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NOTE

Curtailment and acoustic deterrents reduce bat mortality at wind farms

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Abstract

The impacts of wind energy on bat populations is a growing concern because wind turbine blades can strike and kill bats, and wind turbine development is increasing. We tested the effectiveness of 2 management actions at 2 wind-energy facilities for reducing bat fatalities: curtailing turbine operation when wind speeds were <5.0 m/second and combining curtailment with an acoustic bat deterrent developed by NRG Systems. We measured the effectiveness of the management actions using differences in counts of bat carcasses quantified by daily and twice-per-week standardized carcass searches of cleared plots below turbines, and field trials that estimated searcher efficiency and carcass persistence. We studied turbines located at 2 adjacent wind-energy facilities in northeast Illinois, USA, during fall migration (1 Aug–15 Oct) in 2018. We estimated the effectiveness of each management action using a generalized linear mixed-effects model with several covariates. Curtailment alone reduced overall bat mortality by 42.5% but did not reduce silver-haired bat (*Lasionycteris noctivagans*) mortality. Overall bat fatality rates were 66.9% lower at curtailed turbines with acoustic deterrents compared to turbines that operated at manufacturer cut-in speed. Curtailment and the deterrent reduced bat mortality to varying degrees between species, ranging from 58.1% for eastern red bats (*Lasiurus borealis*) to 94.4 for big brown bats (*Eptesicus fuscus*). Hoary (*Lasiurus cinereus*) and silver-haired bat mortality was reduced by 71.4% and 71.6%, respectively. Our

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study lacked a deterrent-only treatment group because of the expense of acoustic deterrents. We estimated the additional reduction in mortality with concurrent deployment of the acoustic deterrent and curtailment under the assumption that curtailment and the acoustic deterrent would have reduced mortality by the same percentage at adjacent wind-energy facilities. Acoustic deterrents resulted in 31.6%, 17.4%, and 66.7% additional reductions of bat mortality compared to curtailment alone for eastern red bat, hoary bat, and silver-haired bat, respectively. The effectiveness of acoustic deterrents for reducing bat mortality at turbines with rotor-swept area diameters >110 m is unknown because high frequency sound attenuates quickly, which reduces coverage of rotor-swept areas. Management actions should consider species differences in the ability of curtailment and deterrents to reduce bat mortality and increase energy production.

KEYWORDS
acoustic, bat, curtailment, deterrent, Illinois, mortality, turbine, wind

Wind energy is a domestic, carbon-free source of energy production and an important measure to reduce the effects of climate change (Gielen et al. 2019). But the potential effects of wind energy on bat populations are a growing concern (Frick et al. 2017). The primary means by which the wind industry reduces bat mortality is wind turbine curtailment. Wind turbine curtailment, also known as blade feathering, is a strategy that prevents turbines from spinning at night at speeds >1–2 rotations/minute, when wind speeds are below a pre-determined value. Wind turbine curtailment reduces fatalities of nearly all bat species affected by wind turbines (Arnett et al. 2013*b*, Martin et al. 2017, Adams et al. 2021). Curtailment (i.e., cut-in speed curtailment) results in lost energy production at night and causes adverse impacts on wind project economics if not optimized. The wind industry needs strategies to reduce bat mortality while minimizing energy lost from curtailment. Discouraging bats from using areas near turbine blades by emitting high-frequency sounds from acoustic deterrents also reduces bat mortality (Arnett et al. 2013*a*, Romano et al. 2019, Weaver et al. 2020). The effectiveness of acoustic deterrents is limited because high-frequency sound attenuates quickly. Arnett et al. (2013*a*) estimated that the high-frequency sound emitted from older versions of acoustic deterrents traveled 20 m under typical conditions in Pennsylvania, USA. Turbines installed at wind-energy projects in 2019 in North America typically have blades that range from 45–60 m in length; thus, acoustic deterrents mounted on turbine nacelles or towers would not be able to emit high-frequency sound that covers the entire length of typical modern turbine blades. The effectiveness of combining cut-in speed curtailment with the acoustic deterrents to further reduce bat mortality has not been tested in North America.

We completed a study in the fall of 2018 to determine whether wind-energy operators could achieve additional reductions in bat fatality when they added NRG Systems (NRGS) acoustic bat deterrents to turbines already curtailed. We predicted that turbines outfitted with acoustic bat deterrents and curtailed when wind speeds were <5.0 m/second would result in additional reductions in bat mortality relative to turbines that were curtailed but not outfitted with acoustic deterrents, and relative to turbines that operated at manufacturer cut-in speed.

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STUDY AREA

We completed the experiment at 2 adjacent wind-energy facilities in northeastern Illinois: the Pilot Hill Wind Farm (PHWF) and the Kelly Creek Wind Farm (KCWF; Figure 1). The experiment occurred from 1 August–15 October 2018, which encompasses the annual period when bat mortality is highest in the United States (Arnett et al. 2008). The PHWF became operational in fall of 2015 and consisted of 91 1.79-megawatt (MW) and 12 1.85-MW wind

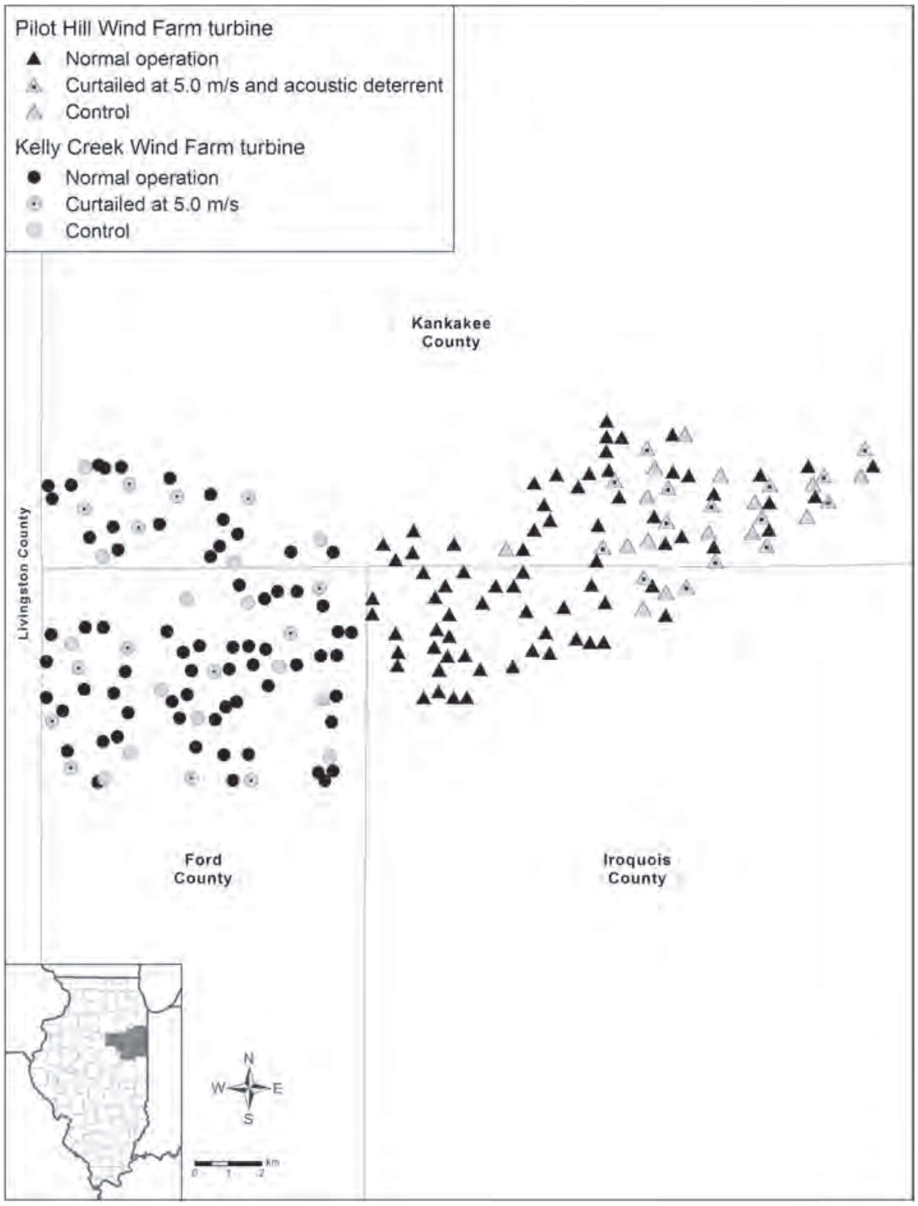

FIGURE 1 The location of the Pilot Hill and Kelly Creek Wind Farms in northeast Illinois, USA, where we measured bat mortality from 1 August–15 October 2018.

turbines. Each turbine had an 80-m hub height; the 1.79-MW turbines had an 87-m rotor diameter and the 1.85-MW turbines had a 100-m rotor diameter. The KCWF became operational in early 2017 and consisted of 92 2.0-MW wind turbines with a 98-m rotor diameter and 80-m hub height. All turbines at KCWF and PHWF had a manufacturer cut-in speed of 3.0 m/second.

The PHWF and KCWF are located in flat topography (~233–366 m) and comprised 8,277 ha and 9,791 ha, respectively, of land within 1.0 km of turbines. Tilled agriculture and developed areas comprised >98% of the land cover within 1.0 km from turbines (Multi-Resolution Land Characteristics Consortium 2019). The remaining area (<2.0%) was composed of small areas of hay and pasture, deciduous forest, herbaceous land, and woody wetlands. Northern Illinois experiences relatively cold winters (Dec–Feb) and warm summers (Jun–Aug), with frequent but short changes in temperature, precipitation, and cloud cover. Mean temperatures and monthly precipitation totals from August through October range from 11–22°C and 7.9–8.4 cm, respectively (University of Illinois 2010). Thirteen species of bats occur within Illinois (Feldhamer et al. 2015), of which the hoary bat (*Lasiurus cinereus*), silver-haired bat (*Lasionycteris noctivagans*), eastern red bat (*Lasiurus borealis*), and big brown bat (*Eptesicus fuscus*) are the most common fatalities at Illinois wind-energy facilities (Romano et al. 2019).

METHODS

Carcass surveys and bat deterrents

We implemented an incomplete block experimental design (Wallis 2016) to assess the effectiveness of the acoustic bat deterrent and curtailment. Incomplete block designs have a long history of application, especially in marketing and agricultural settings (Cochran and Cox 1957, Patterson and Williams 1976) where treatment application is expensive or difficult to manage in more traditional designs (e.g., complete blocks). We chose an incomplete block design because the deterrent systems were expensive, difficult to install, and difficult to manage. The 2 adjacent wind farms operated under different local requirements making implementation of all 3 treatments at both facilities difficult. Search and bias trial frequency varied between the 2 facilities but were sufficient to characterize carcass counts after adjustments for between study differences. Hence, we viewed facilities as experimental blocks and implemented 2 of the 3 experimental groups at each. In the first block (PHWF), we randomly picked and outfitted 15 turbines with acoustic deterrent systems and operated the turbines under a 5.0 m/second curtailment regime. We randomly chose 15 different turbines at PHWF to operate at the manufacturer's cut-in speed (3.0 m/sec). In the second block (KCWF), we randomly chose 15 turbines to operate under a 5.0 m/second curtailment regime (no deterrent) and 15 different turbines to operate at the manufacturer's cut-in speed (3.0 m/sec).

We selected turbines for the study using a systematic sample with a random start. The study was limited to turbines within the eastern half of PHWF to reduce costs associated with the installation and operation of the acoustic bat deterrent. Both PHWF and KCWF lack features that would cause spatial variation in bat fatality. We separated treatment and control turbines at PHWF by ≥400 m to minimize the likelihood that acoustic treatments affected nearby control group turbines. All turbines were available for selection at KCWF (Figure 1).

We used standardized searches under turbines to count the number of bat carcasses found at treatment and control turbines. We searched all turbines within an 80-m radius of the turbine base at the PHWF and within a 60-m radius at KCWF. The radius of searches differed between PHWF and KCWF because the 2 facilities differed in post-construction monitoring requirements. We searched 10 control turbines daily, and 5 control and all 15 treatment turbines 2 times/week at PHWF. We searched all control and treatment turbines weekly at KCWF. A contractor mowed vegetation within each search plot regularly to a height of approximately 10 cm to increase the probability of searchers detecting carcasses. We completed a clearing search prior to the study from 26–31 July 2018 to remove carcasses estimated to have died prior to the beginning of the study. We trained field technicians in proper search techniques prior to conducting carcass searches. Technicians began searches at first light and ended by 1700. Technicians walked transects perpendicular to turbines, spaced 5 m apart at a rate of approximately 45–60 m/minute along each transect, and scanned the area on both sides out to approximately 2.5 m for carcasses, thereby surveying the entire search area. We marked the beginning, end, and middle of each transect to ensure technicians stayed on transects while searching for carcasses.

We measured the probability that field technicians would detect a carcass during blind searcher efficiency trials. We placed 60 bat carcasses on 6 days at PHWF, and 30 bat carcasses on 3 days at KCWF. We used fresh silver-haired, eastern red, and hoary bat carcasses that only exhibited signs of early decomposition found on site, and evenly distributed them between treatment and control turbines. We discreetly marked each trial carcass with a black zip tie around the upper forelimb for identification as a searcher efficiency carcass, and placed carcasses randomly within the same plots searched for carcasses. We dropped carcasses from waist height or higher and allowed them to land in a random posture. Technicians conducting carcass searches did not know when searcher efficiency carcasses were placed or the location of the carcasses. The trial administrator recorded the number and location of carcasses found during the subsequent carcass search, and the number of carcasses available for detection. The trial administrator placed ≤2 carcasses at an individual turbine during a trial.

Carcasses could be removed by scavenging or rendered undetectable to technicians by plot mowing or other farming activities. We measured the amount of time a carcass persisted and was available to be detected during 4 trials at PHWF using 40 bat carcasses, and during 2 trials at KCWF using 20 bat carcasses. We monitored the bat carcasses over a 30-day period, checking carcasses every day for the first 4 days and then on days 7, 10, 14, 20, and 30 after placement. We left bat carcasses at the location until the carcass was removed by scavengers or farming, the carcass was completely decomposed, or at the end of the carcass persistence trial, whichever occurred first. We removed the carcasses that remained at the end of the 30-day period.

A team at NRGS developed and installed a prototype acoustic bat deterrent at 15 wind turbines at the PHWF prior to the study and activated the deterrents on the night of 31 July 2018. Each deterrent system consisted of 8 sound projection units, a controller, cables, power supply, and a communication device that allowed NRGS to monitor the system status. The acoustic deterrent system was designed to produce ultrasonic sounds with frequencies between 20 kilohertz (kHz) and 50 kHz that enveloped large portions of the rotor-swept area of each treated turbine, with lower frequencies covering more and higher frequencies less of the rotor-swept area (NRGS 2021). The deterrent system produced frequencies that overlapped with the frequencies of calls produced by nearly all North American bat species (Britzke et al. 2011, Szewczak et al. 2011). The team from NRGS mounted acoustic deterrents on the outer surface of the wind turbine nacelle and tower, and oriented deterrents toward the rotor-swept area.

Carcass persistence, searcher efficiency, and search area adjustments

We estimated persistence rates to adjust carcass counts for carcasses that did not remain detectable during the study. We modeled carcass persistence rates as a function of turbine operation (control vs. treatment turbines). We estimated carcass persistence from an interval-censored carcass persistence model (Bispo et al. 2013). We fitted exponential, log-logistic, lognormal, and Weibull distributions to individual carcass persistence times and selected the best-fitting distribution using corrected Akaike's Information Criterion (AIC_c; Burnham and Anderson 2002).

We estimated searcher efficiency rates using logistic regression fitted to carcass trial data both without covariates (intercept only) and with turbine operation (control vs. treatment turbines) as the only covariate. We selected the best fitting logistic regression between the 2 models using AIC_c.

The area searched underneath turbines represented a sample of the area in which carcasses could land. Carcasses do not fall a uniform distance from the turbine, and bat carcasses tend to occur at higher density near the turbine (Huso and Dalthorp 2014). We accounted for carcasses that could have fallen outside our search plots by modeling the carcass fall distribution as a function of distance from the turbine and weighting by the proportion of

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each distance band we searched. Given an estimate of the carcass fall distribution, $f(x)$, we computed the area adjustment of the fatality estimate as

$$\hat{a} = \int_0^\infty f(x)\pi(x)dx \approx \sum_{j=1}^{r}(F(j) - F(j-1))a(j),$$

where $\hat{a}$ was the estimated area adjustment factor, $\pi(x)$ was the proportion of the area included in the search area at distance x, j indexed a concentric series of 1-m-wide annuli centered on the turbine, r was the number 1-m-wide annuli between the minimum and maximum search radius (i.e., maximum search radius when using 1-m annuli), $F(j)$ was the probability of a carcass falling between distance zero and distance j, and $a(j)$ was the fraction of the jth annulus that was searched. We estimated the carcass fall distribution, $f(x)$, by fitting truncated Weibull, truncated normal, truncated Gompertz, truncated Rayleigh, and truncated gamma density distributions, where all were truncated to the region between zero and the maximum search distances (r). We selected among these models using AIC_c scores. Following estimation of $f(x)$, we removed the upper truncation bound and summed $(F(j) - F(j-1))a(j)$ until this product was functionally zero (i.e., $<1^{\text{e-8}}$). Hence, we made no assumption about maximum fall distance of a carcass.

We obtained fits of $f(x)$ using a weighted maximum likelihood approach (Khokan et al. 2013). We modeled area corrections separately for control and treatment turbines at each facility We assigned weights based on calculated detection probabilities using searcher efficiency and carcass persistence. Weights were the inverse of the fraction of area searched at the carcass's distance multiplied by the inverse of the probability of detection for that carcass. Thus, these weights adjusted the number of carcasses at each distance for the detection probability at that distance. The area correction method we implemented allowed us to adjust carcasses found on both plot sizes (80 m for PHWF, 60 m for KCWF) to a similar scale. In combination, the searcher efficiency rate, probability of carcass persistence, and the area correction represent an offset term for probability of detection, which we include in the statistical model described below.

Treatment analysis

We estimated effect sizes using generalized linear mixed-effect models (GLMM; Laird and Ware 1982, Pinheiro and Bates 2000, Millar 2011). Our GLMM contained an experimental group factor (curtailment + deterrent, curtailment only, and control), a facility factor (PHWF, KCWF), an offset term, and environmental variables common to both facilities that could have influenced bat mortality (Table 1). We gathered environmental variables from 3 meteorological towers at PHWF and KCWF. We included a facility factor to account for potential differences in the average density of bats between projects. We summarized the fatality data to a weekly time scale to account for different search intervals at KCWF and PHWF.

Our block design was incomplete because we lacked an acoustic deterrent-only group at both facilities, and we lacked a curtailment-only group at the PHWF. To estimate the potential additional reduction in bat mortality resulting from adding the NRGS acoustic deterrent to curtailment, we assumed the reduction in bat fatalities from curtailment at the KCWF also occurred at the PHWF. We applied the percent reduction due to curtailment only at KCWF to PHWF to estimate the additional reduction acoustic deterrents provided when added to curtailment.

We fit an incomplete block GLMM to weekly turbine-level carcass counts to evaluate the percent reduction in fatalities between turbines that operated under the PHWF treatment (5.0 m/sec cut-in speed + acoustic deterrent), under the KCWF treatment (5.0 m/sec cut-in speed), and to turbines that operated as controls (3.0 m/sec manufacturer cut-in speed). We also included non-experimental factors that could affect carcass counts and may be confounded with treatments, such as wind speed or temperature. We identified the best combination of non-treatment factors that helped explain variation in the data and helped ensure the treatment effects were not

TABLE 1 Covariates included and considered for inclusion in the generalized linear mixed model. Primary interest lay in percent reduction of bat mortality between treatment and control turbines (turbine operation) at the Kelly Creek and Pilot Hill Wind Farms, northeast Illinois, USA, from 1 August–15 October 2018.

Variable and units	Covariate description
Turbine operation	Three categories: 3.0 m/sec operation (control), curtailment below 5.0 m/sec + acoustic deterrent (treatment: Pilot Hill Wind Farm [PCWF] only), and below 5.0 m/sec only (Kelly Creek Wind Farm [KCWF] only).
Search location	Turbine identification used as a random effect.
Project	Indicator for KCWF or PHWF.
Offset	Area correction value calculated on a per-turbine basis, searcher efficiency value, and carcass removal rate dependent on the time between searches between visits to each turbine.
Visit	Integer representing the first, second, third, …eleventh visit to a turbine.
Mean wind speed (m/sec)	Average wind speed for the past 6 nights (e.g., if the carcass search date was 8 Aug, the wind speed was averaged from 7 Aug 1800 to 8 Aug 0700 and the 5 nights prior).
Mean wind speed categorized	Average wind speed of the previous 6 nights binned into very low (<3.5 m/sec), low (3.5–5.0 m/sec), high (5.0–7.0 m/sec), very high (>7.0 m/sec).
Mean wind direction (degrees)	Average wind direction for the past 6 nights.
Mean wind direction of cardinal	Average wind direction of cardinal for the past 6 nights.
Mean temp (°C)	Average temp for the past 6 nights.
Mean humidity (percentage)	Average humidity for the past 6 nights.
Mean precipitation (mm)	Average precipitation for the past 6 nights.
Max barometric pressure changes (millibars)	Max. barometric pressure change from 6, 12, 24, 36, or 48 hrs for the past 6 nights.
Sine(visit)	Trigonometric sine function applied as Sine(π × [Visit-1]/10).
Spline(visit)	Cubic (degree = 3) polynomials basis splines with 1, 2, and 3 internal knots.

confounded with non-treatment factors. We fitted the GLMM to counts of all species, and to counts for individual bat species with sufficient sample sizes ($n > 4$ carcasses found).

The general form of the GLMM model was

$$h(E[C_{ij}]) = \eta_{ij} = \beta_0 + \beta_1 X_{1ij} + \beta_2 X_{2ij} + \cdots + \beta_p X_{pij} + a_i + b_j + \log(Offset_{ij}),$$

where $h(.)$ was the log-link function that transformed the expected count ($E[C_{ij}]$) into the linear predictor, η_{ij};i was an index for each turbine; j was an index for 7-day periods after initiation of searches; C_{ij} was the un-inflated number of carcasses found at turbine i observed during searches that occurred during the jth 7-day period after initiation of searches; $\beta_0, \ldots, \beta_p$ were the regression coefficients associated with the p predictors; $X_{1ij}, X_{2ij}, \ldots, X_{pij}$ were the p predictors associated with counts at a turbine during the jth 7-day period (Table 1); a_i was the random intercept for turbine i; b_j was an optional random effect of the jth 7-day period; and $\log(Offset_{ij})$ was an offset term that adjusted for differences in inflation factors of each turbine and each period based on searcher efficiency, carcass removal, and the density-weighted proportion (DWP) for each turbine. We assumed the random effects were independent and identically distributed normal random variables with mean zero and variances σ_a^2 and σ_b^2, respectively. The fixed effects portion of the model (coefficients β_0, β_1, …, β_p) estimated treatment effects, facility effects, and associations between the study covariates and weekly carcass counts. We did not include a treatment by facility interaction term in the fixed part of the model, which effectively assumed equal treatment effects at both facilities. Without the interaction, all treatment effects were estimable even though we lacked deterrent-only turbines. Primary interest lay in the test of the treatment effects (turbine operation; Table 1) against a coefficient value of zero, which represented no effect on bat fatality. For each 7-day period, we aggregated environmental covariates over the previous 6 nights to mimic those covariates affecting the largest average search interval used in the study.

We assumed C_{ij} followed the negative binomial distribution. To account for over-dispersion due to a large proportion of zeros, we considered the zero-inflated negative binomial distribution. We used the glmmTMB package (Brooks et al. 2017) in the R statistical software environment (R Core Team 2019) to generate models. We considered several variance structures for the negative binomial GLMM to account for correlation among counts observed over time at the same turbine (serial correlation) and for correlation among turbines visited at the same time (spatial correlation). We considered a first-order auto-regressive process with autoregressive parameters estimated either by turbine or across all turbines. We selected the final variance structure based on AIC$_c$, residual diagnostic plots, and successful convergence. We modeled potential over-dispersion by assuming either a linear relationship between the mean and the variance (nbinom1 in glmmTMB) or by assuming a quadratic relationship (nbinom2 in glmmTMB).

We identified the best fitting subset of non-experimental factors using standard AIC$_c$ methods (Burnham and Anderson 2002). The initial model included the offset terms, random turbine effect (search location), the treatment factor (turbine operation), and a project factor (PHWF or KCWF). These effects were present in all models. We then added the sine of the search period's date, a seasonal effect fit via a spline, and environmental covariates (Table 1) in separate models. We used the spline effect to remove nuisance temporal variability from the percent reduction estimate and consequently increase power for estimation of treatment effects. We also fitted the models with standardized ($\frac{x_i - \bar{x}}{\sigma}$) non-treatment predictor variables for the selected model of each species to calculate effect sizes associated with those variables.

RESULTS

Overall searcher efficiency rates were 48.3% (90% CI = 38.3–58.3%) at the PHWF and 63% (90% CI = 50.0–77.0%) at the KCWF. Turbine operation was not included in the top searcher efficiency model at either PHWF or KCWF, indicating searcher efficiency rates did not vary between control and treatment turbines. Likewise, turbine operation was not included in the top persistence model, indicating carcass persistence did not vary between control and treatment turbines at PHWF or KCWF. Bat carcasses persisted on average 11.7 days (90% CI = 8.0–18.6 days) at the PHWF and 24.7 days (90% CI = 15.8–39.0 days) at the KCWF.

Adjustment for searched area results

The best-fit search area distribution for the PHWF control turbines was a truncated normal distribution and the best-fit distribution for the PHWF treatment turbines was a truncated Weibull distribution (Table 2). The DWP for the PHWF control turbines was 0.97, or 97% of potential bat carcasses were expected to fall within the 80-m control turbine plots, compared to 0.95, or 95% at 80-m treatment turbine plots (Table 2). The confidence intervals

TABLE 2 Descriptions of models, parameters, and estimated proportion of bat carcasses that fell within search plots using the truncated weighted likelihood method at the Pilot Hill (PHWF) and Kelly Creek Wind Farms (KCWF), northeast Illinois, USA, from 1 August–15 October 2018.

Treatment	Distribution	Parameter 1	Parameter 2	Area correction (90% CI)
PHWF: control (3.0 m/sec cut-in speed)	Normal	31.04	20.65	0.97 (0.94–0.97)
PHWF: treatment (curtailment below 5.0 m/sec + acoustic deterrent)	Weibull	2.42	42.96	0.95 (0.92–0.97)
KCWF: control (3.0 m/sec cut-in speed) and treatment (curtailment below 5.0 m/sec)	Normal	39.75	22.31	0.76 (0.40–0.90)

for the PHWF control and treatment turbine DWP estimates overlapped, which indicated there was not a meaningful difference between the carcass fall distributions for the 2 treatments.

The estimated area correction for control turbines at KCWF predicted an unusually large proportion of carcasses (i.e., >40%) fell beyond 150 m. Hull and Muir (2010) used a physics-based model to predict that 100% of bats fall within 72 m of turbines with a 50-m blade length and 80-m hub height. In addition, the mean fall distance from the raw carcass data of bats from treatment and control turbines were similar (32.5 m for control turbines vs. 32.6 m for treatment turbines). For these reasons, we fit 1 area correction model to both control and treatment turbines. When we combined treatment and control turbines, the best-fit distribution for the area adjustment was the truncated normal distribution. The DWP for KCWF control and treatment turbines was 0.76 (90% CI = 0.400–0.90), or 76% of potential bat carcasses were expected to fall within the 60-m cleared plots (Table 2).

Treatment analysis

The number of carcasses available for GLMM estimation that compared treatment and control turbines at the PHWF and KCWF ranged from 1 to 152 when summarized by species and treatment group (Table 3), after the exclusion of carcasses estimated to have died before the study period or found outside of the search areas.

We included treatment in all models (Appendix A) to estimate the reduction in mortality afforded by the curtailment-only treatment and the curtailment plus acoustic deterrent treatments relative to control turbines. We also included project in all models to estimate the difference in magnitude of bat mortality between KCWF and PHWF. We report the covariates included in the top model for each species and provide standardized coefficient values for all numeric, non-treatment covariates (Table A6) but focus on the estimated treatment effects.

In addition to the treatment effect (included in all models), the top model for all bat species included the following variables: average wind speed (m/sec) over the previous 6 nights, average wind direction over the previous 6 nights, instantaneous rain over the previous 6 nights, maximum barometric pressure change over the previous 6 nights, and a spline seasonal effect that varied based on the project (Table A1). The best model for eastern red bats included wind direction and a spline effect that varied based on the project (Table A2). The best model fitted to hoary bats included average humidity over the previous 6 nights and a spline effect (Table A3). The silver-haired bat model included wind direction over the previous 6 nights, instantaneous rain over the previous 6 nights, and a spline effect (Table A4). The big brown bat model contained only average wind speed over the previous 6 nights, and the model was fitted only to PHWF data because of the low number of bat carcasses (*n* = 1) observed at the KCWF (Table A5).

TABLE 3 Number of bat carcasses found at control and treatment turbines at Kelly Creek (KCWF) and Pilot Hill (PHWF) Wind Farms, northeast Illinois, USA, from 1 August–15 October 2018 that we used to estimate the effectiveness of curtailment and acoustic deterrents for reducing bat mortality. Carcasses included in the analysis died during the study and were found within the search areas.

Species	Treatment[a,b]	Facility	Number of carcasses
Big brown bat	Curtailment + acoustic deterrent	PHWF	1
Big brown bat	Control	PHWF	23
Eastern red bat	Curtailment	KCWF	30
Eastern red bat	Curtailment + acoustic deterrent	PHWF	58
Eastern red bat	Control	KCWF	49
Eastern red bat	Control	PHWF	152
Hoary bat	Curtailment	KCWF	12
Hoary bat	Curtailment + acoustic deterrent	PHWF	29
Hoary bat	Control	KCWF	33
Hoary bat	Control	PHWF	102
Silver-haired bat	Curtailment	KCWF	25
Silver-haired bat	Curtailment + acoustic deterrent	PHWF	28
Silver-haired bat	Control	KCWF	31
Silver-haired bat	Control	PHWF	99
Total bats at curtailment[a] turbines		KCWF	69
Total bats at curtailment[a] + acoustic deterrent turbines		PHWF	118
Total bats at control[b] turbines		KCWF	117
		PHWF	377
Total all bats		Both	681

[a] Curtailment = turbines feathered below 5.0 m/sec wind speed.

[b] Control = 3.0 m/sec cut-in speed.

Combining curtailment with the acoustic deterrent reduced mortality for all bat species compared to control groups (Table 4). Curtailment alone resulted in smaller reductions in mortality of all bats (Figure 2), eastern red bats (Figure 3), and hoary bats (Figure 4). Curtailment did not reduce silver-haired bat mortality, but the addition of the acoustic deterrent to curtailment reduced silver-haired bat mortality (Figure 5). Combining curtailment with acoustic deterrents reduced big brown bat mortality to the largest extent relative to other species (Figure 6).

Our study lacked a deterrent-only treatment. With the addition of KCWF into the analysis, it was possible to estimate the multiplicative effect of the acoustic deterrent above that of curtailment only. By not including a treatment by facility interaction in the GLMM, we effectively assumed that the percent reduction of mortality from curtailment was the same at PHWF as measured at the KCWF. Both facilities have cut-in speeds of 3.0 m/second, are located adjacent to each other, and we would expect the effectiveness of curtailment to be similar at both sites. For all bats combined and for silver-haired bats, we observed fewer fatalities when acoustic deterrents were added to curtailed turbines (Table 5; 90% CIs do not include zero). The addition of the acoustic deterrent also reduced eastern red bats and hoary bat fatalities; however, the 90% confidence intervals included zero, which suggested

TABLE 4 The estimated reduction in bat mortality of each treatment group at the Pilot Hill (PHWF) and Kelly Creek (KCWF) Wind Farms, northeast Illinois, USA, compared to turbines that operated at manufacturer cut-in speed from 1 August–15 October 2018.

Treatment[a]	Group or species	Facility	Point estimate	90% CI
Curtailment and deterrent	All bats	PHWF	66.9%	54.5–75.9%
Curtailment only	All bats	KCWF	42.5%	16.1–60.6%
Curtailment and deterrent	Eastern red bat	PHWF	58.1%	41.1–70.3%
Curtailment only	Eastern red bat	KCWF	38.8%	3.4–61.2%
Curtailment and deterrent	Hoary bat	PHWF	71.4%	55.8–81.5%
Curtailment only	Hoary bat	KCWF	65.4%	35.1–81.5%
Curtailment and deterrent	Silver-haired bat	PHWF	71.6%	56.1–81.7%
Curtailment only	Silver-haired bat	KCWF	14.8%	−41.6–48.8%
Curtailment and deterrent	Big brown bat	PHWF	94.4%	68.8–99.0%

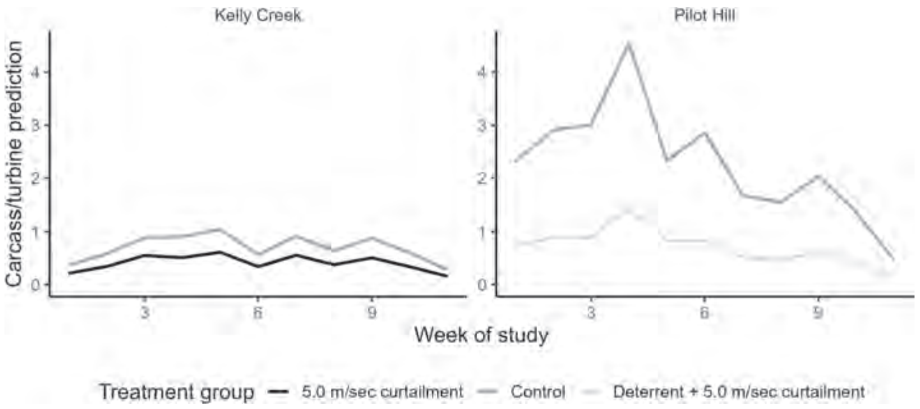

FIGURE 2 Top model results for all bat carcasses found at the Pilot Hill and the Kelly Creek Wind Farms, northeast Illinois, USA, from 1 August–15 October 2018. The *y*-axis is the predicted number of carcasses per turbine.

that the addition of an acoustic deterrent did not have as strong an effect for these species compared to silver-haired bats (Table 5).

DISCUSSION

Reducing bat mortality at wind-energy projects is of growing importance given the potential impacts of wind energy on tree bat populations (Frick et al. 2017). Curtailment at wind speeds below 5.0 m/second reduces bat mortality from 42–78% (Arnett et al. 2013*b*, Hein et al. 2014, Martin et al. 2017, this study), and some evidence exists that greater reductions in bat fatalities can be achieved by curtailing operations at higher wind speeds (Good et al. 2012, Arnett et al. 2013*b*, Adams et al. 2021). Curtailment at higher wind speeds results in greater losses in energy production and may not be economically feasible at many wind-energy projects. Acoustic deterrents used without

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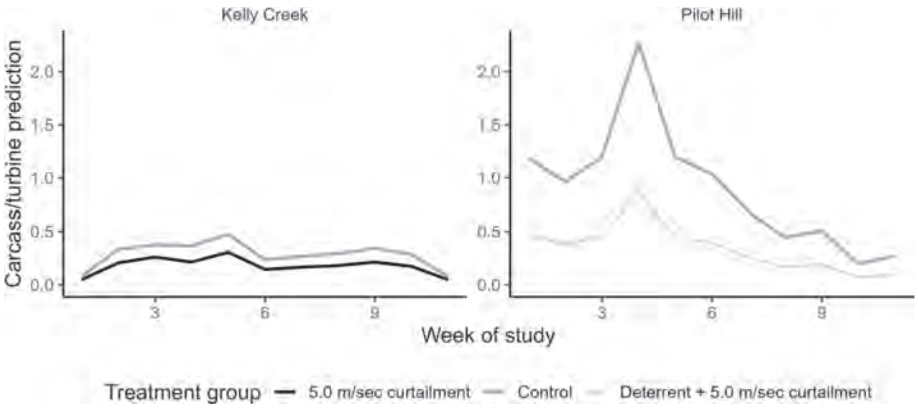

FIGURE 3 Top model results for eastern red bat carcasses found at the Pilot Hill and the Kelly Creek Wind Farms, northeast Illinois, USA, from 1 August–15 October 2018. The *y*-axis is the predicted number of carcasses per turbine.

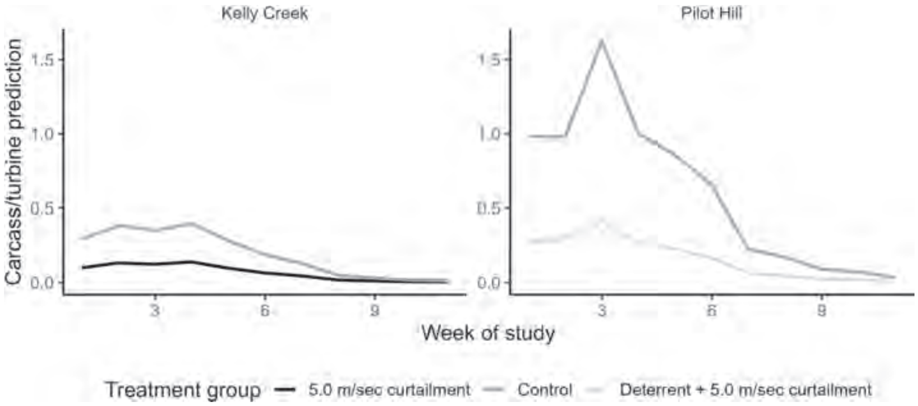

FIGURE 4 Top model results for hoary bat carcasses found at the Pilot Hill and the Kelly Creek Wind Farms, northeast Illinois, USA, from 1 August–15 October 2018. The *y*-axis is the predicted number of carcasses per turbine.

curtailment result in no loss in energy production but result in lower reductions in overall bat mortality (30–50%; Arnett et al. 2013*a*, Romano et al. 2019, Weaver et al. 2020). Wind-energy facilities have varying levels of impacts to bats (American Wind Wildlife Institute [AWWI] 2020, Western EcoSystems Technology, Inc 2021), and some wind-energy projects could require management actions that result in greater reductions in bat mortality than curtailment or acoustic deterrents alone. While both acoustic deterrents and curtailment reduce bat mortality, no researchers have examined if using acoustic deterrents in tandem with curtailment results in additional reductions in bat mortality. Our results suggest that applying the NRGS acoustic deterrent, along with curtailment below a wind speed of 5.0 m/second, resulted in additional reductions in bat mortality compared to curtailment alone, with the level of additional reduction varying by species.

The estimated reduction of overall bat mortality from curtailment alone up to wind speeds of 5.0 m/second at the KCWF of 42% was lower than reductions reported from wind-energy projects in Indiana, USA (50%; Good et al. 2011), West Virginia, USA (47–54%; Hein et al. 2014), and Pennsylvania (72–82%; Arnett et al. 2013*b*). Arnett et al. (2013*b*) suggested that differences in overall bat mortality between curtailment studies were explained by the

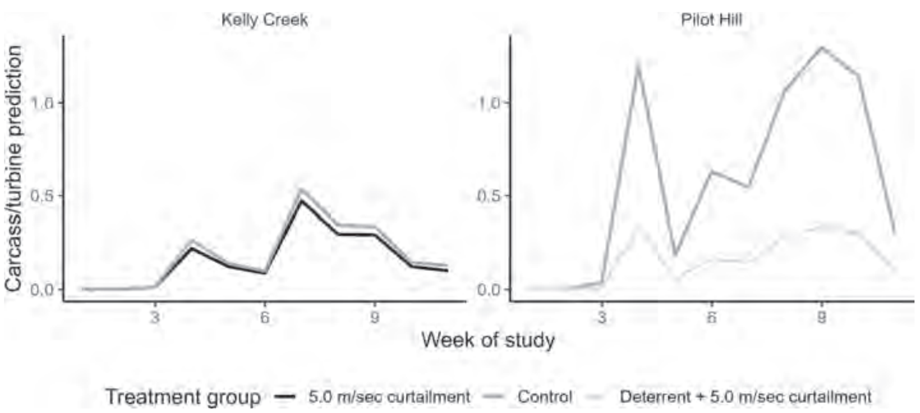

FIGURE 5 Top model results for silver-haired bat carcasses found at the Pilot Hill and the Kelly Creek Wind Farms, northeast Illinois, USA, from 1 August–15 October 2018. The *y*-axis is the predicted number of carcasses per turbine.

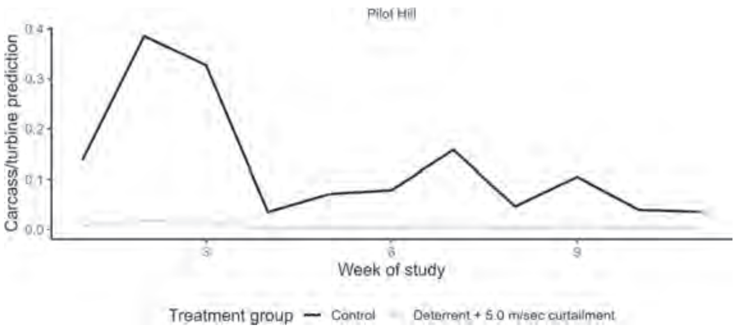

FIGURE 6 Top model results for big brown bat carcasses found at the Pilot Hill Wind Farm, northeast Illinois, USA, from 1 August–15 October 2018. The *y*-axis is the predicted number of carcasses per turbine.

TABLE 5 The estimated reduction in bat mortality of adding the NRG Systems acoustic deterrent to turbines curtailed up to wind speeds at 5.0 m/second from 1 August–15 October 2018 at the Pilot Hill Wind Farm, northeast Illinois, USA.

Group or species	Estimated reduction	90% CI
All bats	42.3%	5.6–64.8%
Eastern red bat	31.6%	−21.0–61.3%
Hoary bat	17.4%	−77.4–61.5%
Silver-haired bat	66.7%	5.6–64.8%

proportion of time treatments were in effect. We did not calculate treatment effect times in our study, which could explain the observed differences between our results and studies in other regions. Our results suggest that differences in relative composition of bat species may play a larger role in explaining why curtailment at the same wind speeds result in differing mortality reductions between projects.

No published studies have measured curtailment effectiveness for individual bat species; rather, researchers typically measure combined mortality rates. Although a useful index, combining mortality rates between species potentially masks important between-species responses to curtailment. Our results show that curtailment at 5.0 m/second without deterrents was most effective for hoary and eastern red bats but was not effective for silver-haired bats. Silver-haired bats compose 14% of bat mortality across the United States (AWWI 2020), and 27% of bat mortality in our study. The Fowler Ridge Wind Farm in Indiana is located approximately 74 km from the PHWF. Silver-haired bats composed a lower percentage (14%) of bat mortalities at a study of curtailment at the Fowler Ridge Wind Farm, which may explain why overall bat mortality was reduced more at the Fowler Ridge Wind Farm (50%; Good et al. 2011) than at KCWF (42%). Silver-haired bat mortality was reduced by 14.8% by curtailment alone with confidence intervals that overlapped zero but was further reduced to 71.6% with the addition of the acoustic deterrent. Arnett et al. (2013*a*) reported silver-haired bat mortality was reduced by an acoustic deterrent when applied without curtailment. Romano et al. (2019) reported silver-haired bat mortality was reduced in 1 of 2 years by the General Electric acoustic deterrent applied without curtailment. Low-frequency sound travels farther than higher frequency sounds because there is greater atmospheric absorption at higher frequencies (Stilz and Schnitzler 2012); acoustic deterrents are likely effective for reducing silver-haired bat mortality because they echolocate at lower frequencies (Britzke et al. 2011).

Arnett et al. (2013*a*) and Romano et al. (2019) were unable to quantify the effectiveness of other deterrents on big brown bats because of low sample sizes. Weaver et al. (2020) suggested that the NRGS deterrent would be effective for big brown bats; our results show that the NRGS deterrents deployed with curtailment reduced big brown bat mortality by 94.4%. We found few big brown bat carcasses at the KCWF, and thus we could not estimate if the addition of acoustic deterrents resulted in reductions in big brown bat mortality. Additional studies with balanced designs are needed to separate the effects of curtailment compared to acoustic deterrents for reducing big brown bat mortality.

Eastern red bats also benefitted from the addition of the acoustic deterrent, with an additional 31.6% reduction in fatalities compared to curtailment alone. Eastern red bat mortality was not reduced consistently by other acoustic deterrents (Arnett et al. 2013*a*, Romano et al. 2019). Eastern red bats have a broader and higher echolocation frequency range than other bat species, which potentially explains the lower effectiveness measured by Arnett et al. (2013*a*) and Romano et al. (2019). The deterrent system tested in this study attempted to increase coverage of the rotor-swept area by placing deterrents on the tower and nacelle, and orienting deterrents toward the rotor-swept area, which may explain the greater reduction we observed compared to Arnett et al. (2013*a*) and Romano et al. (2019).

Hoary bats benefited the least from the addition of the acoustic deterrent. Hoary bat fatalities were reduced the most by the application of curtailment only compared to other bat species (65.4% reduction). Our study was not designed to estimate the effectiveness of the acoustic deterrent without curtailment. Weaver et al. (2020) reported hoary bat mortality was reduced 78% by the NRGS deterrent alone in south Texas, USA, which is equivalent to the combined reduction we observed with curtailment and the acoustic deterrent. Arnett et al. (2013*a*) suggested that humidity increases high frequency sound attenuation, which reduces the distance high-frequency sound travels. Increased humidity was associated with increased hoary bat mortality in our study, which may explain the increased effectiveness of the NRGS deterrent observed by Weaver et al. (2020).

The relationship between humidity and attenuation is nonlinear; attenuation is greatest when humidity is 40–50%, and temperatures are 30–40°C, but decreases rapidly when humidity is greater than 50% and temperatures are lower (NRGS 2021). This suggests the effectiveness of acoustic deterrents for reducing bat mortality may vary geographically and within a season as temperatures decrease, depending on the typical night temperatures and humidity. Future studies should determine if the addition of acoustic deterrents to curtailment consistently results in additional reductions bat mortality at other wind-energy facilities in different regions of North America.

Additional research in other locations of North America that isolate the effectiveness of acoustic deterrents are needed to better understand how acoustic deterrents may reduce mortality of other bat species, and with larger turbines. Other studies of bat mortality from acoustic deterrents (Arnett et al. 2013*a*, Romano et al. 2019, Weaver et al. 2020, this study) have occurred at turbines with rotor diameters ranging from 87–110 m. The blades of newer turbines are much longer, with rotor diameters of 150 m or larger (Vestas 2021). Romano et al. (2019) suggested it is unknown if acoustic deterrents will be as effective for reducing bat mortality at larger turbines.

Curtailment and acoustic deterrents reduce bat mortality; however, both require additional expense in the form of lost energy production or purchase and maintenance of hardware. Frick et al. (2017) described potential negative impacts of wind energy to hoary bat populations but acknowledged the degree of impact depended heavily on population size. Reliable population estimates are lacking for most of North America's bat populations, which makes it difficult for wind-energy operators and wildlife managers to evaluate the costs and benefits of investing in curtailment or acoustic deterrents. Additional studies are needed that provide reliable bat population estimates or trends to better understand the potential effects of wind energy, and to help managers make informed decisions regarding the costs and benefits of actions designed to reduce bat mortality.

MANAGEMENT IMPLICATIONS

Wind-energy operators and regulatory agencies should consider between-species differences and conservation targets when deciding upon management actions and recommendations for reducing bat mortality. Curtailment is an effective strategy for reducing eastern red and hoary bat mortality but does not consistently reduce silver-haired bat mortality. Using acoustic deterrents in addition to curtailment results in additional benefit for silver-haired bats but may not benefit hoary bats. The benefits of adding acoustic deterrents for further reduction in eastern red bat mortality is uncertain. The effectiveness of acoustic deterrents for reducing any bat species mortality at turbines with rotor diameters >110 m is uncertain because of the short distances that high frequency sound travels. Regulators and wind-energy facility managers should consider cost in terms of lost energy production, hardware purchase, and installation when recommending methods for reducing bat mortality at wind-energy projects. Acoustic deterrents are a potentially effective tool for reducing bat mortality for some bat species but require significant investment in hardware, installation, and maintenance costs. The NRGS acoustic deterrent we tested included acoustic deterrents mounted on towers, which require additional installation costs and could be inconsistent with turbine warranties that prevent alteration to turbine structures.

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CONFLICTS OF INTEREST

Western EcoSystems Technology is an ecological consulting firm. We were under contract to EDF Renewables, and were paid by EDF Renewables to complete the study described within the manuscript.

ETHICS STATEMENT

Carcasses were collected under Illinois Department of Natural Resources General Collection permit NH18.5223-1, United States Fish and Wildlife Service Native Endangered and Threatened Species Recovery permit TE234121-9, and Illinois Department of Natural Resources Endangered and Threatened Species permit 2514.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from Western EcoSystems Technology, Inc. Restrictions apply to the availability of these data, which were used under license for this study.

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APPENDIX A: TREATMENT ANALYSIS MODEL RESULTS

TABLE A1 Descriptions of model covariates used to estimate the reduction in all bat mortality at the Kelly Creek and Pilot Hill Wind Farms, northeast Illinois, USA, from 1 August–15 October 2018.

Covariate	Estimate	SE	*P*-value
Intercept	0.154	0.457	0.736
Curtailment[a] + acoustic deterrent	−1.104	0.193	<0.001
Curtailment[a]	−0.554	0.231	0.016
Pilot Hill	2.134	0.419	<0.001
Wind speed	−0.175	0.081	0.031
Southeast wind direction	−0.448	0.184	0.015
Southwest wind direction	0.046	0.229	0.840
Precipitation	9.004	2.797	0.001
Barometric pressure (48-hr lag)	0.056	0.022	0.011
Spline, degree 1	2.157	0.673	0.001
Spline, degree 2	0.188	0.749	0.802
Spline, degree 3	2.193	0.653	0.001
Spline, degree 4	−0.026	0.563	0.964
Pilot Hill × spline, degree 1	−1.316	0.767	0.086
Pilot Hill × spline, degree 2	−0.160	0.775	0.837
Pilot Hill × spline, degree 3	−2.254	0.783	0.004
Pilot Hill × spline, degree 4	−1.736	0.616	0.005

[a] Curtailment = feathered below 5.0 m/sec wind speed.

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TABLE A2 Descriptions of model covariates used to estimate the reduction of eastern red bat mortality at the Kelly Creek and Pilot Hill Wind Farms, northeast Illinois, USA, from 1 August–15 October 2018.

Covariate	Estimate	SE	*P*-value
Intercept	−2.155	0.683	0.002
Curtailment[a] + acoustic deterrent	−0.871	0.209	<0.001
Curtailment[a]	−0.491	0.278	0.078
Pilot Hill	2.560	0.683	<0.001
Southeast wind direction	−0.064	0.260	0.807
Southwest wind direction	0.505	0.266	0.058
Spline, degree 1	3.248	1.188	0.006
Spline, degree 2	0.279	0.923	0.762
Spline, degree 3	2.842	1.057	0.007
Spline, degree 4	0.544	0.855	0.525
Pilot Hill × spline, degree 1	−2.532	1.264	0.045
Pilot Hill × spline, degree 2	0.703	1.098	0.522
Pilot Hill × spline, degree 3	−4.049	1.208	0.001
Pilot Hill × spline, degree 4	−1.992	0.977	0.042

[a] Curtailment = feathered below 5.0 m/sec wind speed.

TABLE A3 Descriptions of model covariates used to estimate the reduction of hoary bat mortality at the Kelly Creek and Pilot Hill Wind Farms, northeast Illinois, USA, from 1 August–15 October 2018.

Covariate	Estimate	SE	*P*-value
Intercept	−2.918	1.259	0.020
Curtailment[a] + acoustic deterrent	−1.252	0.266	<0.001
Curtailment[a]	−1.061	0.383	0.006
Pilot Hill	0.971	0.254	<0.001
Humidity	0.035	0.017	0.036
Spline, degree 1	0.649	0.795	0.414
Spline, degree 2	−1.466	0.848	0.084
Spline, degree 3	−3.574	0.825	<0.001

[a] Curtailment = feathered below 5.0 m/sec wind speed.

TABLE A4 Descriptions of model covariates used to estimate the reduction of silver-haired bat mortality at the Kelly Creek and Pilot Hill Wind Farms, northeast Illinois, USA, from 1 August–15 October 2018.

Covariate	Estimate	SE	*P*-value
Intercept	−165.449	34.910	<0.001
Curtailment[a] + acoustic deterrent	−1.260	0.267	<0.001
Curtailment[a]	−0.160	0.310	0.605
Pilot Hill	0.975	0.262	<0.001
Southeast wind direction	−0.882	0.310	0.004
Southwest wind direction	−0.392	0.404	0.332
Precipitation	11.282	3.828	0.003
Spline, degree 1	174.668	36.311	<0.001
Spline, degree 2	159.800	34.323	<0.001
Spline, degree 3	168.491	35.263	<0.001
Spline, degree 4	164.796	34.868	<0.001
Spline, degree 5	164.186	34.977	<0.001

[a] Curtailment = feathered below 5.0 m/sec wind speed.

TABLE A5 Descriptions of model covariates used to estimate the reduction of big brown bat mortality at the Pilot Hill Wind Farm, northeast Illinois, USA, from 1 August–15 October 2018.

Covariate	Estimate	SE	*P*-value
Intercept	3.177	1.215	0.009
Curtailment[a] + acoustic deterrent	−2.886	1.049	0.006
Wind speed	−0.785	0.224	<0.001

[a] Curtailment = feathered below 5.0 m/sec wind speed.

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TABLE A6 The effect sizes for non-treatment predictors of bat carcass counts at the Pilot Hill and the Kelly Creek Wind Farms, northeast Illinois, USA, from 1 August–15 October 2018. The standard deviation is of the data for each predictor. The effect size (%) indicates the percentage that carcass count increased or decreased with each standard deviation change in the associated predictor. For example, in the all species model, carcass count decreased by 19% for each 1.21 m/second increase wind speed. We calculated effect size (%) as (exp[standardized coefficient estimate] − 1) × 100. Exponentiation of the standardized regression coefficient was necessary because we modeled the response using a log-link for the negative binomial distribution.

Group or species	Covariate	SD	Effect size (%)	Standardized coefficient estimate	95% CI
All	Wind speed	1.21	−19	−0.212	−0.404–−0.019
All	Precipitation	0.03	32	0.276	0.108–0.444
All	Barometric pressure (48 hr lag)	3.07	19	0.171	0.038–0.303
Hoary bat	Humidity	5.5	21	0.191	0.013–0.369
Silver-haired bat	Precipitation	0.03	41	0.346	0.116–0.576
Big brown bat	Wind speed	1.21	−61	−0.948	−1.479–−0.417