Wildlife Society Bulletin 1–11; 2019; DOI: 10.1002/wsb.1025

Original Article

Evaluation of an Acoustic Deterrent to Reduce Bat Mortalities at an Illinois Wind Farm

W. BRAD ROMANO,[1] *Environmental and Wildlife Permitting, Invenergy LLC, One South Wacker Drive, Suite 1800, Chicago, IL 60606, USA*
JOHN R. SKALSKI, *Columbia Basin Research, School of Aquatic and Fishery Sciences, University of Washington, 1325 Fourth Avenue, Suite 1515, Seattle, WA 98101, USA*
RICHARD L. TOWNSEND, *Columbia Basin Research, School of Aquatic and Fishery Sciences, University of Washington, 1325 Fourth Avenue, Suite 1515, Seattle, WA 98101, USA*
KEVIN W. KINZIE, *GE Renewable Energy, 300 Garlington Road, Greenville, SC 29615, USA*
KARYN D. COPPINGER, *GE Renewable Energy Contractor, 1080 Shadow Ridge Road, Laporte, CO 80535, USA*
MYRON F. MILLER, *GE Renewable Energy, 327 Overlook Drive, West Lafayette, IN 47906, USA*

ABSTRACT From 2014 to 2016, GE Renewable Energy and California Ridge Wind Energy tested an ultrasonic bat deterrent system during the autumn bat migration period at an operating wind farm in Illinois, USA. The deterrent system consisted of air-jet ultrasonic emitters mounted on nacelles and towers in a different configuration each year. Each year we conducted a randomized block experiment to determine whether the acoustic deterrent reduced bat mortalities at the wind farm. Effectiveness was based on estimates of bat mortalities during 3-day trials. The operation of the acoustic deterrent resulted in significant overall bat fatality reductions of 29.2% ($\widehat{SE} = 7.5\%$) and 32.5% ($\widehat{SE} = 6.8\%$) in 2014 and 2015, respectively. All-bat fatality rates were not reduced in 2016; however, annual all-bat effectiveness estimates were influenced by species composition. We analyzed deterrent effectiveness for eastern red (*Lasiurus borealis*), hoary (*Lasiurus cinereus*), and silver-haired (*Lasionycteris noctivagans*) bats, the 3 species most commonly found during the carcass searches. Hoary bats were consistently deterred each year, but annual deterrent effectiveness varied for eastern red and silver-haired bats. © 2019 The Authors. *Wildlife Society Bulletin* published by Wiley Periodicals, Inc. on behalf of The Wildlife Society.

KEY WORDS eastern red bat, hoary bat, *Lasiurus cinereus*, *Lasionycteris noctivagans*, *Lasiurus borealis*, minimization, mortality, renewable energy, silver-haired bat.

Wind energy is one of the fastest growing sources of renewable energy in North America. Bat mortality at wind farms has been well-documented and is estimated to be >600,000 bats/year in North America (Kunz et al. 2007, Hayes 2013, O'Shea et al. 2016, Smallwood et al. 2018). To date, the primary means of reducing wind energy effects on bats include proper siting of wind farms away from important bat habitat and curtailing, or reducing, operations during periods of risk. During curtailment, operators reduce the number of bat mortalities that could occur at wind farms by raising the threshold (cut-in) wind speed at which the blade feathering is released and turbines begin rotating to generate electric power.

Formal studies have demonstrated the effectiveness of using curtailment to reduce bat mortalities (Baerwald et al. 2009; Arnett et al. 2010, 2013*a*, *b*, 2016; Young et al. 2013; Martin et al. 2017; Schirmacher et al. 2018). Feathering below manufacturer's cut-in wind speed has been demonstrated to reduce bat fatalities by ≥35%, and cutting-in at higher wind speeds often results in greater reductions in bat fatalities (Baerwald et al. 2009, Good et al. 2012, Young et al. 2013).

Selected cut-in speeds vary by site and are determined in consideration of site-specific conditions such as seasonal bat activity patterns, and regulatory considerations such as the presence or absence of legally protected bat species. However, annual energy production is also reduced by raising cut-in speeds, sometimes considerably, depending on the site's facility attributes such as turbine type and environmental factors such as the characteristics of the wind resource (Hayes et al. 2019). This lost electrical production has incentivized the wind power industry to seek alternate means of reducing bat fatality rates (U.S. Department of Energy 2014).

Received: 16 October 2018; Accepted: 12 October 2019
Published:

[1] *E-mail: bromano@invenergyllc.com*

Wildlife control through acoustic deterrents has been studied for decades, although establishment of controlled field experiments has proven difficult (Bomford and O'Brien 1990). Since at least 2007, researchers, industry, and wildlife managers have considered the use of acoustic deterrents to reduce wind energy effects on bats, and some research has been conducted (Szewczak and Arnett 2007, Horn et al. 2008, Arnett et al. 2013*a*, Weaver et al. 2019). Arnett et al. (2013*a*) found acoustic deterrents may reduce bat mortality at wind energy facilities by up to 51%. However, that study was deemed inconclusive because the reported 95% confidence interval ranged from a 2% increase in bat fatalities to a 64% decrease in bat fatalities at deterrent-configured turbines. Weaver et al. (2019) showed that acoustic deterrents reduced bat fatalities by 50%. In addition, they demonstrated that Brazilian free-tailed bat (*Tadarida brasiliensis*) and hoary bat (*Lasiurus cinereus*) fatalities were reduced by 54% (CI = 41%–67%) and 78% (CI = 62%–95%), respectively, but the deterrent was not effective for northern yellow bats (*Lasiurus intermedius*). Effective bat deterrence continues to be sought by industry and regulatory stakeholders so renewable electric power demands can be met in a manner that minimizes effects to wild populations.

Bat mortalities at wind farms in North America are typically greatest during autumn migration (Arnett et al. 2008, Hein and Schirmacher 2016). Except in southern states, where some species may be active year-round, bats either migrate to and winter in hibernacula or migrate and winter in warmer climes. Although the phenomenon of greater bat mortality during autumn has been repeatedly documented throughout North America, its causes are unknown.

Recent research indicates certain bat species (e.g., eastern red [*Lasiurus borealis*], hoary, and silver-haired bats [*Lasionycteris noctivagans*]) may view turbines as potential roosts, trees, or foraging or water sources (McAlexander 2013, Foo et al. 2017). Cryan et al. (2014) observed bats typically approaching wind turbine towers from the leeward side. It remains unclear why bats approach wind turbines; what part(s) of turbines, if any, attract bats; and why fatalities occur (Cryan et al. 2014, Bennett and Hale 2018). Fatalities occur at rotors that are moving faster than a few revolutions per minute, whereas stationary or slow-moving rotors are not apparently lethal to bats (Arnett et al. 2016). Consequently, deterrent research, including this study, has focused on warning bats away from moving rotors.

From 2014 to 2016, we tested the efficacy of an ultrasonic bat-deterrent system during the autumn bat migration period at an operational wind-energy facility. We deployed deterrent systems on a set of turbines and, using different deterrent configurations and signals each year, we assessed whether operation of the deterrent effectively reduced bat fatalities at the wind farm. We tested a null hypothesis H_o: the deterrent system does not reduce bat fatalities at wind turbines, versus the alternative hypothesis H_a: the deterrent system reduces bat fatalities at wind turbines.

STUDY AREA

The California Ridge Wind Energy Facility (CRWEF) consisted of 134 GE 1.6-100 turbines, which have a 100-m tower height and 100-m rotor diameter, generating a nameplate capacity of 1.6 megawatts. The CRWEF Study Area was located on approximately 13,567 ha in Champaign and Vermilion counties, Illinois, USA, approximately 16 km northwest of Danville and 32 km east-northeast of Champaign (Fig. 1). The study area, and much of central Illinois, was located within the Central Corn Belt Plains Ecoregion and on glaciated plains (Woods et al. 2007). Much of this region was historically dominated by tallgrass prairie with groves of trees and marshes scattered across the flat uplands. The study area was located within the Vermilion River watershed, and its topography was flat to rolling with elevations ranging from approximately 61 m to 76 m above sea level. The Middle Fork River, a tributary of the Vermilion River, flowed along the eastern side of the study area and was approximately 3.2 km from the nearest CRWEF turbine at its closest point (Fig. 1). Land use within the study area was 92% row crops, primarily planted in corn (*Zea* spp.) and soybean (*Glycine max*). Other land cover types included developed lands (5%), pasture–hay fields (2%), with deciduous forest, open water, woody wetlands, and grassland–herbaceous comprising a combined 1% of the land cover (Homer et al. 2015).

Nine bat species of the family Vespertilionidae, including: big brown bat (*Eptesicus fuscus*), silver-haired bat, eastern red bat, hoary bat, little brown bat (*Myotis lucifugus*), northern long-eared bat (*M. septentrionalis*), Indiana bat (*M. sodalis*), tri-colored bat (*Perimyotis subflavus*), and evening bat (*Nycticeius humeralis*) have geographic range distributions that include the study area (Bat Conservation International 2018). Of the 9 bat species, 3 are federally protected. The Indiana bat was listed under the federal 1973 Endangered Species Act (as amended) as endangered (U.S. Fish and Wildlife Service 1973), the northern long-eared bat is listed as threatened (U.S. Fish and Wildlife Service 2016*a*), and the U.S. Fish and Wildlife Service is currently conducting a status review of the little brown bat to be concluded in 2023 (U.S. Fish and Wildlife Service 2016*b*).

The sparsely distributed forest within the study area was available for foraging and roosting by these bat species. Many of the species may also forage along stream corridors, over standing water, and over open land covers adjacent the wooded areas (Bat Conservation International 2018). Big brown and evening bats are also likely to forage over cropland within the study area (Boyles et al. 2011). Foraging and roosting behavior during autumn migration, however, is poorly understood (Bennett and Hale 2018). All these species have been observed as fatalities at wind farms located in cropland-dominated landscapes similar to the study area (Gruver and Bishop-Boros 2015, Good et al. 2018).

METHODS

We performed the deterrent studies daily from 1 August 2014 to 8 October 2014, 10 August 2015 to 2 October 2015, and 1 August 2016 to 11 September 2016. There was a brief gap due to a site-wide power outage during the 2014 study, from 24 to 26 September; no other site-wide interruptions occurred during the studies.

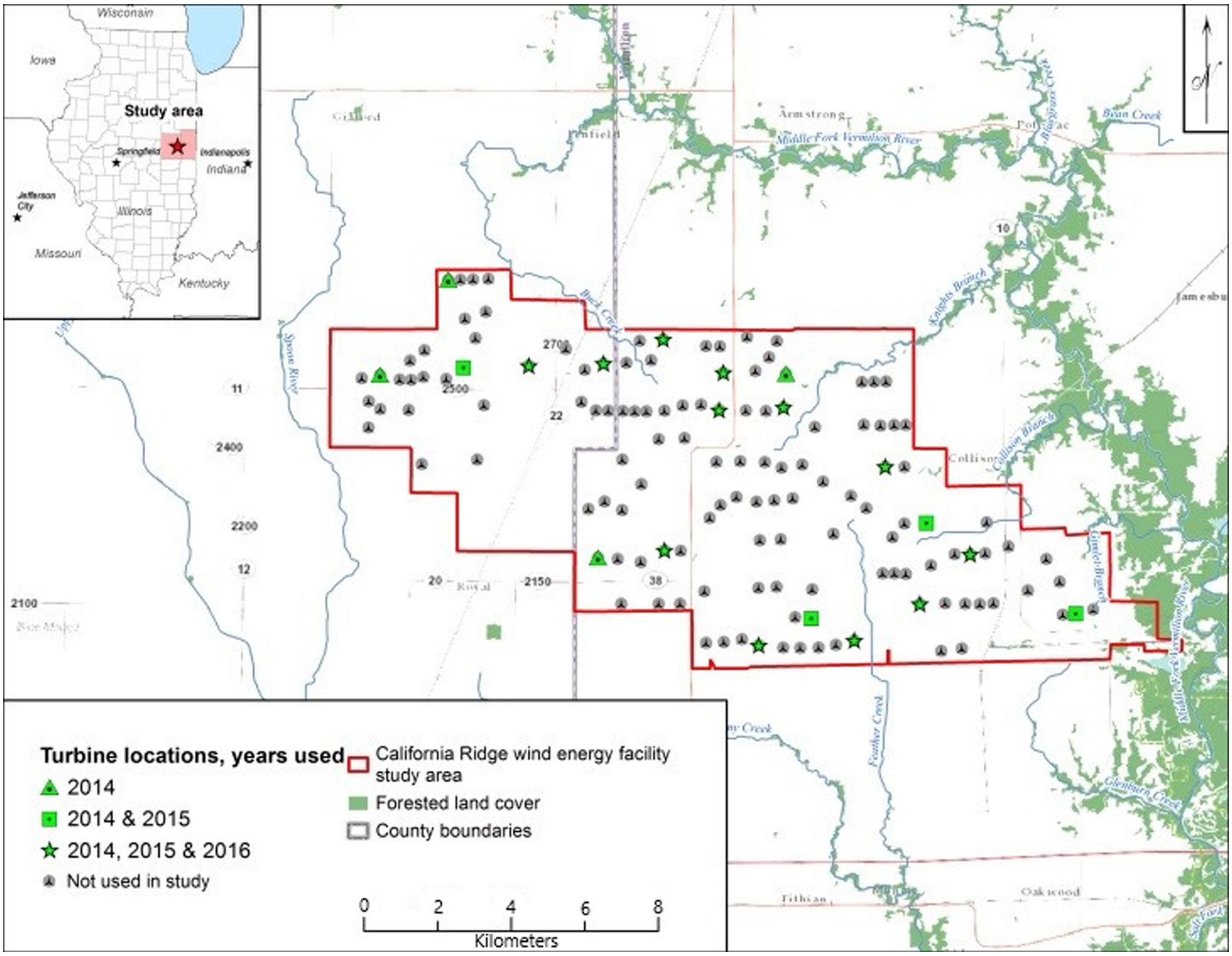

Figure 1. Study area, turbine locations, and study turbine selections for 2014, 2015, and 2016, California Ridge Wind Energy Facility, Champaign and Vermilion counties, Illinois, USA.

Experimental Design

Finite sampling without replacement produces samples that are not independent (Cochran 1977). This was the analogous situation we had to contend with when designing our study with a finite number of available wind turbines equipped with the deterrent device each year. Each year, we used a randomized block design with within-block replication. This design also goes by the names "generalized 2-factor experiment" (Snedecor and Cochran 1967:746–747) and "generalized randomized block design" (Wilk 1955, Addelman 1969). Test blocks were of 6-day duration. Within a block, we randomized available turbines with half designated as controls (i.e., deterrent off) and the other half as treatments (i.e., deterrent on). A trial lasted for 3 days, then we switched the control–treatment designations of the wind turbines, and performed a second trial for the next 3 days (Table 1). The result was that for every 6-day test block, we generated 2 control and 2 treatment estimates of bat mortality. In this approach, all turbines served as both controls and treatments within a block, avoiding any bias due to the happenstance of the initial randomization. Switching treatment designations within a block maximized the contrasts between replicate control or treatment values. The intended consequence was an error variance based on between-replicate, within-block variance that was potentially inflated and thereby assuring our tests of treatment effects were valid but conservative.

Table 1. Example of control (C) and treatment (T) assignment during the bat deterrent studies, California Ridge Wind Energy Center, Champaign and Vermilion counties, Illinois, USA, 2014–2016. Study blocks represent 6-day periods within which 2 3-day treatment replicates were performed. Treatment designations were randomly assigned within the first 3-day trial, and treatment designations then reversed during the second 3-day trial within a block. Treatment designations were rerandomized for each 6-day study block.

		Turbine number							
Study block	**Trial period days**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	1–3	T	C	C	T	C	T	C	T
	4–6	C	T	T	C	T	C	T	C
2	1–3	C	T	C	T	T	T	C	C
	4–6	T	C	T	C	C	C	T	T
i	1–3	C	T	T	C	C	T	T	C
	4–6	T	C	C	T	T	C	C	T

Turbine Selection

In 2014, we used 16 to 20 randomly selected turbines in each block. One of the 20 study turbines became non-operational and we removed it from the study. We reserved 3 of the remaining 19 turbines as alternates and human teams searched them daily to ensure that if any of the 16 primary turbines were unable to be used in a study block (e.g., shut down for scheduled maintenance), an alternate was available, and integrity of the study design maintained. In 2015 and 2016, we used randomly selected sets of 16 and 12 turbines, respectively. Alternate turbines were not needed in 2015 and 2016 because no extensive turbine maintenance was scheduled for the study periods.

Turbine Operations, Deterrent Technology, and Deterrent Nozzle Placement

Study turbines started operating at manufacturers' default cut-in wind speed of 3.5 m/second, and below that speed the rotor blades were fully feathered (i.e., with blades oriented parallel to the wind) and rotors moved <3 revolutions/minute. For "deterrent on" treatments, deterrent systems operated each night from 1800 to 0630.

The deterrent system jets (nozzles) produced a broad-band sound designed to overlap the entire range of frequencies (~30–100 kHz) generated by and audible to most bat species (University of Michigan, Museum of Zoology 2014). The broad-band deterrent sound was emitted by forcing compressed air through the nozzles using a network of air lines connected to 2 5-horsepower compressors installed inside the turbine tower. Jet-based emitters produce sound in a roughly ellipsoidal volume around the nozzle (i.e., it produces sound not only in front of the nozzle but also to the sides and even behind). Based on the results of on-ground and turbine tests, the deterrent system is effective to ≥30 m (Kinzie et al. 2018). Bat activity near wind turbines appears to be concentrated below the nacelle and behind the tower (Cryan et al. 2014, Kinzie et al. 2018), so for this study we ensonified this area of greatest activity. We did not attempt to ensonify the entire blade, but we estimate that between 35% and 56% of a rotor-swept area was within the ensonified zone at any given time, depending on nozzle configuration (which varied each year, as described in the next paragraph) and blade position (which varied as the rotor turned), and depending on environmental factors such as relative humidity.

Each year of the study, we mounted deterrent nozzles in different nacelle and tower configurations to ensure coverage in areas where bat activity was thought to be concentrated (2014, 2015) and increase overall coverage (2016). In 2014, we mounted 2 nozzles on each nacelle (one facing rearward–upward and one facing rearward–downward), and 2 nozzles on each tower approximately 26 m below the nacelle (one facing the prevailing wind direction [magnetic north] and the other facing directly opposite). In 2014, a concurrent thermal camera study of bat activity at a deterrent-equipped turbine showed bats frequently using the airspace below the nacelle and downwind of the tower (Kinzie et al. 2018), which is consistent with published results from another study of bat behavior around wind turbines (Cryan et al. 2014). Thus, in 2015, we mounted 4 deterrent nozzles on the tower only, 2 each at 26 m and 50 m below the nacelle, also facing magnetic north and directly opposite, thereby increasing the affected airspace in the high activity area below the nacelle, downwind of the tower, and throughout more of the lower rotor swept area than in 2014.

In 2016, we reconfigured the deterrent system to emit sound in pulses. This system change allowed 6 nozzles to be operated with roughly the same amount of air used by the 4-nozzle constant-emission system, increasing the volume of airspace covered by the acoustic signal. We selected the pulse system in response to results of ground-based signal testing conducted in 2015, which suggested a pulse signal may be as effective as a constant signal (Lindsey 2017, Kinzie et al. 2018). The pulse signal was emitted for 4.9–7.9 seconds and followed by a 3.0-second silent period. We mounted 2 nozzles on the rear of the nacelle, facing rearward–upward and rearward–downward, and 4 nozzles on the tower in the configuration used in 2015.

Carcass Search Methods

We conducted carcass searches on 60-m-radius circular plots centered beneath the study turbines; this plot size is sufficient to encompass the majority of bat carcasses beneath wind turbines, though bat carcasses are known to fall beyond this radius (Hull and Muir 2010). We established 4–6-m spaced transects to guide human searches within the plots. To maximize carcass detection, we controlled vegetation through a combination of regular mowing, periodic herbicide treatment, or more infrequently, controlled burns. Just prior to commencing the deterrent experiment each year (or resuming monitoring after the site-wide outage), we searched and cleared all plots of bat carcasses.

Carcass searches included both visual searches by human crews and scent-based searches by dog and handler teams provided by Conservation Canines at the University of Washington (USA). We used a combined search strategy over the 3-day trials to maximize carcass recovery probabilities, thus minimizing carryover of carcasses that could blur treatment effects from one treatment block to the next (Mathews et al. 2013).

In 2014, a human crew visually searched the plots on days 1 and 2 of each 3-day trial. The dog and handler crews searched on day 3. This search deployment was used to help assure any carcasses missed by the human crew on days 1–2 were recovered, as well as most bat mortalities occurring on day 3. To further improve carcass recovery rates in 2015 and 2016, human crews searched day 1 and dog and handler crews searched on days 2 and 3. Both human and dog and handler teams are hereafter referred to as "searcher(s)," unless otherwise specified.

Each carcass discovered during the searches was flagged and the search continued until the plot was completed. Afterward, searchers took photographs, recorded field data, and bagged carcasses, labeled them with a unique identification number, and stored them in an onsite freezer. Human searchers used laser rangefinders (Nikon ProStaff 550 or similar; Nikon Corporation, Minato, Tokyo, Japan) and compasses to measure distance and direction of each carcass to the base of the tower. Dog handlers used a Columbus V-900 Bluetooth GPS Data Logger (Victory Technology Co., Ltd., Suzhou, China) to mark their search path and document carcass locations. For each carcass, searchers recorded species, estimated number of days old (1, 2, 3, or 4+ days old), age (adult–juvenile), sex (male–female), time discovered, weather conditions, and plot conditions where the carcass was found.

Calibration Trials

We integrated calibration trials into the daily searches for bat carcasses to estimate bat carcass recovery probabilities (a function of both searcher efficiency and scavenger removal rates) and total carcass abundance during the 3-day experimental trials. We randomly distributed known numbers of discreetly tagged bat carcasses within the 60-m search plots; search teams were blind to placement numbers and schedule; as they discovered each calibration trial carcass, the searcher gathered data and collected the carcass following the protocol described in the previous section. In 2014, we placed trial carcasses prior to day 1 of the 3-day experimental trials; in 2015 and 2016 we placed trial carcasses prior to days 1, 2, and 3 of the 3-day trials. In all, we placed 187 bat carcasses in 2014, 177 carcasses in 2015, and 87 carcasses in 2016 (Table 2). The random disbursements of tagged carcasses occurred throughout the annual experiments in 9 (2014), 30 (2015), and 35 (2016) placements and at densities consistent with actual carcass deposition rates, or between 0 and 4 carcasses/turbine/placement day. We did not disclose the calibration trial locations or schedules to searchers. Retrieval of the calibration trial carcasses by searchers occurred concurrently with the daily carcass searches. We recorded trial carcass recoveries according to day of deposition (i.e., 1, 2, 3) and day of recovery (i.e., 1, 2, 3). Searchers always wore gloves while handling bat carcasses. Bat carcasses used for calibration trials were entire and in good condition (i.e., not severely decayed or damaged) and included hoary bat, silver-haired bat, eastern red bat, and big brown bat.

Animal Use and Care

We conducted the 2014 and 2015 investigations under federal Endangered Species Act permit number TE03502B-0; federal Special Purpose-Utility Permit MB01827B-0 (2014); and Illinois Department of Natural Resources (IDNR) permit numbers 13-27 S, S14-071, NH14.5846, NH15.5846, and S15-031. In 2016, we conducted the investigation under a Biological Opinion dated 15 July 2015 and prepared by the U.S. Fish and Wildlife Service (USFWS), Rock Island Field Office, Rock Island, Illinois, and IDNR permit numbers NH16.5940 and S15-031. This research program was developed in consultation with and approved by the USFWS Rock Island Field Office, the USFWS Midwestern Regional Office, Bloomington, Minnesota, and the IDNR, Springfield, Illinois.

Estimation of Bat Mortalities—Statistical Methods

The calibration trials confirmed not all carcasses were found due to imperfect searches and some scavenging of carcasses; therefore, adjustments to the raw number of carcasses found needed to be made. To estimate the total number of bats that may have fallen in the search area for each treatment and during each 3-day trial, we adjusted the raw number of bat carcasses found by the probabilities of carcass recovery derived from the calibration-trial carcass data. The relationship between raw carcass recovery numbers and total mortality during a 3-day trial was not strictly proportional (See Appendix; available online). For instance, bat carcasses deposited on the first day of trials were exposed to 3 days of scavenging and searches whereas carcasses deposited on the last day of the trial were subject to only a single day of scavenging and search. Consequently, carcasses recovered

Table 2. Number of bat carcasses placed and found during calibration trials, for each day of the 3-day trial periods, and estimated probabilities of carcass retrieval during the 3-day trial periods during the deterrent study at the GE California Ridge Wind Energy Facility, Champaign and Vermilion counties, Illinois, USA, 2014–2016.

			No. carcasses found			$\hat{\theta}$(SE)[a]		
Year	**Calibration trial day**	**No. carcasses placed**	**Day 1**	**Day 2**	**Day 3**	**Day 1**	**Day 2**	**Day 3**
2014[b]	Day 1	187[b]	90	14	61	0	0	0
	Day 2	0	0	0	0	0	0	0
	Day 3	0	0	0	0	0	0	0
							Overall = 0.882 (0.024)	
2015[b]	Day 1	57	21	27	5	0.368 (0.064)	0.474 (0.066)	0.088 (0.038)
	Day 2	60	0	55	3	0	0.917 (0.036)	0.050 (0.028)
	Day 3	60	0	0	58	0	0	0.997 (0.023)
							Overall = 0.954 (0.016)	
2016[b]	Day 1	48	9	35	2	0.188 (0.056)	0.729 (0.064)	0.042 (0.029)
	Day 2	22	0	18	4	0	0.818 (0.082)	0.182 (0.082)
	Day 3	17	0	0	15	0	0	0.882 (0.078)
							Overall = 0.947 (0.028)	

[a] 2014 used a constant-effort model to estimate $\hat{\theta}$ because all calibration trial carcasses were seeded before day 1 of each 3-day trial; 2015 and 2016 used a variable-effort model because calibration trial carcasses were seeded before each day of a 3-day trial.

[b] In 2014, carcasses were placed in 9 trial periods, with 0–4 carcasses/turbine/trial. In 2015, carcasses were placed in 10 trial periods, with 0–2 carcasses placed/turbine/trial/day. In 2016, carcasses were placed in 11 trials, with 0–2 carcasses placed/turbine/trial/day.

during the individual days of a 3-day trial had unique adjustments based on the observed rates of carcass recovery during the calibration trials.

A joint maximum likelihood model was developed that incorporated both the recovery counts from the calibration trials and the carcass recoveries from the experimental trials. The joint likelihood model (See Appendix) assumed the bat carcasses used in the calibration trials and mortalities during the 3-day experimental trials shared the same carcass retention rates and conditional probabilities of recovery on days 1, 2, and 3. The likelihood model produced estimates of total 3-day mortality during the trials along with standard errors (SE; see Appendix). We used calibration data to convert raw carcass counts from the experimental trials into estimates of total mortalities with associated standard errors in 2014 and 2015. In 2016, we did not adjust the raw carcass recovery counts by the calibration trial data. For example, in 2016 the average carcass adjustment for the number of eastern red bats in a 3-day trial was 0.43, with an average standard error of 2.47 bats, suggesting more statistical noise was being added to the estimate of bat mortality than the adjustment for bias was correcting. This situation in 2016 arose because, although the overall recovery rate was high (i.e., 0.947), the number of carcasses used in the calibration trials was less than half of previous years. From the perspective of minimizing the mean square error (i.e., $\mathrm{MSE}(\hat{\Theta}) = BIAS^2 + \mathrm{Var}(\hat{\Theta} \mid \Theta)$), we decided the best action in 2016 was to ignore the calibrated correction for that year and model deterrent effectiveness based on the unadjusted bat counts.

We placed trial carcasses only prior to day 1 of a 3-day trial in 2014; therefore, a simplified carcass recovery model assuming a constant daily retrieval effort was necessary. However, in 2015 and 2016, we distributed trial carcasses before each of the 3 days of the trial, allowing for a more refined model with variable daily retrieval effort (See Appendix) to account for the varied sequence of human- and dog-assisted search crews.

Statistical Analysis—Deterrent Effects

The basic response model for the estimated number of bat mortalities was of the following form:

$$\hat{y}_{ijk} = \mu \cdot \beta_i \cdot \tau \cdot \beta\tau_{ij} \cdot \mathrm{OP}_{ijk} + \epsilon_{ijk} \tag{1}$$

where,

$\hat{y}_{ijk}$ = estimate of bat mortality for the ith block ($i = 1, \ldots, B$), jth treatment ($j = 1$ for control, 2 for treatment,), and k replicate ($k = 1, 2$);

μ = baseline value for control in block 1, replicate 1;

β_i = block effect ($i = 2, \ldots, B$);

τ = treatment effect;

$\beta\tau_{ij}$ = block-by-treatment interaction;

OP_{ijk} = total turbine operating hours for the ith block ($i = 1, \ldots, B$), jth treatment ($j = 1, 2$), and k replicates ($k = 1, 2$);

ϵ_{ijk} = random error term.

The response model (1) corresponds to a randomized block experimental design with within-block replication of 2 treatments. In essence, this analysis is comparing the frequency of bat mortality per turbine operating hour between treatments.

Based on the multiplicative response model (1), we used a log-link in generalized linear models (GLM) to produce the linear predictors (McCullagh and Nelder 1989). In 2014 and 2015, when we used maximum likelihood estimation (MLE) to estimate total carcass abundance during a trial, we assumed the error term to be normally distributed because MLEs are asymptotically normally distributed. Hence, in those years, we used a GLM with a normal error and log-link. In 2016, when we used the actual unadjusted carcass counts in the analysis, because adjustments for nonrecovery were inconsequential the model structure (1) remained the same, but we assumed the error structure to be Poisson in the GLM analysis. To account for overdispersion in the 2016 Poisson error model, we used quasi-likelihood methods based on analysis of deviance (ANODEV) and asymptotic F-tests to test the significance of the same model term in (1) as in 2014 and 2015. We estimated deterrent effects for all bat species combined and for select species with adequate carcass counts in separate analyses.

We used the natural log of turbine operating hours, calculated as the sum-total of hours during nightly (1800–0630) treatment operations, as an offset to adjust for variation in operating hours between control and deterrent wind turbines within a 3-day trial. We obtained the study turbine operating data from the turbine control module in 10-minute averages, which we used to tally the number of hours each night each turbine was operating. Adjustment for turbine operating hours generally had little effect on the results because operating hours were very similar for control and deterrent treatments. In no year was the block-by-treatment interaction found to be significant ($P > 0.10$).

We estimated the $\hat{y}_{ijk}$ with unequal precision when the observed carcass counts were corrected for recovery efficiency in 2014 and 2015, so we used a weighted GLM, weighting (w_{ijk}) inversely proportional to the variance of $\ln(\hat{y}_{ijk})$ that is,

$$w_{ijk} = \frac{1}{\mathrm{Var}(\ln\hat{y}_{ijk})} \doteq \frac{1}{\mathrm{Var}(\hat{y}_{ijk}) \cdot \left(\frac{1}{y_{ijk}}\right)^2} \doteq \frac{1}{CV\,(\hat{y}_{ijk})^2} \tag{2}$$

where CV is the coefficient of variation for $\hat{y}_{ijk}$.

We directly estimated the relative effect of the deterrent compared with the control by $\widehat{\ln\tau}$ using a log-link and the response model equation (1) in the GLM analyses. We estimated the value of $\hat{\tau}$ by the back-transformation:

$$\hat{\tau} = e^{\widehat{\ln\tau}}$$

to estimate the proportional effect (i.e., τ = deterrent/control ratio) with estimated variance based on the delta method (Bishop et al. 1975:486–488; Seber 1982:7–9) where

$$\widehat{\mathrm{Var}}(\hat{\tau}) = \widehat{Var}\left(e^{\widehat{\ln\tau}}\right) \doteq \widehat{\mathrm{Var}}(\widehat{\ln\tau})\hat{\tau}^2. \tag{3}$$

The delta method also goes by the name "method of statistical differentials" (Kotz et al. 1988: 646–647). We then estimated the percent reduction in bat mortality due to the deterrent by $(1 - \hat{\tau})100\%$. The tests of deterrent effect were based on 1-tailed tests at $\alpha = 0.10$. A 1-tailed test was considered appropriate (Sokal and Rohlf 1995:168–169) in this context because the wind turbine industry is only interested in installing the acoustic equipment if it is proved to reduce the incidence of bat mortalities.

Bat carcasses are known to fall beyond a 60-m plot radius (Good et al. 2012, Huso and Dalthorp 2014), which was the plot size used in this study. Given this, and recognizing the potential for the deterrents to shift where bats collided with the turbine blades and subsequently where they fell within the plots, we therefore assessed the spatial distribution of carcasses recovered under control and treatment conditions. We tested the assumption of homogeneous spatial patterns by constructing the empirical cumulative distribution frequencies for the number of carcasses found by distance from the respective control and deterrent wind turbines within each year as well as pooled across years. We used the 2-sample Kolmagorov–Smirnov test to test for nonhomogeneous distributions between treatments and across years (Sokal and Rohlf 1981).

RESULTS

Bat Carcass Recoveries

In 2014, we found 322 bat carcasses from 5 species; 192 and 130 bat carcasses at control and treatment turbines, respectively (Table 3). In 2015, we found 426 bat carcasses from 6 bat species; 255 and 171 at control and treatment turbines, respectively. In 2016, we recovered 227 bat carcasses from 6 bat species and 1 unidentified species; 113 at control turbines and 114 at treatment turbines.

The most frequently found species was the eastern red bat, representing 47%, 58%, and 67% of all bats found in 2014, 2015, and 2016, respectively (Table 3). Hoary bats represented 22%, 17%, and 22% of the carcasses in 2014, 2015, and 2016, respectively. Silver-haired bats represented 26%, 20%, and 8% of the carcasses each year, respectively. Remaining bat species constituted <6% of the carcasses recovered in any year.

Calibration Trials

Overall carcass recovery probabilities (accounting for searcher efficiency and removal of carcasses by scavengers or other means) were estimated to be 0.882 ($\widehat{SE} = 0.024$), 0.954 ($\widehat{SE} = 0.016$), and 0.947 ($\widehat{SE} = 0.028$) in 2014, 2015, and 2016, respectively (Table 2).

The high recovery rates (from 0.882 to 0.954) resulted in calibration corrections for missed bat carcasses that were generally small. Moreover, the high rates of recovery also assured that carryover effects from one 3-day trial to the next were small.

Carcass Distribution

Within a test year, there were no differences in spatial distribution of bat carcasses within the search plots between control and deterrent treatments ($0.298 \leq P \leq 0.663$). Across years, there was no difference in bat carcass distributions between controls ($0.619 \leq P \leq 0.972$), nor between treatments ($0.164 \leq P \leq 0.884$; Fig. 2). These latter results allowed us to pool the carcass annual distribution data across years. There was also no difference in bat carcass distribution between pooled-year controls versus pooled-year deterrent treatments, ($P = 0.39$) and the cumulative distributions of the control and treatment recoveries are nearly identical (Fig. 2). This portion of our analysis indicates it was unlikely the deterrent on the treatment turbines created a shift in the carcass distribution that could have biased recovery numbers and subsequent evaluation of deterrent effects.

Deterrent Effectiveness

The constant signal deterrent system was effective in reducing overall bat fatalities in 2014 and 2015, with a 29.2% ($\widehat{SE} = 7.5\%$) reduction in 2014 and a 32.5% ($\widehat{SE} = 6.8\%$) reduction in 2015 ($P < 0.05$). The 2016 pulse signal effectiveness (1.7%, $\widehat{SE} = 13.1\%$) was not significant ($P = 0.45$; Table 4; Fig. 3).

For some bat species, deterrent effects were observed across multiple years. Hoary bat fatalities were reduced in all 3 years. In 2014 and 2015, the deterrent system reduced hoary bat fatalities an estimated 26.0% ($\widehat{SE} = 8.5\%$; $P = 0.007$) and 35.9% ($\widehat{SE} = 10.8\%$; $P = 0.001$), respectively. In 2016, hoary bat fatalities were reduced 33.5% ($\widehat{SE} = 19.4\%$; $P = 0.052$; Table 4; Fig. 3).

Table 3. Number of bat carcass recoveries by year, species, and treatment group during the deterrent systems deployed at the California Ridge Wind Energy Facility, Champaign and Vermilion counties, Illinois, USA, 2014–2016.

	2014[a]		2015[b]		2016[c]	
Species	**Control**	**Treatment**	**Control**	**Treatment**	**Control**	**Treatment**
Eastern red bat	84	66	131	117	68	85
Hoary bat	45	27	50	23	29	20
Silver-haired bat	53	31	59	27	14	4
Big brown bat	9	5	14	2	1	3
Little brown bat	0	0	1	1	0	0
Tri-colored bat	0	0	0	1	0	1
Evening bat	0	0	0	0	1	0
Myotis species	1	1	0	0	0	0
Unknown species	0	0	0	0	0	1
Total	192	130	255	171	113	114

[a] Sixteen turbines, constant-emission deterrent system only, 10 6-day study blocks.
[b] Sixteen turbines, constant-emission deterrent system only, 9 6-day study blocks.
[c] Twelve turbines, pulsed-emission deterrent system only, 9 6-day study blocks.

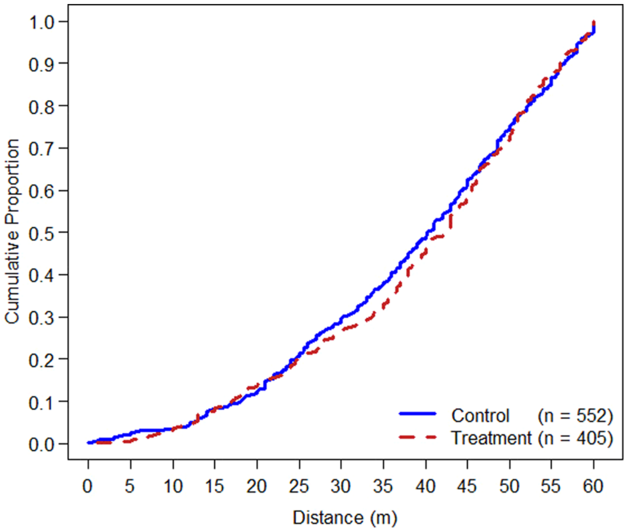

Figure 2. Cumulative distribution of bat carcasses as a function of distance (m) from plot center, by treatment. Data are pooled across years of the bat deterrent study at the California Ridge Wind Energy Facility, Champaign and Vermilion counties, Illinois, USA, 2014–2016.

Silver-haired bat fatalities were reduced in 2015 (56.9%, $\widehat{SE} = 9.9\%$; $P < 0.001$) and in 2016 (72.9%, $\widehat{SE} = 15.4\%$; $P = 0.001$). A reduction of 9.8% ($\widehat{SE} = 13.7\%$) was observed in 2014, but it was not significant ($P = 0.25$; Table 4; Fig. 3). Eastern red bat fatalities were reduced in 2014 (38.7%, $\widehat{SE} = 9.0\%$; $P < 0.001$), but not in 2015 (−2.5%, $\widehat{SE} = 10.8\%$; $P = 0.59$) or 2016 (−22.5%, $\widehat{SE} = 19.9\%$; $P = 0.86$ [Table 4; Fig. 3]).

DISCUSSION

The acoustic deterrent we tested, when emitting a constant signal, reduced bat fatalities by approximately 30%. Our results support the alternative hypothesis that the acoustic deterrent can effectively reduce bat fatalities and indicates deterrents are promising for use as an effective impact-minimization strategy. Furthermore, the fatality reductions we documented due to deterrence were in addition to reductions from feathering turbine blades below manufacturer's cut-in, which other research suggests can reduce fatalities by 35.0% to 57.5% and does not result in additional lost energy production (Baerwald et al. 2009, Young et al. 2013, Good et al. 2012).

Fatality reductions at the species level were determined to be an important factor of the overall effectiveness of the deterrent system. Across years, our data show that hoary bats were consistently deterred (~30% reductions in hoary bat fatalities each year), which was a welcome result considering recent suggestion by Frick et al. (2017) that population-level declines may occur as a result of wind energy generation. This may also have implications for wind-energy conservation planning in Hawaii, USA, which is the range of the endemic and endangered Hawaiian hoary bat (*Lasiurus cinereus semotus*; Amlin and Siddiqi 2015).

In 2014, eastern red bats were deterred but silver-haired bats were not, and in 2015 and 2016 the opposite occurred. Had eastern red bats and silver-haired bats either been deterred or not deterred in the same year, our conclusions about all-bat deterrent effectiveness might be different. Other studies have also indicated that eastern red bats are not deterred (Arnett et al. 2013*a*, C.D. Hein et al., National Renewable Energy Laboratory, unpublished data). The 2016 all-bat data led us to conclude that the deterrent was not effective in 2016; however, if eastern red bats are removed from the data set, the deterrent was >50% effective on the other species combined, and it was 33% and 73% effective for hoary bats and silver-haired bats, respectively.

It is unknown whether the type of emitter is an important factor in successful deterrence. Although our study and studies performed by Arnett et al. (2013*a*) and Weaver et al. (2019) indicate acoustic deterrents are effective, the

Table 4. Summary of percent relative reduction in bat fatalities due to the deterrent treatment ($1 - \hat{\tau}$), its standard error ($\widehat{SE}(1 - \hat{\tau})$), 90% confidence interval (CI), and P-value associated with the 1-tailed test of $H_0 : \tau \leq 0$ *vs* $\tau > 0$. Data are reported for all bat species combined and by species for the 3 most-frequently found species in the 2014–2016 study at the California Ridge Wind Energy Facility, Champaign and Vermilion counties, Illinois, USA.

Year (Deterrent signal)	Species group	$1 - \hat{\tau}$	$\widehat{SE}(1 - \hat{\tau})$	90% CI	P (1-tailed)
2014 (Constant)	All bats	29.18	7.49	15.71–40.49	0.001
	Eastern red bat	38.66	8.96	22.01–51.76	<0.001
	Hoary bat	25.98	8.54	10.51–38.78	0.007
	Silver haired bat	9.82	13.69	−15.76–29.75	0.252
2015 (Constant)	All bats	32.50	6.82	20.87–44.13	<0.001
	Eastern red bat	−2.48	10.82	−15.98–20.94	0.590
	Hoary bat	35.89	10.80	17.47–54.31	0.001
	Silver haired bat	56.93	9.91	40.02–73.84	<0.001
2016 (Pulse)	All bats	1.71	13.05	−21.17–24.59	0.449
	Eastern red bat	−22.51	19.94	−57.46–12.44	0.862
	Hoary bat	33.45	19.35	−0.47–67.37	0.052
	Silver haired bat	72.90	15.37	45.95–99.84	<0.001

Note: a negative value of τ estimates an increase in mortality.

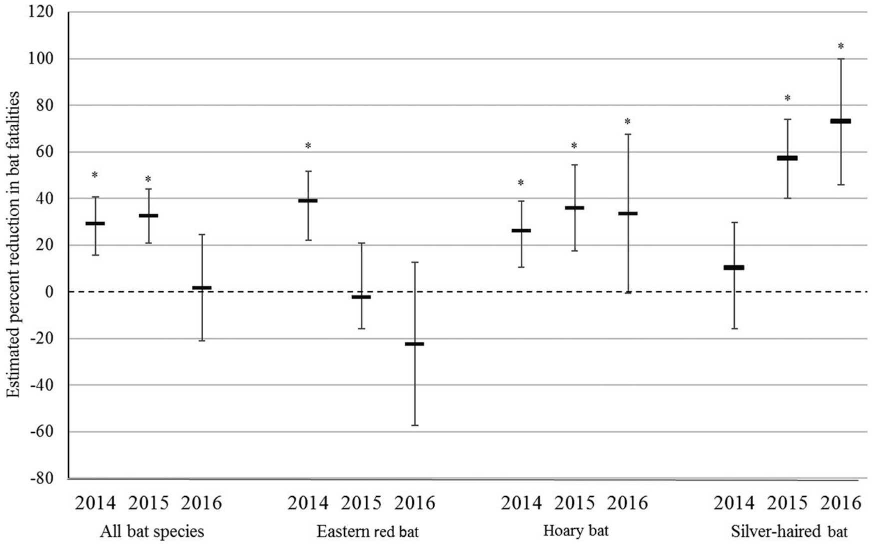

Figure 3. Point estimates of reduction in bat mortalities (percent), associated 90% confidence intervals by year for all bat species combined, eastern red bats, hoary bats, and silver-haired bats at the California Ridge Wind Energy Facility, Champaign and Vermilion counties, Illinois, USA, 2014–2016. Note interval estimates not crossing the $(1 - \tau) = 0$ line indicate significant at $\alpha = 0.05$, 1-tailed (*).

51% effectiveness result obtained by Arnett et al. (2013*a*) was inconclusive, whereas the approximately 30% and 50% results obtained from the current study and by Weaver et al. (2019) were conclusive. A major difference between this study and the other 2 was the type of transmitter used to generate the acoustic signal—the Arnett et al. (2013*a*) and Weaver et al. (2019) studies used speakers (transducers) to emit the acoustic signal, whereas the current study used ultrasonic jets. Jet-based emitters produce sound in a roughly ellipsoidal volume around the nozzle, whereas speakers produce a conical unidirectional sound directly in front of the speaker. The jet ensonifies approximately 10 times the airspace of the transducer, and therefore may create a larger warning zone for bats near moving rotors. Additionally, the pneumatic based system we tested operated reliably, with no faults during 3 years of study.

Other wildlife deterrence studies have demonstrated that target species often habituate to a source of deterrence (Koehler et al. 1990; Schakner and Blumstein 2013). However, several factors, and a closer look at the species-specific data, suggest that habituation was not a major factor affecting deterrent effectiveness in our study. We conducted the study each year during autumn migration, and while summering bats were likely still present in the study area and thus may have had time to habituate, some proportion of the study population were migrants and thus exposed to the deterrent during short-term flyovers or stopovers. Our data showed a relatively consistent ratio in numbers of bat carcasses at control and deterred turbines and no significant effect of study block was detected during the study, both of which also suggest that habituation is not occurring or is not occurring at a level that could be detected.

Our data are insufficient to provide within-year analyses of deterrent effectiveness over time (a possible approach to assessing whether within-year habituation is occurring). Within- and between-year changes in deterrent effectiveness, by species, at the scale of operating wind farms, is an important research question.

The interannual variation in our study results could be due to a nozzle placement effect, with eastern red bats using the higher airspace around the nacelle (and therefore being deterred when nozzles were mounted on nacelles in 2014) and silver-haired bats using the lower airspace around midtower height (and therefore being deterred when nozzles were mounted on towers in 2015 and 2016). However, nozzles were mounted on nacelles in 2016, and eastern red bats were not deterred, so clearly other factors (such as the introduction of a pulse signal) influenced species-specific deterrence.

Although the study cannot tell us exactly why a species was or was not deterred in a given year, we have demonstrated that species-specific effects are measurable, and we should work to understand the cause of these differences. For example, if the species-specific effects are due to deterrent system configurations, an improved understanding of species-specific use of the turbine airspace would allow for systems to target the airspace preferred by the focal species.

Our work provides a basis for more widespread use of deterrents to reduce wind energy impacts on bats. Based on our results, there are still numerous opportunities for future research to increase our understanding of bat deterrents in the wind energy industry, including a better understanding of effectiveness across technology types (e.g., transducers vs. ultrasonic jets), of effectiveness by species, and long-term deployment effects (e.g., if resident bats become habituated), a better understanding of species' use in and around turbine airspaces, and how environmental variables such as local habitat affect deterrent effectiveness.

Installing and operating acoustic deterrents at wind farms can be a cost-effective strategy for reducing effects to bats.

Current application of bat impact-reduction strategies is likely to remain site-specific for the foreseeable future. The strategy implemented at each site, and in some cases each turbine, depends on variables such as potential for presence of species of concern; requirement to curtail operations (raised cut-in speeds may be voluntary or regulatory); wind speed regime, temperature, or other environmental variables; and market characteristics such as power prices. Costs of raising cut-in speeds, the traditional impact-reduction strategy, varies based upon curtailment schedule, wind regime, and power price interactions; as such, it is difficult to prescribe a broad-brush threshold where deterrent costs will offset effects of raised cut-in speeds. However, deterrent costs will be competitive with raised cut-in speeds under some scenarios. In addition, deterrents may be a highly desirable strategy if deployment reduces the time and expense associated with procuring permits or other regulatory authorizations.

Finally, effects of any number of environmental factors, such as species composition and relative abundance, landscape and habitat, prey, weather, disease, and disturbance would elicit variation in species-specific responses and thus changes in deterrent effectiveness. Although it may be possible to isolate such variables in controlled experimental settings (e.g., flight rooms), the large spatial and temporal scales for research at operating wind farms makes controlling for these variables impossible. As such, we suggest that further deployment and testing of the deterrent, in different landscapes, with studies that are designed to detect species-level effects, be one focus of future research.

MANAGEMENT IMPLICATIONS

Finding effective alternatives to turbine curtailment, which results in lost renewable energy production, is important to both the wind energy industry and regulatory agencies to facilitate bat conservation while meeting public goals for renewable energy generation. Industry and regulatory stakeholders have adopted curtailment strategies that currently address conservation and energy production needs. However, the demand for electric power continues to increase, and increasing efficiency and operating power plants at a higher percentage of their installed capacity (in this case wind plants but the goal also applies to other types of power plants) will help meet this demand. Furthermore, the industry trend is toward large wind turbines to more efficiently capture low wind speeds and make sites of lower wind speed more productive; a negative byproduct of this strategy is that traditional curtailment strategies have an increasing effect on production. The effectiveness of a bat deterrent system deployed on larger turbines has yet to be tested, but this study provides evidence that targeting the areas of high bat activity below the nacelle and behind the tower can yield notable species-specific reductions. In addition, the bat deterrent system tested in this study could reduce bat mortalities without affecting power generation and, coupled with feathering below manufacturers' cut-in speed, should help achieve important bat conservation goals without impeding energy production.

ACKNOWLEDGMENTS

These investigations were supported by California Ridge Wind Energy LLC and GE in 2014, 2015, and 2016. In 2016, project funding was also provided by the U.S. Department of Energy under grant number DE-EE0007035 to GE. None of the authors have a vested interest in the acoustic deterrent system tested. W. B. Romano currently works for Invenergy LLC, while K. D. Coppinger has previously worked for the company. Both K. W. Kinzie and M. F. Miller work for GE. We would like to thank the Associate Editor of the Wildlife Society Bulletin and reviewers for their contributions toward this manuscript.

LITERATURE CITED

Addelman, S. 1969. The generalized randomized block design. The American Statistician 23(4):35–36.

Amlin, A., and A. Siddiqi. 2015. Endangered species recovery committee Hawaiian hoary bat guidance document. State of Hawai'i Department of Land and Natural Resources Division of Forestry and Wildlife, Honolulu, Hawaii, USA.

Arnett, E. B., E. F. Baerwald, F. Mathews, and C. C. Voigt. 2016. Impacts of wind energy development on bats: a global perspective. Pages 295–323 *in* C. Voigt and T. Kingston, editors. Bats in the anthropocene: conservation of bats in a changing world. Springer, Cham, Switzerland.

Arnett, E. B., W. K. Brown, W. P. Erickson, J. K. Fiedler, B. L. Hamilton, T. H. Henry, A. Jain, G. D. Johnson, J. Kerns, R. R. Koford, C. P. Nicholson, T. J. O'Connell, M. D. Piorkowski, and R. D. Tankersley. 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*a*. Evaluating the effectiveness of an ultrasonic acoustic deterrent for reducing bat fatalities at wind turbines. PLoS ONE 8(6):e65794.

Arnett, E. B., M. M. P. Huso, J. P. Hayes, and M. Schirmacher. 2010. Effectiveness of changing wind turbine cut-in speed to reduce bat fatalities at wind facilities. A final report submitted to the Bats and Wind Energy Cooperative. Bat Conservation International. Austin, Texas, USA.

Arnett, E. B., G. D. Johnson, W. P. Erickson, and C. D. Hein. 2013*b*. A synthesis of operational mitigation studies to reduce bat fatalities at wind energy facilities in North America. National Renewable Energy Laboratory, Golden, Colorado, USA.

Baerwald, E. F., J. 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.

Bat Conservation International. 2018. Species profiles database. <http://www.batcon.org/resources/media-education/species-profiles>. Accessed 24 Jun 2018.

Bennett, V. J., and A. M. Hale. 2018. Resource availability may not be a useful predictor of migratory bat fatalities or activity at wind turbines. Diversity 10(2).

Bishop, Y. M. M., S. E. Fienberg, and P. W. Holland. 1975. Discrete multivariate analysis. MIT Press, Cambridge, Massachusetts, USA.

Bomford, M., and P. H. O'Brien. 1990. Sonic deterrents in animal damage control: a review of device tests and effectiveness. Wildlife Society Bulletin 18:411–422.

Boyles, J. G., P. M. Cryan, G. F. McCracken, and T. H. Kunz. 2011. Economic importance of bats in agriculture. Science 332(6025):41–42.

Cochran, W. G. 1977. Sampling techniques. Wiley, New York, New York, USA.

Cryan, P. M., P. M. Gorresen, C. D. Hein, M. R. Schirmacher, R. H. Diehl, M. M. P. 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 Science 111(42):15126–15131.

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

Frick, W. F., E. F. Baerwald, J. F. Pollock, R. M. R. Barclay, J. A. Symanski, 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.

Good, R. E., G. Iskali, K. Nasman, and A. Ciecka. 2018. Bat evaluation monitoring studies at the Fowler Ridge Wind Farm, Benton County, Indiana, 1 August–15 October 2017. Fowler Ridge Wind Farm, Fowler, Indiana, USA. Prepared by Western EcoSystems Technology, Bloomington, Indiana, USA.

Good, R. E., A. Merrill, S. Simon, K. Murray, and K. Bay. 2012. Bat monitoring studies at the Fowler Ridge Wind Farm, Benton County, Indiana. Final Report: 1 April 1–31 October 2011. Prepared for Fowler Ridge Wind Farm, Fowler, Indiana, USA. Prepared by Western EcoSystems Technology, Bloomington, Indiana, USA.

Gruver, J., and L. Bishop-Boros. 2015. Summary and synthesis of myotis fatalities at wind facilities with a focus on northeastern North America. EDP Renewables North America, Houston, Texas, USA.

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

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 29(4):e01881.

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

Homer, C. G., J. A. Dewitz, L. Yang, S. Jin, P. Danielson, G. Xian, J. Coulston, N. D. Herold, J. D. Wickham, and K. Megown. 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.

Horn, J. W., E. B. Arnett, M. Jensen, and T. H. Kunz. 2008. Testing the effectiveness of an experimental acoustic bat deterrent at the Maple Ridge wind farm. Bats and Wind Energy Cooperative and Bat Conservation International, Austin, Texas, USA.

Hull, C. L., and S. Muir. 2010. Search areas 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., and D. Dalthorp. 2014. Accounting for unsearched areas in estimating wind turbine-caused fatality. Journal of Wildlife Management 78:347–358.

Kinzie, K. W., A. Hale, V. Bennett, W. B. Romano, J. R. Skalski, and K. D. Coppinger. 2018. Final technical report, ultrasonic bat deterrent technology. U. S. Department of Energy, DE-EE0007035.

Koehler, A. E., R. E. Marsh, and T. P. Salmon. 1990. Frightening methods and devices/stimuli to prevent mammal damage—a review. Proceedings of the 14th Vertebrate Pest Conference, 6–8 March 1990, Sacramento, California, USA.

Kotz, S., N. L. Johnson, and C. B. Read. 1988. The encyclopedia of statistical sciences, regressograms to St. Petersburg paradox. Volume 8. Wiley, New York, New York, USA.

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

Lindsey, C. T. 2017. Assessing changes in bat activity in response to an acoustic deterrent—implications for decreasing bat fatalities at wind facilities. Thesis, Texas Christian University, Fort Worth, USA.

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.

Mathews, F., M. Swindells, R. Goodhead, T. A. August, P. Hardman, D. M. Linton, and D. J. Hosken. 2013. Effectiveness of search dogs compared with human observers in locating bat carcasses at wind-turbine sites: a blinded randomized trial. Wildlife Society Bulletin 37:34–40.

McAlexander, A. 2013. Evidence that bats perceive wind turbine surfaces to be water. Thesis, College of Science and Engineering, Texas Christian University, Fort Worth, USA.

McCullagh, P., and J. A. Nelder. 1989. Generalised linear models. Second edition. Chapman & Hall, London, England, United Kingdom.

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

Schakner, Z. A., and D. T. Blumstein. 2013. Behavioral biology of marine mammal deterrents: a review and prospectus. Biological Conservation 167:380–389.

Schirmacher, M. R., A. Prichard, T. Mabee, and C. D. Hein. 2018. Evaluating a novel approach to optimize operational minimization to reduce bat fatalities at the Pinnacle Wind Farm, Mineral County, West Virginia, 2015. NRG Energy and the Bats and Wind Energy Cooperative. Prepared by Bat Conservation International, Austin, Texas, USA.

Seber, G. A. F. 1982. The estimation of animal abundance and related parameters. Edward Arnold, London, England, United Kingdom.

Smallwood, K. S., D. A. Bell, E. L. Walther, E. Leyvas, S. Standish, J. Mount, and B. Karas. 2018. Estimating wind turbine fatalities using integrated detection trials. Journal of Wildlife Management 82:1169–1184.

Snedecor, G. W., and W. G. Cochran. 1967. Statistical methods. Iowa State University Press, Ames, USA.

Sokal, R. R., and F. J. Rohlf. 1981. Biometry. Freeman and Company, New York, New York, USA.

Sokal, R. R., and F. J. Rohlf. 1995. Biometry: the principles and practice of statistics in biological research. Third edition. Freeman and Company, New York, New York, USA.

Szewczak, J. M., and E. B. Arnett. 2007. Field test results of a potential acoustic deterrent to reduce bat mortality from wind turbines. Bats and Wind Energy Cooperative. Prepared by Bat Conservation International, Austin, Texas, USA.

U.S. Department of Energy. 2014. Office of Energy Efficiency and Renewable Energy (EERE) wind energy—bat impact minimization technologies and field testing opportunities. Funding Opportunity Announcement (FOA) Number: DE-FOA-0001181. U.S. Department of Energy, Washington, D.C., USA.

U.S. Fish and Wildlife Service. 1973. Endangered Species Act of 1973, as amended, Pub. L. No. 93-205, 87 Stat. 884 (Dec. 28, 1973). http://www.fws.gov/endangered/esa-library/pdf/ESAall.pdf

U.S. Fish and Wildlife Service. 2016*a*. Endangered and threatened wildlife; 4(d) rule for the northern long-eared bat, final rule. Federal Register 81(9):1900–1922, U.S. Fish and Wildlife Service, Washington, D.C., USA.

U.S. Fish and Wildlife Service. 2016*b*. National listing workplan—7-year workplan. <https://www.fws.gov/endangered/what-we-do/listing-workplan.html>. Accessed 15 Sep 2016.

University of Michigan, Museum of Zoology. 2014. Animal diversity web species database, vespertilionidae. <https://animaldiversity.org/accounts/Vespertilionidae>. Accessed 5 Aug 2018.

Weaver, S., I. Castro-Arellano, T. Simpson, and C. Hein. 2019. Testing ultrasonic acoustic deterrents for reducing bat fatalities at wind turbines in south Texas. Proceedings of the National Wind Coordinating Collaborative, Wind-Wildlife Research Meeting, XII, 27–30 November 2018, St. Paul, Minnesota, USA. National Wind Coordinating Collaborative, Washington, D.C., USA.

Wilk, M. 1955. The randomization analysis of a generalized randomized block design. Biometrika 42:70–79.

Woods, A. J., J. M. Omernik, C. L. Pederson, and B. C. Moran. 2007. Ecoregions of Illinois. U.S. Geological Survey. <https://www.epa.gov/eco-research/ecoregion-download-files-state-region-5#pane-11>.

Young, D., C. Nations, M. Lout, and K. Bay. 2013. 2012 post-construction monitoring study criterion wind project Garrett County, Maryland, April–November 2012. Criterion Power Partners, LLC, Oakland, Maryland, USA. Prepared by: Western EcoSystems Technology, Cheyenne, Wyoming and Waterbury, Vermont, USA.

Associate Editor: Ober.

SUPPORTING INFORMATION

Additional supporting information on the methods used to convert raw carcass counts into estimates of bat mortalities based on the maximum likelihood method may be found in the Appendix of the online version of this article.