occur in the region was not known at the time of this study, and while there are some morphological differences between it and *L. borealis*, they are very similar and easy to confuse if a carcass is partially scavenged. Given the number of morphologically similar species in the region around the study site and difficulty of species identification in the field based on partially decomposed and scavenged remains, I recommend species identifications should be checked using DNA barcoding techniques prior to analysis for species-specific patterns or impacts in the future (Korstian et al., 2016; Jones & Weaver, 2019; A. Hale, personal communication, March, 2019). Results of genetic analyses are forthcoming.

***Data Analysis***

I report summary statistics for treatment and control groups, and compared carcass fall distribution from turbines for each group to determine if deterrents caused a shift in bat activity towards the blade tips, which could result in carcasses falling further from treatment turbines than control turbines. I randomly assigned turbine operation treatments (deterrents on or off) each night and blocked on the turbine, as well as randomly assigned the search schedule. Thus, any difference in configuration of the searchable area, searcher efficiency, or population of scavengers that might affect how many carcasses I found were a part of the blocking factor. Therefore, adjustments for detectability between turbines were not necessary. In addition, field technicians were unaware of nightly turbine assignment to eliminate any potential searching bias. I calculated percent reduction and 95% confidence intervals (CI) for all bats and by species, when sample size was sufficient. To assess the effectiveness of acoustic deterrents at reducing bat fatalities, I used a randomized block design with turbine as the blocking factor and night-within-turbine as sampling unit for the treatment. Total number of carcasses attributed to each treatment at each turbine per night was the response variable. To quantify effectiveness of deterrents, I used a generalized linear mixed model (GLMM), with turbine as random effect and treatment as fixed effect, using the package "glmmTMB" version 0.2.3 (Brooks et al., 2017) in R version 3.5.3 (R Development Core Team 2019). This package is flexible and allows models to fit Poisson and negative binomial error distributions with or without zero-inflation (Brooks et al., 2017), which have been demonstrated to perform best with count data (Brooks et al., 2017; Lindén & Mäntyniemi, 2011). I tested Poisson, type 1 negative binomial (NB1), and type 2 negative binomial (NB2) error distributions with and without zero-inflation, and selected the lowest Akaike information criterion (AIC) value to determine the best-fit model. I did this for all bats and by species when sample size was large enough.  I conducted an additional GLMM to test if configuration influenced effectiveness, again testing for best fit family distrubtion, but only included carcasses discovered at treatment turbines as the response variable, year as a fixed effect, and turbine as a random effect.

**RESULTS**

Based on combined data from both years, I conducted a total of 2,560 searches, 1,282 at control turbines and 1,278 at treatment turbines, out of a possible 2,944. As previously stated, I abandoned searches due to inclement weather or site conditions unconducive to search. I found 627 bat carcasses comprised of 5 species and three species groups during standardized searches for carcasses identified as killed the previous night. Due to scavenging, I was unable to determine to species 4 carcasses. Of the 627 carcasses, 486 (78%) were *Tadarida brasiliensis* (Table 4.1). I found approximately 33% of carcasses at treatment turbines, and 67% at control turbines. Total number of carcasses discovered at individual turbines, irrespective of treatment schedule, ranged from 23 at turbine 3-86, to 40 at turbine 3-34. Total number of carcasses discovered by day ranged from 0 to 35, with the latter occurring on October 19, 2018. The largest percentage (26%) of fatalities occurred during the month of September 2017 (n=160), followed by 20% in October 2018 (n=126), 18% in August 2018 (n=113), 14% in September 2018 (n=90), 13% in August 2017 (n=81), and finally 10% in October 2017 (n=61). Additionally, when comparing carcass fall distribution from turbines between controls and treatments, box plots indicate a similar distribution between turbine groups (Figure 4.1).

TABLE 4.1 Total number of fresh bat carcasses and species composition of carcasses discovered at treatment and control turbines during scheduled carcass searches at Los Vientos wind energy facility, Starr County, Texas from August 1–October 31, 2017 and 2018.

| **Species** | **Total at Treatments** | **Total at Controls** | **Total** |
|---|---|---|---|
| *Tadarida brasiliensis* | 152 | 334 | 486 |
| *Lasiurus* [*Dasypterus*] *intermedius* | 27 | 21 | 48 |
| *Lasiurus cinereus* | 8 | 37 | 45 |
| *Lasiurus* [*Dasypterus*] *ega/xanthinus* | 14 | 11 | 25 |
| *Nycticeius humeralis* | 6 | 10 | 16 |
| Unidentified spp. | 0 | 4 | 4 |
| *Lasiurus borealis/blossevillii* | 2 | 0 | 2 |
| *Myotis velifer* | 0 | 1 | 1 |
| **Total Bats** | **209** | **418** | **627** |

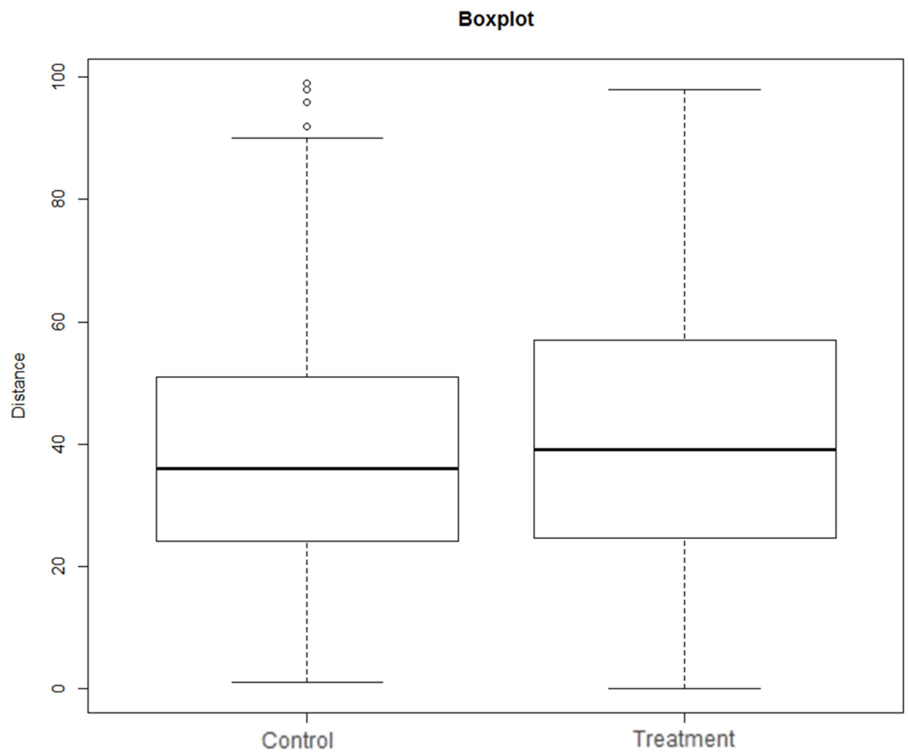



FIGURE 4.1 Box plots of distance from turbine of bat carcasses at control and treatment turbines discovered during deterrent fatality monitoring at the Los Vientos Wind Energy facility in Starr County, Texas from 1 August 2017 through 31 October 2017 and 2018.

Data for all bats during both years were overdispersed and I selected a negative binomial 2 distribution in which the variance increases quadratically with the mean (Hardin & Hilbe, 2018). *Tadarida brasiliensis*, *L. cinereus*, and *L. intermedius* were the only species with a sample size large enough to meaningfully assess reduction rates. The best fit family distribution for *T. brasiliensis* was also a negative binomial 2, and a negative binomial 1 for *L. cinereus*, in which the variance increases linearly with the mean (Hardin & Hilbe, 2018). For both *L. intermedius* and the pooled yellow bats, the data were not overdispersed and a poisson distribution was selected, again based on the lowest AIC value. I found that acoustic deterrents had a significant effect on overall bat fatalities ($\beta$ = -0.688, SE = 0.111, $Z$ = -6.21, $p$ < 0.001). The mean number of bat carcasses found at control turbines per night was 0.326 (95% *CI*: 0.280–0.372), which was 2.0 times higher than at treatment turbines of 0.164 (95% *CI*: 0.127–0.200; Figure 4.2a). Overall, there was a 49.8% (95% *CI*: 38.5–61.2%) reduction in fatalities at treatment versus control turbines for all bats independent of species. Deterrents also significantly reduced fatalities for *L. cinereus* ($\beta$ = -1.56, SE = 0.416, $Z$ = -3.74, $p$ < 0.001) and *T. brasiliensis* ($\beta$ = -0.782, SE = 0.132, $Z$ = -5.91, $p$ < 0.001). The average number of *L. cinereus* found at control turbines per night was 0.029 (95% *CI*: 0.019–0.039), which was 4.61 times higher than those found at treatment turbines of 0.006 (95% *CI*: 0.002–0.011; Figure 4.2b). The average number of *T. brasiliensis* carcasses found at control turbines per night was 0.261 (95% *CI*: 0.219–0.302), which was 2.19 times higher than those at treatment turbines of 0.119 (95% *CI*: 0.086–0.152; Figure 4.2c). Overall, there was a 78.3% (95% *CI*: 61.5–95.1%) reduction in fatalities for *L. cinereus*, and a 54.3% (95% *CI*: 41.5–67.1%) reduction in *T. brasiliensis* fatalities. Deterrents did not significantly affect fatalities of *L. intermedius* ($\beta$ = 0.254, SE = 0.291, $Z$ = 0.874, $p$ = 0.382), and there was no reduction in fatalities (-29.0% [95% *CI*: -78.0–21.0%; Figure 4.2d]). Finally, results indicate deterrent configuration did not influence number of carcasses found between 2017 and 2018 ($\beta$ = 0.194, SE = 0.179, $Z$ = 1.08, $p$ =0.279).

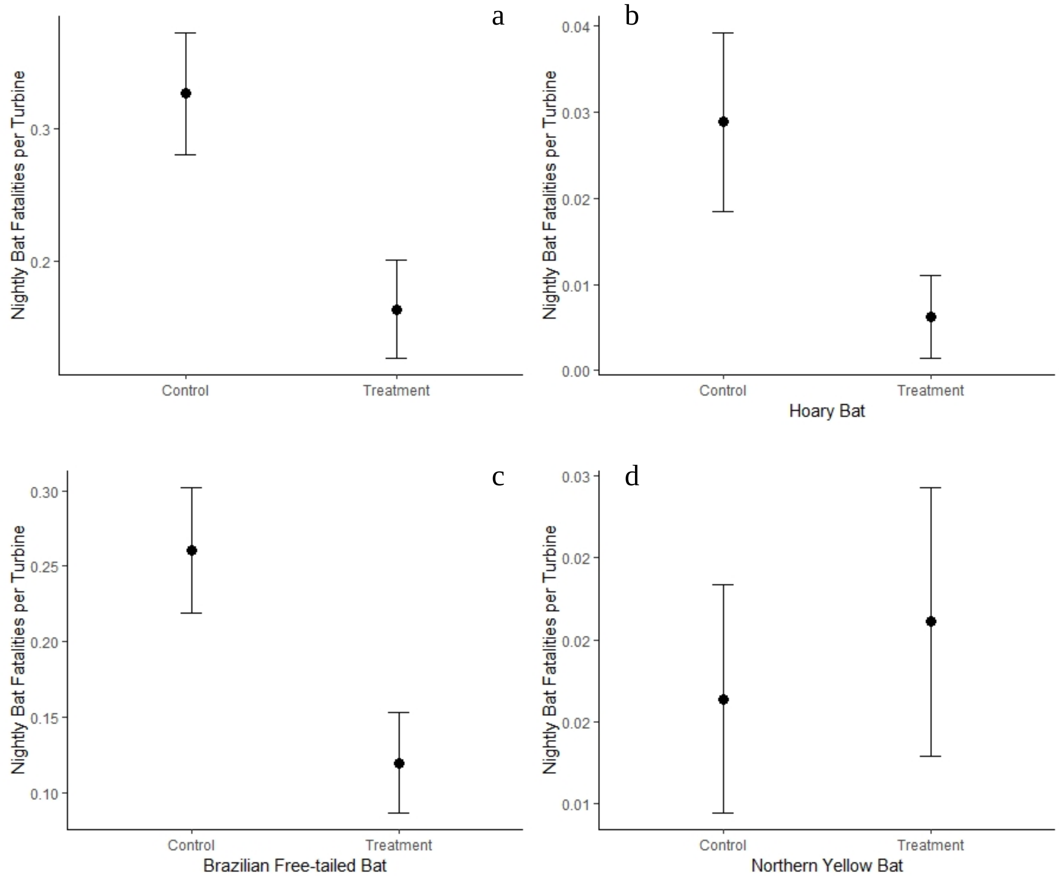



FIGURE 4.2 Point estimates and 95% confidence intervals of nightly bat fatalities per turbine at control and treatment turbines for all bats (a), *Lasiurus cinereus* (b), *Tadarida brasiliensis* (c), and *Lasiurus* [*Dasypterus*] *intermedius* (d).

When I assessed the mechanical performance of deterrent units, I found only a single subarray on one deterrent (Turbine 3-34) needed replacing during testing in 2017. No mechanical or functional issues occurred for any units during testing in 2018. Between 2017 and 2018 when testing was not occurring, an additional 4 subarrays failed (1 each at turbines 3-59 and 4-25, and 2 on one unit at turbine 4-11) and were replaced before the 2018 testing season. No whole unit failures were detected at any point during or after testing either year. This is a failure rate of <1%, meaning deterrents functioned as expected during more than 99% of the study period.

## DISCUSSION

Acoustic deterrents reduced overall bat fatalities between 38.5 to 61.2%. When considering species-specific effectiveness, they reduced *T. brasiliensis* fatalities between 41.5 to 67.1%, and between 61.5 to 95.1% for *L. cinereus*. Based on these results, deterrents can be an effective impact reduction strategy for these two species, which can incur high fatalities at wind energy facilities (Piorkowski and O'Connell, 2010; Frick et al., 2017; Weaver et al., 2019).

*Lasiurus cinereus* is consider a species at risk of extinction from wind energy impacts (Frick et al., 2017). However, Frick et al. (2017) were unable to account for the effect of implementing impact reduction strategies in population models. A recent study expanding on their efforts was conducted to determine reduction levels at wind energy facilities necessary to lower probability of extinction to <1% by 2050. In this study, they found that a reduction of 78% would be necessary if initial populations were 1.25 million (N. Friedenberg, personal communication, February 2019). According to Frick et al. (2017), the most likely population size of *L. cinereus*, based on expert elicitation, is 2.25 million. This indicates that if deterrents are widely implemented within the range of *L. cinereus* and effectiveness remains similar to my study, then risk of extinction derived from wind energy impacts will be minimized. Additionally, the largest populations of *T. brasiliensis* in the world occur in Texas during the summer with most migrating through south Texas during fall (Ammerman et al., 2012, Schmidly and Bradley, 2016), which is an area of expanding wind energy development (American Wind Energy Association [AWEA] 2019). Therefore, finding viable impact reduction strategies for this species is of high importance, and I recommend deployment of deterrents within their range as well.

Although deterrents were effective for some species, I did not detect an effect for northern yellow bats, confirming species-specific responses. Arnett et al. (2013) also reported differences among species with significant reductions in fatalities for *L. cinereus* and *L. noctivagans* only. Species-specific responses are not surprising given differences in echolocation call characteristics and behaviors among species. For example, *L. cinereus* and *T. brasiliensis* calls have lower characteristic frequencies (19–24 kHz and 22–26 kHz, respectively; Szewczak 2011) than that of *L.* [*Dasypterus*] *intermedius* (27–30 kHz; Szewczak 2011) and *L.* [*Dasypterus*] *ega* (27–34 kHz; Rydell et al., 2011). Sound attenuates faster as frequency level increases (Arnett et al., 2013). Therefore, the deterrent's effective range is lower at higher frequencies. Bats using lower frequency calls may interact and respond to the deterrents at a greater distance from the turbine compared to those using higher frequency calls.

Because sound attenuates with distance in space, it is unlikely deterrents were able to ensonify the entire rotor swept area at all frequencies (Arnett et al., 2013). It is possible bats could shift their activity centers towards the edge of the rotor swept area where blade speed is highest to avoid deterrent broadcasts. If this was true, I would expect a difference in distance bats fall from the wind turbine, with bats being found further from treatment turbines than from controls. However, based on carcass distribution data (Figure 4.1), this pattern did not emerge indicating it is not a concern for the species in south Texas.

While freezing temperatures do not often occur in south Texas, there was a rare winter storm event in January 2018 in which ice accumulated on wind turbines. Although this storm event occurred when the units were not operating the deterrents were nevertheless exposed to both ice conditions and extreme heat during my study and the failure rate was extremely low given the difficult conditions at Los Vientos (temperatures ranging from 0–39°C and absolute humidity ranging from 1.53–24.62 g/m$^3$). This is encouraging given equipment malfunctions experienced by Arnett et al. (2013).

A potential anomaly occurred during the night of September 4 2017 when at least 18 bats were killed at a treatment turbine (3-25). This is 110x higher than the mean of 0.164 carcasses per treatment turbine. Of the 18 fresh bats discovered during searches the following day, 17 were *T. brasiliensis* and 1 was a *L. ega*. While the cause of this fatality event is currently unknown, it is possible this was a coincidental event due to a large migratory group of *T. brasiliensis* moving through the area. Griffin (1970) suggested that migrating groups of bats might not use echolocation for orientation and could rely on other senses. This is supported by the discovery of 54 bat carcasses at a television tower with guy wires in Florida (Crawford and Baker 1981). In addition, *T. brasiliensis* are known to fly at high speeds (>50 km/h) in large groups numbering more than 100 (Williams et al., 1973). If these conditions are met, I would not expect deterrents to be effective at reducing fatalities during such events. Given that overall fatalities of bats did not increase at deterrent turbines, it is doubtful that the signal output attracted bats and this event was an anomaly.

Few studies have tested acoustic deterrents in field trials, and this study represents an important advancement in knowledge of their effectiveness (Arnett et al., 2013). I recommend continued studies in a controlled environment in which species-specific behavioral responses can be observed and further refinement to increase effectiveness for more species can be tested. This technology is a promising tool for wind energy operators that offers alternative strategies for bat impact reductions and does not result in power loss.


## ACKNOWLEDGMENTS

I thank Duke Energy for allowing us to conduct research at their wind energy facility, and Vestas for project support. I also thank NRG Systems for deterrent design and project support. Funding and additional support provided by Texas Parks and Wildlife Department, Duke Energy, NRG Systems, and Bat Conservation International. Finally, I thank the crew leaders, technicians, and volunteers who helped with data collection.

## LITERATURE CITED

American Wind Energy Association. (2019). Texas wind energy [PDF file]. Retrieved from https://www.awea.org/Awea/media/Resources/StateFactSheets/Texas.pdf

Ammerman, L. K., Hice, C. L., & Schmidly, D. J. (2012). *Bats of Texas*. College Station, TX: Texas A&M University Press.

Arnett, E. B., Hein, C. D., Schirmacher, M. R., Huso, M. M. P., & Szewczak, J. M. (2013). Evaluating the effectiveness of an ultrasonic acoustic deterrent for reducing bat fatalities at wind turbines. *PLoS ONE, 8,* 1–11. doi: 10.1371/journal.pone.0065794

Arnett, E. B., Huso, M. M. P., Schirmacher, M. R., & Hayes, J. P. (2011). Altering turbine speed reduces bat mortality at wind-energy facilities. *Frontiers in Ecology and the Environment, 9,* 209–214. doi: 10.1890/100103

Baerwald, E. F., Edworthy, J., Holder, M., & Barclay, R. M. R. (2009). A large-scale mitigBation experiment to reduce bat fatalities at wind energy facilities. *Journal of Wildlife Management, 73,* 1077–1081. doi: 10.2193/2008-233

Bernstein, M. A., Griffin, J. & Lempert, R. J. (2006). Impacts on U.S. energy expenditures of increasing renewable energy use. Retrieved from RAND Corporation Website https://www.rand.org/pubs/technical_reports/TR384-1.html

Brooks, M. E., Kristensen, K., Van Benthem, K. J., Magnusson, A., Berg, C. W., Nielsen, A., … Bolker, B. M. (2017). glmmTMB balances speed and flexibility among packages for zero-inflated generalized linear mixed modeling. *The R Journal, 9*, 378–400. Retrieved from https://journal.r-project.org/archive/2017/RJ-2017-066/RJ-2017-066.pdf

Corcoran, A. J., Barber, J. R., & Conner, W. E. (2009). Tiger moth jams bat sonar. *Science*, *325,* 325-327. doi: 10.1126/science.1174096

Corcoran, A. J., & Conner, W. E. (2012). Sonar jamming in the field : effectiveness and behavior of a unique prey defense. *Journal of Experimental Biology, 215,* 4278–4287. doi: 10.1242/jeb.076943

Corcoran, A. J., & Conner, W. E. (2014). Bats jamming bats: Food competition through sonar interference. *Science, 346*, 745–747. doi: 10.1126/science.1259512

Crawford, R. L., & Baker, W. W. (1981). Bats killed at a north Florida television tower: a 25-year record. *Journal of Mammalogy*, *62*, 651-652. doi: 10.2307/1380421

Cryan, P. M., Gorresen, P. M., Hein, C. D., Schirmacher, M. R., Diehl, R. H., Huso, M. M. P., … Dalton, D. C. (2014). Behavior of bats at wind turbines. *Proceedings of the National Academy of Sciences of the United States of America, 111*, 15126–15131. doi: 10.1073/pnas.1406672111

Frick, W. F., Baerwald, E. F., Pollock, J. F., Barclay, R. M. R., Szymanski, J. A., Weller, T. J., … McGuire, L. P. (2017). Fatalities at wind turbines may threaten population viability of a migratory bat. *Biological Conservation, 209*, 172–177. doi: 10.1016/j.biocon.2017.02.023

Griffin, D. R. (1970). Migration and homing of bats. In W. A. Wimsatt, (Ed.), *Biology of bats* (pp. 233–264). New York, NY: Academic Press.

Griffith, G., Bryce, S., Omernik, J., & Rogers, A. (2007). Ecoregions of Texas. Texas Commission on Environmental Quality, Austin, TX.

Hall, L. S., & Richards, G. C. (1972). Notes on *Tadarida australis*. *Australian Mammalogy, 1*, 46–47.

Hardin, J. W., & Hilbe, J. M. (2018). *Generalized linear models and extensions* (4th ed.). College Station, TX: Stata Press.

Hayes, M. A., Hooton, L. A., Gilland, K. L., Grandgent, C., Smith, R. L., Lindsay, S. R., … Goodrich-Mahoney, J. (2019). A smart curtailment approach for reducing bat fatalities and curtailment time at wind energy facilities. *Ecological Applications,* e01881. doi: 10.1002/eap.1881

Homer, C. G., Dewitz, J., Yang, L., Jin, S., Danielson, P., Xian, G., … Megown, K. (2015). Completion of the 2011 National Land Cover Database for the conterminous United States – representing a decade of land cover change information. *Photogrammetric Engineering and Remote Sensing, 81*, 345–354.

Jones, G., & Holderied, M. W. (2007). Bat echolocation calls: adaptation and convergent evolution. *Proceedings of the Royal Society of London B, 274,* 905–912.

Jones, G., & Teeling, E. C. (2006). The evolution of echolocation in bats. *Trends in Ecology and Evolution, 21*, 149-156. doi: 10.1016/j.tree.2006.01.001

Jones, A. K., & Weaver, S. P. (2019). Big free-tailed bat (*Nyctinomops macrotis*) discovered at a wind energy facility in the Lower Rio Grande Valley, Texas. *Southwestern Naturalist, 63*, 75–76. doi: 10.1894/0038-4909.63.75

Korstian, J. M., Hale, A. M., Bennett, V. J. & Williams, D. A. (2013). Advances in sex determination in bats and its utility in wind-wildlife studies. *Molecular Ecology Resources, 13,* 776–780. doi: 10.1111/1755-0998.12118

Korstian, J. M., Hale, A. M., Bennett, V. J. & Williams, D. A. (2016). Using DNA barcoding to improve bat carcass identification at wind farms in the United States. *Conservation Genetics Resources,* 8, 27–34. doi: 10.1007/s12686-015-0509-4

Lindén, A. & Mäntyniemi, S. (2011). Using the negative binomial distribution to model overdispersion in ecological count data. *Ecology, 92*, 1414-1421. doi: 10.1890/10-1831.1

Martin, C. M., Arnett, E. B., Stevens, R. D., & Wallace, M. C. (2017). Reducing bat fatalities at wind facilities while improving the economic efficiency of operational mitigation. *Journal of Mammalogy, 98,* 378-385. doi: 10.1093/jmammal/gyx005

O'Shea, T. J., Cryan, P. M., Hayman, D. T. S., Plowright, R. K., & Streicker, D. G. (2016). Multiple mortality events in bats: a global review. *Mammal Review, 46,* 175–190. doi: 10.1111/mam.12064

Piorkowski, M. D., & O'Connell, T. J. (2010). Spatial pattern of summer bat mortality from collisions with wind turbines in mixed-grass prairie. *American Midland Naturalist, 164,* 260–269. doi: 10.1674/0003-0031-164.2.260

R Development Core Team. (2019). R: a language and environment for statistical computing (version 3.5.1) [computer software]. Available from https://www.R-project.org/

Rydell, J., Arita, H. T., Santos, M., & Granados, J. (2011). Acoustic identification of insectivorous bats (order Chiroptera) of Yucatan, Mexico. *Journal of Zoology, London, 257,* 27-36. doi: 10.1017/S0952836902000626

Schmidly, D. J., & Bradley, R. D. (2016). *The mammals of Texas*. Austin, TX: University of Texas Press.

Schnitzler, H. U., Moss, C. F., & Denzinger, A. (2003). From spatial orientation to food acquisition in echolocating bats. *Trends in Ecology and Evolution, 18,* 386–394.

Szewczak, J. M. (2011). Echolocation call characteristics of eastern U.S. bats [PDF file]. Retrieved from http://www.sonobat.com/download/EasternUS_Acoustic_Table_Mar2011.pdf doi: 10.1016/S0169-5347(03)00185-X

Weaver, S. P., Jones, A. K., Hein, C. D., & Castro-Arellano, I. (2019). Estimating bat fatalities at a wind energy facility in south Texas: implications transcending the U.S.-Mexico border. *Journal of Mammalogy* in review.

Williams, T. C., Ireland, L. C., & Williams, J. M. (1973). High altitude flights of the free-tailed bat, Tadarida brasiliensis, observed with radar. *Journal of Mammalogy, 54*, 807-821. doi: 10.2307/1379076

## APPENDIX SECTION

**Appendix, Table 1.** Description of all discovered bat fatalities during post-construction fatality monitoring for Chapter II at Los Vientos from March 24, 2017–March 23, 2018.

| Date | Common Name | Location | Distance From Turbine (m) | Search Type |
|---|---|---|---|---|
| 03/21/2017 | Brazilian Free-tailed Bat | 4-86 | 5 | Incidental |
| 03/21/2017 | Brazilian Free-tailed Bat | 5-32 | 49 | Incidental |
| 03/21/2017 | Unknown Bat | 4-86 | 70 | Incidental |
| 03/27/2017 | Brazilian Free-tailed Bat | 3-58 | 15 | Search |
| 04/04/2017 | Big Free-tailed Bat | 4-86 | 5 | Search |
| 04/04/2017 | Brazilian Free-tailed Bat | 3-58 | 15 | Search |
| 04/05/2017 | Brazilian Free-tailed Bat | 4-60 | 12 | Incidental |
| 04/05/2017 | Brazilian Free-tailed Bat | 4-57 | 69 | Search |
| 04/05/2017 | Brazilian Free-tailed Bat | 4-34 | 27 | Search |
| 04/18/2017 | Brazilian Free-tailed Bat | 3-92 | 0 | Search |
| 04/22/2017 | Southern Yellow Bat | 5-17 | 37 | Search |
| 04/22/2017 | Unknown Bat | 3-44 | 81 | Search |
| 04/25/2017 | Brazilian Free-tailed Bat | 4-96 | 64 | Search |
| 05/04/2017 | Evening Bat | 4-3 | 1 | Search |
| 05/04/2017 | Brazilian Free-tailed Bat | 4-5 | 7 | Search |
| 05/06/2017 | Unknown Bat | 5-17 | 1 | Search |
| 05/08/2017 | Unknown Bat | 3-8 | 39 | Search |
| 05/08/2017 | Brazilian Free-tailed Bat | 3-8 | 22 | Search |
| 05/09/2017 | Brazilian Free-tailed Bat | 4-96 | 50 | Search |
| 05/09/2017 | Brazilian Free-tailed Bat | 4-93 | 27 | Search |
| 05/10/2017 | Brazilian Free-tailed Bat | 4-41 | 34 | Search |
| 05/12/2017 | Brazilian Free-tailed Bat | 3-71 | 16 | Search |
| 05/12/2017 | Brazilian Free-tailed Bat | 3-80 | 28 | Search |
| 05/13/2017 | Brazilian Free-tailed Bat | 5-5 | 32 | Search |
| 05/14/2017 | Brazilian Free-tailed Bat | 5-12 | 4 | Search |
| 05/15/2017 | Brazilian Free-tailed Bat | 3-8 | 16 | Search |
| 05/16/2017 | Brazilian Free-tailed Bat | 4-96 | 56 | Search |
| 05/16/2017 | Brazilian Free-tailed Bat | 4-95 | 30 | Search |
| 05/16/2017 | Brazilian Free-tailed Bat | 4-67 | 46 | Search |
| 05/17/2017 | Brazilian Free-tailed Bat | 4-43 | 25 | Search |
| 05/18/2017 | Brazilian Free-tailed Bat | 4-16 | 5 | Search |
| 05/18/2017 | Brazilian Free-tailed Bat | 4-19 | 28 | Search |
| 05/20/2017 | Brazilian Free-tailed Bat | 3-44 | 57 | Search |
| 05/22/2017 | Brazilian Free-tailed Bat | Warehouse | NA | Incidental |
| 05/23/2017 | Hoary Bat | 5-13 | 10 | Incidental |
| 05/24/2017 | Brazilian Free-tailed Bat | 4-52 | 29 | Search |
| 05/27/2017 | Brazilian Free-tailed Bat | 3-44 | 37 | Search |

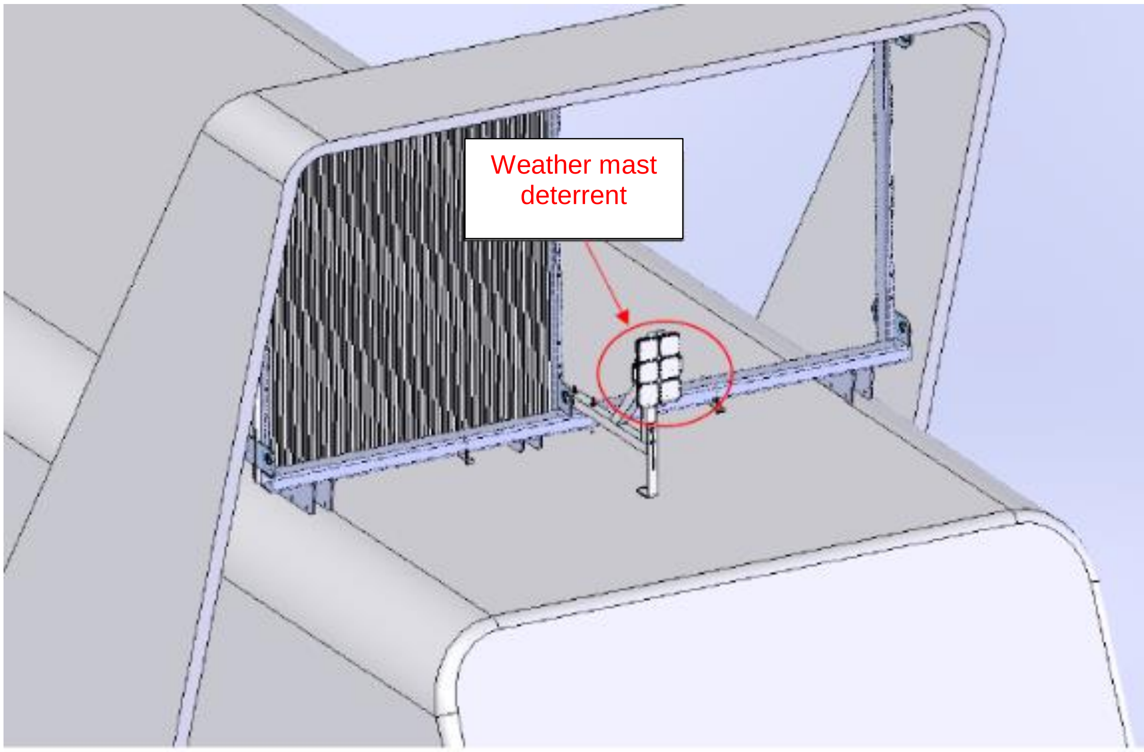
| Date | Common Name | Location | Distance From Turbine (m) | Search Type |
|---|---|---|---|---|
| 05/30/2017 | Brazilian Free-tailed Bat | 4-86 | 5 | Search |
| 05/31/2017 | Brazilian Free-tailed Bat | 4-43 | 11 | Incidental |
| 05/31/2017 | Brazilian Free-tailed Bat | 4-57 | 10 | Search |
| 05/31/2017 | Brazilian Free-tailed Bat | 4-41 | 1 | Search |
| 06/01/2017 | Brazilian Free-tailed Bat | 3-8 | 30 | Search |
| 06/01/2017 | Brazilian Free-tailed Bat | 4-8 | 10 | Search |
| 06/04/2017 | Brazilian Free-tailed Bat | 5-30 | 20 | Search |
| 06/05/2017 | Brazilian Free-tailed Bat | 3-8 | 63 | Search |
| 06/06/2017 | Brazilian Free-tailed Bat | 4-36 | 16 | Incidental |
| 06/06/2017 | Brazilian Free-tailed Bat | 4-99 | 6 | Search |
| 06/06/2017 | Brazilian Free-tailed Bat | 4-95 | 23 | Search |
| 06/06/2017 | Brazilian Free-tailed Bat | 4-93 | 30 | Search |
| 06/08/2017 | Brazilian Free-tailed Bat | 3-45 | 33 | Search |
| 06/09/2017 | Brazilian Free-tailed Bat | 3-92 | 5 | Search |
| 06/10/2017 | Brazilian Free-tailed Bat | 5-17 | 36 | Search |
| 06/13/2017 | Brazilian Free-tailed Bat | 4-93 | 30 | Search |
| 06/13/2017 | Brazilian Free-tailed Bat | 4-86 | 2 | Search |
| 06/14/2017 | Brazilian Free-tailed Bat | 4-41 | 52 | Search |
| 06/15/2017 | Brazilian Free-tailed Bat | 4-9 | 52 | Search |
| 06/23/2017 | Unknown Bat | 3-83 | 42 | Search |
| 06/27/2017 | Brazilian Free-tailed Bat | 4-86 | 50 | Search |
| 06/27/2017 | Brazilian Free-tailed Bat | 4-86 | 7 | Search |
| 06/27/2017 | Brazilian Free-tailed Bat | 4-86 | 60 | Search |
| 06/28/2017 | Evening Bat | 4-57 | 8 | Search |
| 06/28/2017 | Brazilian Free-tailed Bat | 4-38 | 8 | Search |
| 06/28/2017 | Northern Yellow Bat | 3-1 | 2 | Search |
| 06/29/2017 | Brazilian Free-tailed Bat | 4-16 | 26 | Search |
| 07/03/2017 | Brazilian Free-tailed Bat | 3-8 | 50 | Search |
| 07/06/2017 | Evening Bat | 4-5 | 31 | Search |
| 07/06/2017 | Evening Bat | 4-19 | 1 | Search |
| 07/10/2017 | Western Yellow Bat | 3-27 | 35 | Search |
| 07/10/2017 | Brazilian Free-tailed Bat | 3-8 | 72 | Search |
| 07/12/2017 | Brazilian Free-tailed Bat | 4-60 | 29 | Search |
| 07/12/2017 | Brazilian Free-tailed Bat | 4-60 | 2 | Search |
| 07/12/2017 | Brazilian Free-tailed Bat | 3-3 | 42 | Search |
| 07/13/2017 | Brazilian Free-tailed Bat | 4-20 | 44 | Search |
| 07/13/2017 | Northern Yellow Bat | 4-20 | 10 | Search |
| 07/13/2017 | Brazilian Free-tailed Bat | 4-1 | 21 | Search |
| 07/13/2017 | Brazilian Free-tailed Bat | 3-43 | 37 | Search |
| 07/14/2017 | Northern Yellow Bat | 3-71 | 29 | Search |

| Date | Common Name | Location | Distance From Turbine (m) | Search Type |
|---|---|---|---|---|
| 07/14/2017 | Brazilian Free-tailed Bat | 3-92 | 58 | Search |
| 07/14/2017 | Brazilian Free-tailed Bat | 3-76 | 37 | Search |
| 07/15/2017 | Southern Yellow Bat | 3-44 | 38 | Search |
| 07/15/2017 | Northern Yellow Bat | 3-44 | 25 | Search |
| 07/15/2017 | Brazilian Free-tailed Bat | 5-25 | 28 | Search |
| 07/16/2017 | Brazilian Free-tailed Bat | 5-12 | 40 | Search |
| 07/16/2017 | Southern Yellow Bat | 5-52 | 43 | Search |
| 07/16/2017 | Northern Yellow Bat | 5-46 | 52 | Search |
| 07/16/2017 | Northern Yellow Bat | 5-30 | 45 | Search |
| 07/18/2017 | Northern Yellow Bat | 4-86 | 6 | Search |
| 07/20/2017 | Brazilian Free-tailed Bat | 4-20 | 51 | Search |
| 07/21/2017 | Southern Yellow Bat | 3-92 | 5 | Search |
| 07/21/2017 | Brazilian Free-tailed Bat | 3-84 | 44 | Search |
| 07/21/2017 | Southern Yellow Bat | 3-71 | 68 | Search |
| 07/22/2017 | Northern Yellow Bat | 5-5 | 44 | Search |
| 07/24/2017 | Northern Yellow Bat | 3-30 | 40 | Search |
| 07/26/2017 | Southern Yellow Bat | 4-60 | 56 | Search |
| 07/29/2017 | Northern Yellow Bat | 3-34 | 12 | Incidental |
| 07/30/2017 | Brazilian Free-tailed Bat | 5-55 | 39 | Search |
| 07/31/2017 | Northern Yellow Bat | 3-21 | 31 | Search |
| 08/01/2017 | Brazilian Free-tailed Bat | 4-96 | 28 | Search |
| 08/01/2017 | Brazilian Free-tailed Bat | 4-93 | 38 | Search |
| 08/02/2017 | Brazilian Free-tailed Bat | 4-48 | 9 | Search |
| 08/03/2017 | Brazilian Free-tailed Bat | 4-3 | 18 | Search |
| 08/04/2017 | Brazilian Free-tailed Bat | 3-94 | 3 | Search |
| 08/04/2017 | Northern Yellow Bat | 3-97 | 3 | Search |
| 08/04/2017 | Brazilian Free-tailed Bat | 3-97 | 0 | Search |
| 08/04/2017 | Northern Yellow Bat | 3-81 | 3 | Search |
| 08/04/2017 | Brazilian Free-tailed Bat | 3-71 | 32 | Search |
| 08/05/2017 | Northern Yellow Bat | 3-44 | 44 | Search |
| 08/05/2017 | Brazilian Free-tailed Bat | 3-44 | 9 | Search |
| 08/05/2017 | Northern Yellow Bat | 3-44 | 6 | Search |
| 08/06/2017 | Brazilian Free-tailed Bat | 5-30 | 30 | Search |
| 08/07/2017 | Northern Yellow Bat | 3-30 | 10 | Search |
| 08/07/2017 | Brazilian Free-tailed Bat | 3-36 | 64 | Search |
| 08/08/2017 | Brazilian Free-tailed Bat | 4-96 | 31 | Search |
| 08/08/2017 | Brazilian Free-tailed Bat | 4-93 | 10 | Search |
| 08/09/2017 | Northern Yellow Bat | 4-60 | 74 | Search |
| 08/09/2017 | Brazilian Free-tailed Bat | 4-38 | 7 | Search |
| 08/09/2017 | Northern Yellow Bat | 3-16 | 4 | Search |

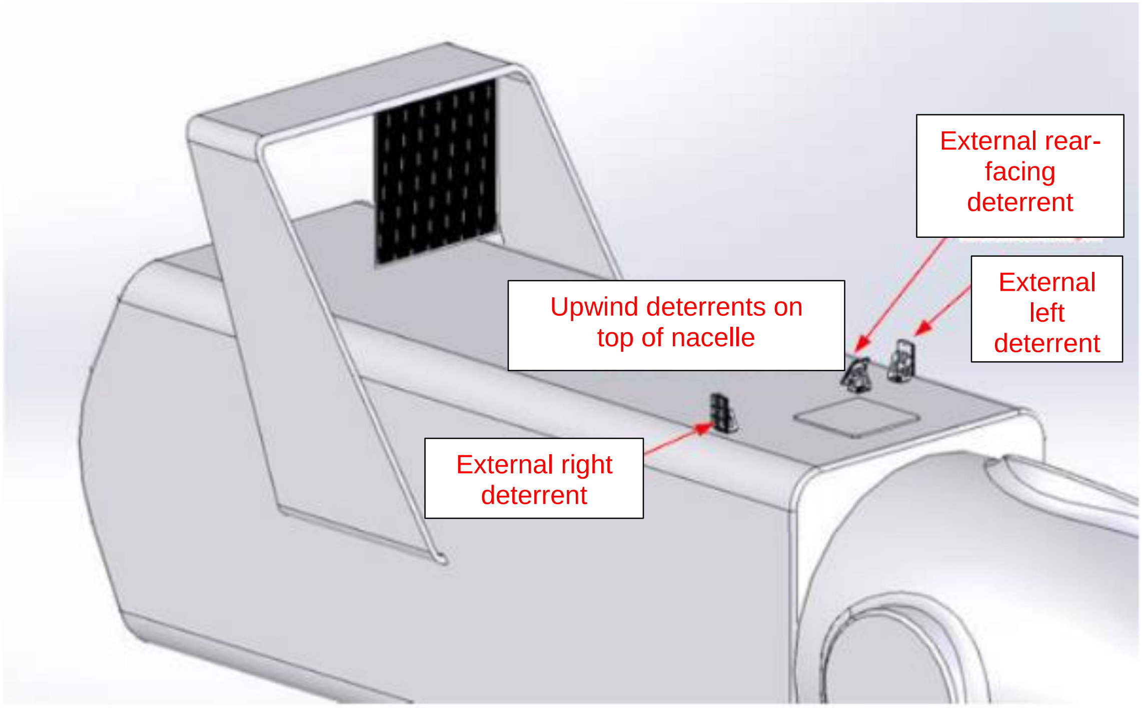
| Date | Common Name | Location | Distance From Turbine (m) | Search Type |
|---|---|---|---|---|
| 08/09/2017 | Brazilian Free-tailed Bat | 3-3 | 7 | Search |
| 08/10/2017 | Brazilian Free-tailed Bat | 4-9 | 2 | Search |
| 08/10/2017 | Southern Yellow Bat | 4-27 | 69 | Search |
| 08/11/2017 | Western Yellow Bat | 3-71 | 10 | Incidental |
| 08/11/2017 | Northern Yellow Bat | 3-71 | 50 | Search |
| 08/11/2017 | Brazilian Free-tailed Bat | 3-71 | 13 | Search |
| 08/11/2017 | Brazilian Free-tailed Bat | 3-97 | 35 | Search |
| 08/11/2017 | Brazilian Free-tailed Bat | 3-97 | 33 | Search |
| 08/11/2017 | Northern Yellow Bat | 3-84 | 38 | Search |
| 08/12/2017 | Brazilian Free-tailed Bat | 4-60 | 28 | Incidental |
| 08/15/2017 | Brazilian Free-tailed Bat | 4-96 | 19 | Search |
| 08/16/2017 | Brazilian Free-tailed Bat | 3-3 | 0 | Search |
| 08/21/2017 | Unknown Bat | 3-8 | 74 | Search |
| 08/22/2017 | Brazilian Free-tailed Bat | 5-12 | 82 | Incidental |
| 08/22/2017 | Brazilian Free-tailed Bat | 4-96 | 40 | Search |
| 08/23/2017 | Eastern Red Bat | 3-58 | 8 | Search |
| 08/24/2017 | Northern Yellow Bat | 3-45 | 19 | Search |
| 08/24/2017 | Brazilian Free-tailed Bat | 3-43 | 9 | Search |
| 08/26/2017 | Southern Yellow Bat | 3-44 | 62 | Search |
| 08/26/2017 | Brazilian Free-tailed Bat | 3-44 | 12 | Search |
| 08/26/2017 | Brazilian Free-tailed Bat | 3-44 | 12 | Search |
| 08/26/2017 | Brazilian Free-tailed Bat | 3-44 | 21 | Search |
| 08/27/2017 | Brazilian Free-tailed Bat | 5-12 | 18 | Search |
| 08/30/2017 | Hoary Bat | 3-3 | 31 | Search |
| 08/30/2017 | Evening Bat | 4-57 | 6 | Search |
| 08/31/2017 | Brazilian Free-tailed Bat | 3-53 | 4 | Search |
| 08/31/2017 | Brazilian Free-tailed Bat | 4-10 | 12 | Search |
| 09/01/2017 | Cave Myotis | O&M | NA | Incidental |
| 09/01/2017 | Brazilian Free-tailed Bat | 3-71 | 19 | Search |
| 09/02/2017 | Brazilian Free-tailed Bat | 3-33 | 38 | Incidental |
| 09/02/2017 | Brazilian Free-tailed Bat | 5-9 | 41 | Search |
| 09/02/2017 | Brazilian Free-tailed Bat | 5-5 | 33 | Search |
| 09/02/2017 | Brazilian Free-tailed Bat | 3-44 | 38 | Search |
| 09/02/2017 | Brazilian Free-tailed Bat | 3-44 | 39 | Search |
| 09/03/2017 | Brazilian Free-tailed Bat | 5-52 | 31 | Incidental |
| 09/03/2017 | Brazilian Free-tailed Bat | 5-48 | 41 | Incidental |
| 09/03/2017 | Brazilian Free-tailed Bat | 5-48 | 21 | Search |
| 09/03/2017 | Brazilian Free-tailed Bat | 5-32 | 32 | Search |
| 09/05/2017 | Brazilian Free-tailed Bat | 4-96 | 34 | Search |
| 09/05/2017 | Brazilian Free-tailed Bat | 4-96 | 37 | Search |

| Date | Common Name | Location | Distance From Turbine (m) | Search Type |
|---|---|---|---|---|
| 09/05/2017 | Brazilian Free-tailed Bat | 4-96 | 24 | Search |
| 09/05/2017 | Northern Yellow Bat | 4-96 | 29 | Search |
| 09/05/2017 | Unknown Bat | 4-96 | 9 | Search |
| 09/05/2017 | Brazilian Free-tailed Bat | 4-96 | 47 | Search |
| 09/06/2017 | Brazilian Free-tailed Bat | 4-41 | 23 | Search |
| 09/06/2017 | Brazilian Free-tailed Bat | 4-60 | 60 | Search |
| 09/06/2017 | Brazilian Free-tailed Bat | 4-52 | 0 | Search |
| 09/06/2017 | Brazilian Free-tailed Bat | 4-38 | 8 | Search |
| 09/07/2017 | Brazilian Free-tailed Bat | 4-20 | 33 | Search |
| 09/08/2017 | Brazilian Free-tailed Bat | 3-84 | 32 | Search |
| 09/09/2017 | Brazilian Free-tailed Bat | 3-44 | 41 | Search |
| 09/10/2017 | Brazilian Free-tailed Bat | 5-12 | 32 | Search |
| 09/16/2017 | Brazilian Free-tailed Bat | 3-44 | 38 | Search |
| 09/18/2017 | Brazilian Free-tailed Bat | 3-8 | 44 | Search |
| 09/18/2017 | Brazilian Free-tailed Bat | 3-8 | 38 | Search |
| 09/18/2017 | Northern Yellow Bat | 3-22 | 82 | Search |
| 09/20/2017 | Brazilian Free-tailed Bat | 4-41 | 72 | Search |
| 09/23/2017 | Brazilian Free-tailed Bat | 5-46 | 41 | Search |
| 09/24/2017 | Brazilian Free-tailed Bat | 5-46 | 34 | Search |
| 09/29/2017 | Northern Yellow Bat | 3-83 | 48 | Search |
| 09/30/2017 | Hoary Bat | 5-13 | 65 | Search |
| 10/01/2017 | Brazilian Free-tailed Bat | 5-55 | 48 | Incidental |
| 10/05/2017 | Brazilian Free-tailed Bat | 4-27 | 31 | Search |
| 10/09/2017 | Brazilian Free-tailed Bat | 3-10 | 50 | Search |
| 10/09/2017 | Brazilian Free-tailed Bat | 3-33 | 0 | Search |
| 10/09/2017 | Brazilian Free-tailed Bat | 3-33 | 2 | Search |
| 10/10/2017 | Brazilian Free-tailed Bat | 4-86 | 1 | Search |
| 10/12/2017 | Brazilian Free-tailed Bat | 4-20 | 33 | Incidental |
| 10/12/2017 | Brazilian Free-tailed Bat | 4-12 | 5 | Search |
| 10/12/2017 | Brazilian Free-tailed Bat | 4-20 | 45 | Search |
| 10/12/2017 | Hoary Bat | 4-20 | 44 | Search |
| 10/12/2017 | Brazilian Free-tailed Bat | 4-20 | 27 | Search |
| 10/14/2017 | Brazilian Free-tailed Bat | 3-44 | 42 | Search |
| 10/16/2017 | Brazilian Free-tailed Bat | 3-8 | 28 | Search |
| 10/16/2017 | Brazilian Free-tailed Bat | 3-6 | 1 | Search |
| 10/21/2017 | Brazilian Free-tailed Bat | 5-5 | 26 | Search |
| 10/22/2017 | Brazilian Free-tailed Bat | 5-31 | 39 | Search |
| 10/25/2017 | Brazilian Free-tailed Bat | 4-57 | 8 | Search |
| 11/02/2017 | Brazilian Free-tailed Bat | 4-43 | 6 | Incidental |
| 11/02/2017 | Brazilian Free-tailed Bat | 4-86 | 3 | Incidental |

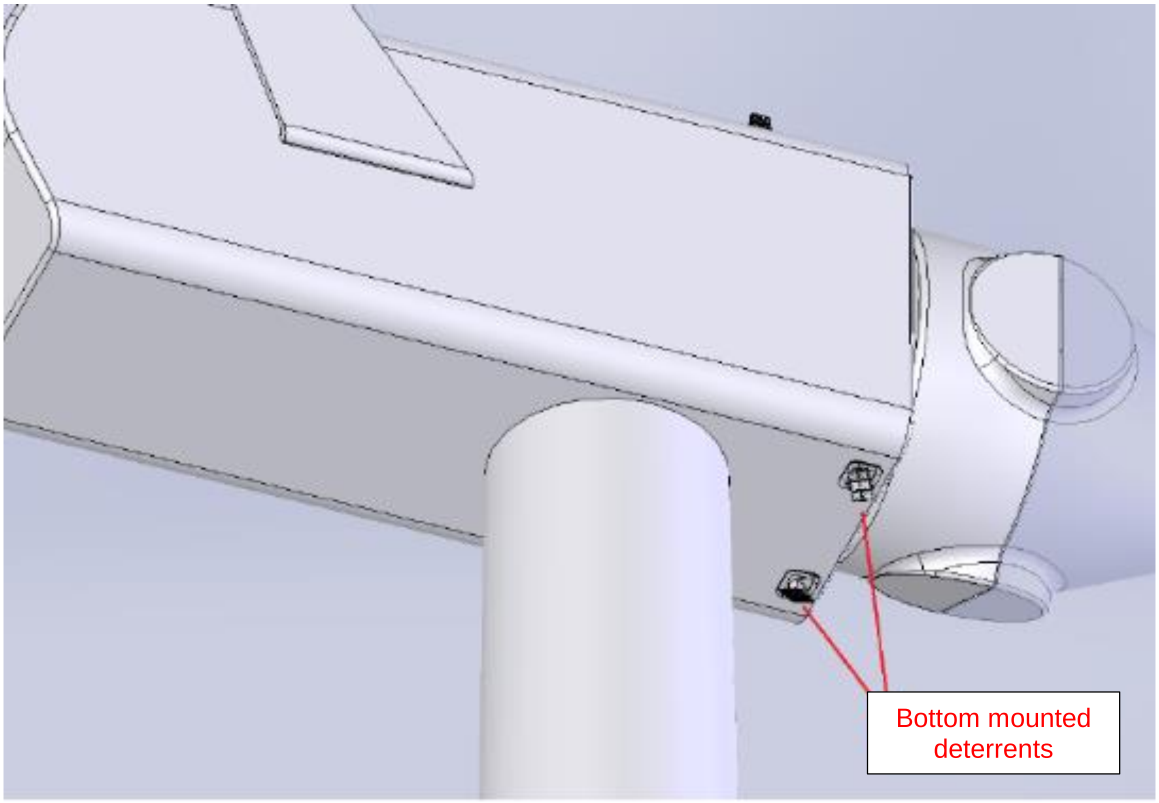
| Date | Common Name | Location | Distance From Turbine (m) | Search Type |
|---|---|---|---|---|
| 11/02/2017 | Brazilian Free-tailed Bat | 4-20 | 1 | Search |
| 11/02/2017 | Brazilian Free-tailed Bat | 4-20 | 11 | Search |
| 11/02/2017 | Brazilian Free-tailed Bat | 3-43 | 4 | Search |
| 11/06/2017 | Brazilian Free-tailed Bat | 3-34 | 0 | Incidental |
| 11/07/2017 | Brazilian Free-tailed Bat | 4-96 | 65 | Search |
| 11/08/2017 | Brazilian Free-tailed Bat | 3-1 | 29 | Search |
| 11/08/2017 | Brazilian Free-tailed Bat | 4-29 | 25 | Search |
| 11/08/2017 | Hoary Bat | 4-60 | 25 | Search |
| 11/08/2017 | Brazilian Free-tailed Bat | 4-60 | 42 | Search |
| 11/12/2017 | Brazilian Free-tailed Bat | 4-12 | 10 | Search |
| 11/12/2017 | Brazilian Free-tailed Bat | 4-12 | 16 | Search |
| 11/13/2017 | Brazilian Free-tailed Bat | 3-8 | 11 | Search |
| 11/13/2017 | Brazilian Free-tailed Bat | 3-8 | 59 | Search |
| 11/14/2017 | Brazilian Free-tailed Bat | 4-96 | 34 | Search |
| 11/15/2017 | Brazilian Free-tailed Bat | 3-71 | 2 | Incidental |
| 11/16/2017 | Brazilian Free-tailed Bat | 4-1 | 27 | Search |
| 11/21/2017 | Brazilian Free-tailed Bat | 3-86 | 1 | Incidental |
| 12/04/2017 | Brazilian Free-tailed Bat | 3-19 | 16 | Search |
| 12/05/2017 | Brazilian Free-tailed Bat | 4-86 | 3 | Search |
| 12/20/2017 | Hoary Bat | 4-48 | 28 | Incidental |
| 01/02/2018 | Brazilian Free-tailed Bat | 4-86 | 25 | Search |
| 01/28/2018 | Brazilian Free-tailed Bat | 5-38 | 0 | Incidental |
| 01/30/2018 | Brazilian Free-tailed Bat | 4-96 | 35 | Search |
| 02/11/2018 | Brazilian Free-tailed Bat | 5-12 | 66 | Search |
| 02/17/2018 | Brazilian Free-tailed Bat | 5-19 | 6 | Search |
| 03/03/2018 | Brazilian Free-tailed Bat | 3-44 | 43 | Search |
| 03/07/2018 | Brazilian Free-tailed Bat | 4-52 | 11 | Search |
| 03/07/2018 | Brazilian Free-tailed Bat | 4-31 | 7 | Search |
| 03/09/2018 | Brazilian Free-tailed Bat | 3-87 | 35 | Search |
| 03/10/2018 | Brazilian Free-tailed Bat | 3-44 | 73 | Search |
| 03/14/2018 | Brazilian Free-tailed Bat | 4-60 | 60 | Search |
| 03/14/2018 | Brazilian Free-tailed Bat | 4-60 | 33 | Search |
| 03/14/2018 | Brazilian Free-tailed Bat | 4-60 | 5 | Search |
| 03/20/2018 | Brazilian Free-tailed Bat | 4-84 | 18 | Incidental |
| 03/20/2018 | Brazilian Free-tailed Bat | 4-84 | 17 | Incidental |



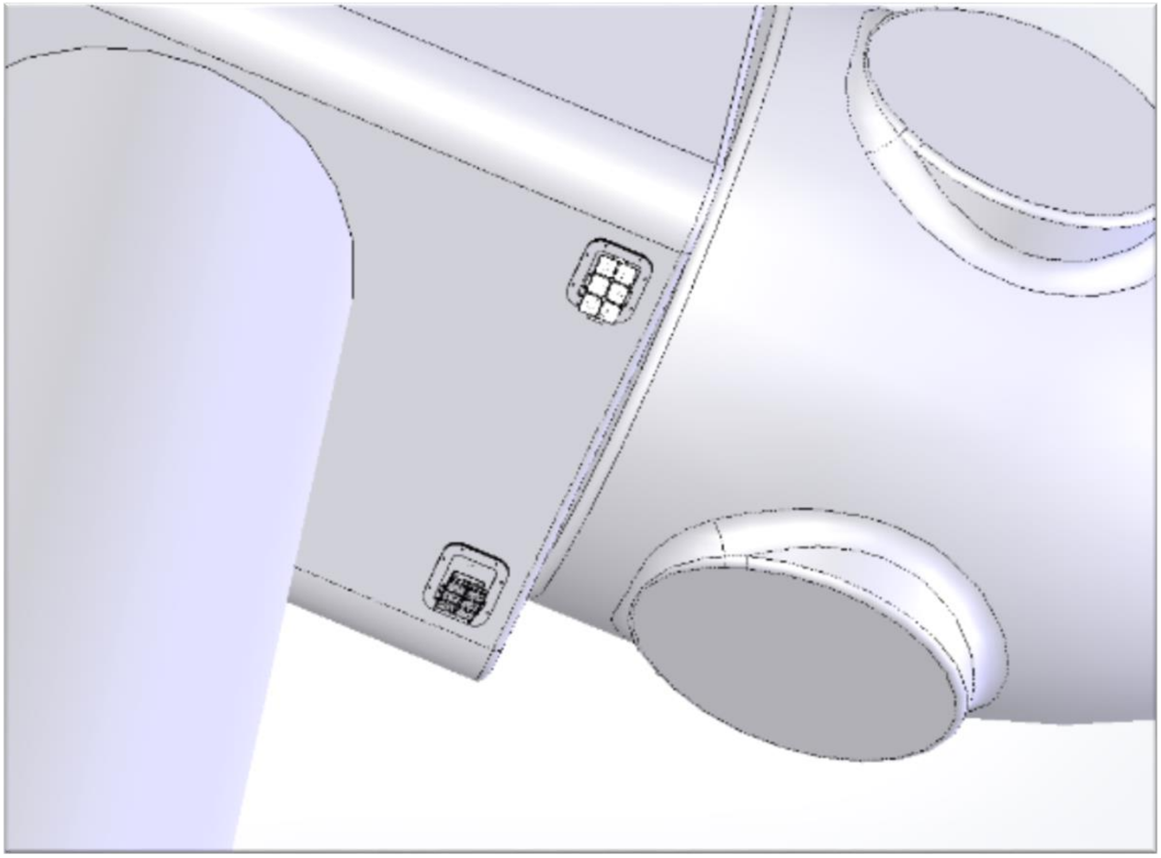

**Appendix, Figure 1.** Image depicting the position of the deterrent array on the weather mast facing off the rear of the nacelle at Los Vientos during deterrent testing in 2017. Orientation shows the unit pointed towards the leeward side of the nacelle. This unit was removed during deterrent testing in 2018.



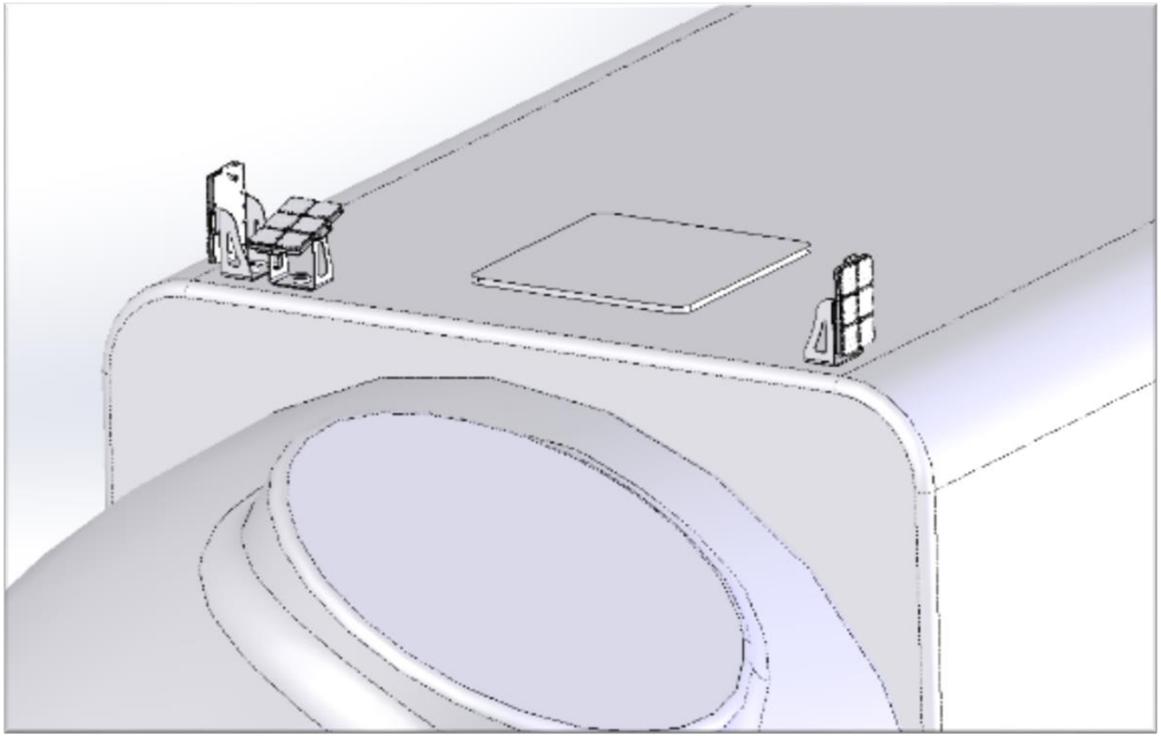

**Appendix, Figure 2.** Image depicting the position of deterrent arrays located on top of the nacelle, upwind at Los Vientos during deterrent testing in 2017. Orientation shows the external rear-facing deterrent pointed towards the leeward side of the nacelle.




**Appendix, Figure 3.** Image depicting the position of deterrent arrays located on the bottom of the nacelle, upwind at Los Vientos during deterrent testing in 2017. Orientation shows units pointed towards leeward side of the nacelle.



**Appendix, Figure 4.** Image depicting the new orientation of the bottom-facing deterrent arrays repositioned towards the rotor swept area at Los Vientos Wind Energy Facility during deterrent testing in 2018.



**Appendix, Figure 5**. Image depicting the new orientation of the top mounted deterrent arrays repositioned towards the rotor swept area at Los Vientos Wind Energy Facility during deterrent testing in 2018.