Journal of Mammalogy, 98(2):378–385, 2017
DOI:10.1093/jmammal/gyx005
Published online March 10, 2017

Reducing bat fatalities at wind facilities while improving the economic efficiency of operational mitigation

Colleen M. Martin,* Edward B. Arnett, Richard D. Stevens, and Mark C. Wallace

Department of Natural Resources Management, Texas Tech University, Box 42125, Lubbock, TX 79409, USA (CMM, EBA, RDS, MCW)
Theodore Roosevelt Conservation Partnership, Loveland, CO 80537, USA (EBA)

* *Correspondent: colleen.martin@ttu.edu*

Concerns about cumulative population-level effects of bat fatalities at wind facilities have led to mitigation strategies to reduce turbine-related bat mortality. Operational mitigation that limits operation may reduce fatalities but also limits energy production. We incorporated both temperature and wind speed into an operational mitigation design fine-tuned to conditions when bats are most active in order to improve economic efficiency of mitigation. We conducted a 2-year study at the Sheffield Wind Facility in Sheffield, Vermont. Activity of bats is highest when winds speeds are low (< 6.0 m/s) and, in our region, when temperatures are above 9.5°C. We tested for a reduction in bat mortality when cut-in speed at treatment turbines was raised from 4.0 to 6.0 m/s whenever nightly wind speeds were < 6.0 m/s and temperatures were > 9.5°C. Mortalities at fully operational turbines were 1.52–4.45 times higher than at treatment turbines. During late spring and early fall, when overnight temperatures generally fell below 9.5°C, incorporating temperature into the operational mitigation design decreased energy losses by 18%. Energy lost from implementation of our design was < 3% for the study season and approximately 1% for the entire year. We recommend that operational mitigation be implemented during high-risk periods to minimize bat fatalities and reduce the probability of long-term population-level effects on bats.

Key words: bat fatalities, bats, cut-in speed, mitigation, operational mitigation, temperature, wind energy, wind turbines

Installation of wind energy capacity has grown exponentially worldwide in the last decade and is now the largest provider of new electric generating capacity in many countries (AWEA 2015; CanWEA 2015; WWEA 2015). However, unprecedented numbers of bat fatalities have been observed at wind facilities across the globe (Arnett et al. 2016), with particularly high fatalities in the Midwest and forested Northeast of North America (Arnett et al. 2008; Arnett and Baerwald 2013; Drake et al. 2015) and in Germany (Rydell et al. 2010; EUROBATS 2015). Estimates of annual turbine-related bat fatalities are in the hundreds of thousands (Arnett and Baerwald 2013; Smallwood 2013; Voigt et al. 2015). Although population numbers of bats are unknown, it is projected that current levels of turbine-related fatalities are not sustainable and, if trends continue, will result in cumulative population-level effects (Kunz et al. 2007; Arnett and Baerwald 2013; Erickson et al. 2015). Most bats reproduce once yearly and typically give birth to 1–2 young (Altringham 1996). Low recruitment results in low intrinsic rates of population growth, making bats highly susceptible to population declines and limits their ability to recover (Barclay and Harder 2003). Additionally, stable isotope analyses of bat carcasses found at wind facilities in both North America (Baerwald et al. 2014; Cryan et al. 2014) and Europe (Voigt et al. 2012; Lehnert et al. 2014) have determined that bats killed at turbines include long-distance migrants as well as local residents, indicating that bat mortality at a single wind facility could have broad-scale effects to bat populations and ecosystems.

In response to these concerns, studies have assessed operational mitigation as a means to reduce bat fatalities at wind facilities (Baerwald et al. 2009; Arnett et al. 2011; Arnett et al. 2013). Raising cut-in speed of turbines (defined as the lowest wind speed when electricity is generated into the power grid, usually 3.5–4.0 m/s for contemporary turbines) reduces turbine blade rotation during slow wind periods of the night. Raising turbine cut-in speed from 4.0 to 5.5 m/s in Alberta, Canada, and from 3.5 to 5.0 and 6.5 m/s in Pennsylvania, United States, resulted in 60% and 44–93% reductions in bat fatalities, respectively (Baerwald et al. 2009; Arnett et al. 2011). Studies investigating raised cut-in speed also have been conducted in other parts of North America (see Arnett et al. 2013) and Europe (Behr and von Helversen 2006), with most demonstrating at least a 50% reduction in bat fatalities. However, this approach has only been tested in relation to wind speed. Bat activity is known to vary with other environmental conditions including temperature and precipitation (Erickson and West 2002; Reynolds 2006; Wolbert et al. 2014). Consequently, studies that incorporate other weather variables in addition to wind speed in order to fine-tune designs are essential (Baerwald et al. 2009; Arnett et al. 2011; Weller and Baldwin 2012). Variables that predict bat activity and can be set at thresholds that reduce fatalities and minimize energy losses would be ideal.

Given high numbers of bat fatalities at many wind facilities, it is essential that effective mitigation strategies be cost-effective in order to achieve broad implementation by the wind-power industry. Bat activity in our region has been shown to increase with warmer temperatures (Reynolds 2006; Brooks 2009; Wolbert et al. 2014). Thus, the objective of our study was to test the effectiveness of operational mitigation in reducing bat fatalities while incorporating temperature into the design to improve economic efficiency by fine-tuning it to weather conditions when bats are most active.

Materials and Methods

We conducted our study at the Sheffield Wind Facility (SWF) in Sheffield, Caledonia County, Vermont (44°39′47″N, 72°07′18″W). SWF is at 594–728 m elevation along 2 mountain ridges consisting primarily of new-growth deciduous hardwood forest. Topography in the region consists of rolling foothills and river valleys (Thompson 2002). Surrounding land uses include open space, rural residential, dairy farming, and logging. SWF is owned and operated by Vermont Wind, LLC (Vermont Wind), and began operation in October 2011. It is a 40 MW facility, consisting of 16 Clipper 2.5 MW wind turbines. All of the turbines have 80-m tall masts; 4 turbines have a 96-m rotor diameter with a rotor-swept area of 7,238 m^2 and 12 turbines have 93-m rotor diameter with a rotor-swept area of 6,793 m^2.

Fatality surveys.—We conducted daily fatality searches at all 16 turbines from 3 June to 30 September in 2012 and 2013. We established rectangular study plots around each turbine center, with plot size ranging from 3,629 to 5,746 m^2. Only exposed areas where a bat would have 100% chance of landing on the ground were included in study plots; areas that were wooded or densely vegetated were not included. As a result, plot size was dependent on vegetation present at each turbine. All study plots had transects that were oriented north-south and spaced 6 m apart. Searchers walked along each transect searching out to 3 m on each side for bat carcasses for 100% survey plot coverage. When a carcass was located, we recorded the date, time found, turbine number, species, and estimated time of death (i.e., fresh: died on previous night; non-fresh: died > 1 night before survey—Good et al. 2011). All surveyors were trained on proper search techniques and identification of locally occurring bat species. Collections were made under permit numbers VDFW SR-2012-05, USFWS MB75107A-0, and Texas Tech University ACUC #: 12030-03. This study conformed to guidelines of the American Society of Mammalogists (Sikes et al. 2016). This manuscript is part of a broader study that also estimated bat fatalities and assessed patterns in mortality. Detailed methodology for these portions of the study can be found in Martin (2015).

Operational mitigation.—We conducted an operational mitigation study to test the effectiveness of raising turbine cut-in speed to reduce bat fatalities. Surveys were performed in both 2012 and 2013 during a 120-night period to capture the entire fall bat migration season and seasonal weather variation in late spring and early fall. There were 2 turbine treatments: 1) fully operational (i.e., cut-in speed at 4.0 m/s), and 2) cut-in speed at 6.0 m/s whenever temperatures were > 9.5°C. We used a randomized complete block design (Hurlbert 1984) where the observational unit in our analysis was the turbine-night. Turbines were considered a random blocking factor that varied each year. Treatments were randomly assigned to turbines each night of the study for an equal number of nights at each turbine, with night when treatments were applied being the sampling unit and the set of 60 nights at a turbine during which it received 1 of the treatments being the experimental unit. To do this, each of the 16 turbines was randomly assigned to 1 of 2 treatments, with each treatment having 8 replicates on each night of the study. Treatments were balanced every 8 nights to achieve a balanced assignment of treatments over the study period, for a total of 60 nights of treatment for each turbine for each year.

The Supervisory Control and Data Acquisition (SCADA) system for each turbine was programmed to incorporate treatments into their daily operation. Treatments were implemented from 30 min before sunset until sunrise during periods when ambient air temperature was > 9.5°C and wind speeds were < 6.0 m/s. We chose this temperature threshold because regional studies suggest little or no bat activity below 10°C (Reynolds 2006; Brooks 2009; Wolbert et al. 2014). These variables were programmed into the turbine's software and whenever both conditions were met for a total of 5 consecutive minutes the turbine was placed in "standby," which is a non-generating state with the blades in a stand-by pitch of 80°. This pitch prevented the blades from being affected by air flow. Although the blades were not locked in place, they could move only at a maximum of 1 rpm, which is approximately 18 kph at blade tip. Once 1 of the weather conditions (i.e., temperature or wind speed) was no longer met for a total of 10 consecutive minutes the turbines went back to being fully operational.

Effectiveness of mitigation.—We combined carcass count data for both years and modeled total number of fresh fatalities in each treatment at each turbine as a Poisson random variable. We summed the total number of fresh carcasses found beneath each turbine following each treatment (n = 60 nights per treatment in each year). We fit these data to a generalized linear mixed model (GLMM; SAS PROC GLIMMIX), assuming a

Poisson distribution with a log link for carcass count, treatment as a fixed effect, and turbine * year interaction as a random effect. Because treatments were randomly assigned to turbines and changed on a nightly basis, only fresh carcasses found at either fully operational or treatment turbines were used in our analysis. Because treatment comparisons are calculated after removing block effects (turbine served as a block effect), adjustments for imperfect detection typically made when estimating fatality were not necessary. Analyses were performed in program SAS (SAS Institute Inc. 2008).

Incorporating temperature as a variable.—Because the treatment in our design included both wind speed and temperature as variables, we were not able to statistically isolate the independent effect that incorporating temperature had on reducing bat fatalities. To assess whether or not temperature affected treatment implementation, we examined median nightly temperatures and wind speeds for the site for each night of the study to determine if treatment thresholds (i.e., wind speed < 6.0 m/s and temperature > 9.5°C) were being met. We then compared this to nights with fatality occurrences. To determine whether temperature and wind speed differed between 2012 and 2013, we conducted 2 different *t*-tests after a Bonferroni adjustment between years using median nightly temperature and wind speed. Analyses were performed in program SPSS (IBM Corp. 2013).

We used wind speed and temperature data to evaluate the influence of temperature in reducing energy losses. Weather data were collected in 10-min increments from half an hour before sunset to sunrise from anemometers and thermometers located on turbine nacelles to compare a wind speed-temperature and wind speed-only treatment design. To do this, we wrote a code in program MATLAB (MathWorks Inc. 2014) that assigned a "Yes" when thresholds were met and a "No" when thresholds were not met for both design types. Thus, for the wind speed-temperature design a "Yes" was assigned when temperature was > 9.5°C and wind speed was < 6 m/s. For the wind speed-only design a "Yes" was assigned when wind speed was < 6 m/s. For each design type, we determined hypothetical portion of each night the treatment would have been implemented based on weather data for each turbine on each night. We then calculated mean portion of night the treatment would have been implemented for the entire site for each night of the study. We conducted a *t*-test where treatment design was the independent variable and percent of night treatment would have been implemented was the dependent variable. Analyses were performed in program SPSS (IBM Corp. 2013).

Financial costs.—Financial cost of operational mitigation was assessed based on percent of energy lost due to implementation of the treatment. We used operational information from the turbines to calculate the percentage of a night that a treatment was implemented for each turbine for each night. This was calculated by dividing the amount of time the turbine was non-operational by total nightly hours of the operational mitigation study (i.e., half an hour before sunset to sunrise) for each night of the study. We refer to this variable as treatment percentage night.

Percentage of energy lost was estimated by dividing energy loss at the Point of Interconnect (POI; in megawatt hours [MWh]), which was based on treatment percentage night, by the expected energy at POI (MWh), which was based on company projections. This was determined for the 8 treatment turbines each night of the study and estimated for the remaining 8 turbines had the treatment been implemented. Percentage energy loss was determined for the study period (3 June to 30 September) and the entire year. Energy loss and company projections data were computed by First Wind. Obtaining energy loss data related to the actual sunset and sunrise times for 2 full years would have required First Wind to write a computer code that would query their entire database. Due to the cost and labor intensity they would have incurred to do this, it was assumed that sunset was 18:00 and sunrise was 6:00 for all months.

Results

We surveyed a total of 231 complete days out of 240 possible search days, for a total of 3,793 out of 3,840 possible searches for both years combined. Surveys classified as not conducted were either not completed or not attempted due to severe weather or turbine maintenance.

We found a total of 99 bats of 3 species during the study: 54 hoary bats (*Lasiurus cinereus*), 24 eastern red bats (*L. borealis*), and 21 silver-haired bats (*Lasionycteris noctivagans*). Seventy-two of the 99 bat carcasses found were fresh. In 2012, a minimum of 1 fresh bat was found at all 16 turbines, whereas in 2013 a fresh bat carcass was only found at 7 of the 16 turbines. Fifty-one of the 72 (71%) fresh carcasses were found at fully operational turbines. Detailed fatality results can be found in Martin (2015).

Effectiveness of mitigation.—We found that operational mitigation had a significant effect on bat fatalities ($F_{1,31}$ = 13.19, $P \leq 0.01$; Fig. 1). An average of 0.54 (95% confidence interval [*CI*]: 0.31–0.92) fresh bats per turbine was found at treatment turbines compared to 1.39 (95% *CI*: 0.93–2.09) fresh bats per turbine at fully operational turbines. There were 2.60 (95%

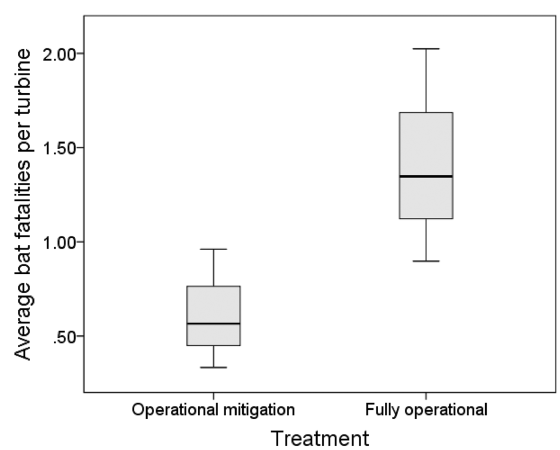

Fig. 1.—Effectiveness of operational mitigation at reducing bat fatalities at the Sheffield Wind Facility, Caledonia County, Vermont, 3 June to 30 September 2012 and 2013. Error bars: 95% *CI*. $F_{1,31}$ = 13.19, $P \leq 0.01$.

CI: 1.52–4.45) times as many fatalities at fully operational turbines than at treatment turbines, resulting in a 62% (95% *CI*: 34–78) decrease in bat fatalities from operational mitigation. The number of bats found was too low for a meaningful comparison of effectiveness of operational mitigation by species.

Incorporating temperature as a variable.—Temperature dropped below the 9.5°C threshold only at the beginning and end of the study season (Fig. 2A). In contrast, wind speed oscillated around the 6.0 m/s threshold throughout the season (Fig. 2B). Periods when temperature dropped below the threshold (late spring [early June] and early fall [mid- to late-September]) fell outside the period of high bat fatality at our site. Most (85%) fatalities were found from mid-July to mid-September (Fig. 2A). Of the fatalities that occurred during late spring and early fall (15% of all fatalities), only 5 (5%) occurred on nights when median temperature was < 9.5°C. It is possible that fatalities occurred earlier in the evening when temperatures were > 9.5°C even though median temperature for the night was < 9.5°C. Only 1 (1%) fatality was found when temperature remained below 9.5°C for the entire night. There were no significant differences in median temperature (t_{238} = 1.41, P = 0.16) or wind speed (t_{238} = 0.09, P = 0.93) between 2012 (Fig. 2) and 2013.

Overall, we found only a minimal difference in potential loss of energy production (i.e., cost) between the 2 operational mitigation designs (i.e., wind speed-temperature and wind speed-only) across the entire study season. On average, the wind speed-temperature design was implemented 44% of each night, whereas the wind speed-only design was implemented 49% of the time (Fig. 3A). There was only a 5% difference for the entire season, which was not significant (t_{478} = −1.72, P = 0.09). However, temperature fell below the threshold primarily in late spring and early fall (Fig. 2A). When only those 2 periods were examined, the average percent of night treatment was implemented for the wind speed-temperature design was 28% compared to 46% for the wind speed-only design (Fig. 3B). This resulted in a significant 18% difference in percent of night when turbines were non-operational for the late spring and early fall season (t_{102} = −2.67, $P \leq 0.01$).

Financial costs.—Energy loss due to operational mitigation during our field seasons when 8 of the 16 turbines had a raised cut-in speed was 2.79% in 2012 and 2.69% in 2013. This resulted in a 0.67% and 0.60% energy loss for all of 2012 and 2013, respectively. Energy losses had the treatment been implemented every night at all 16 turbines were estimated to be 4.67% and 5.34% for the field season and 1.13% and 1.20% for the year in 2012 and 2013, respectively (Table 1). In addition

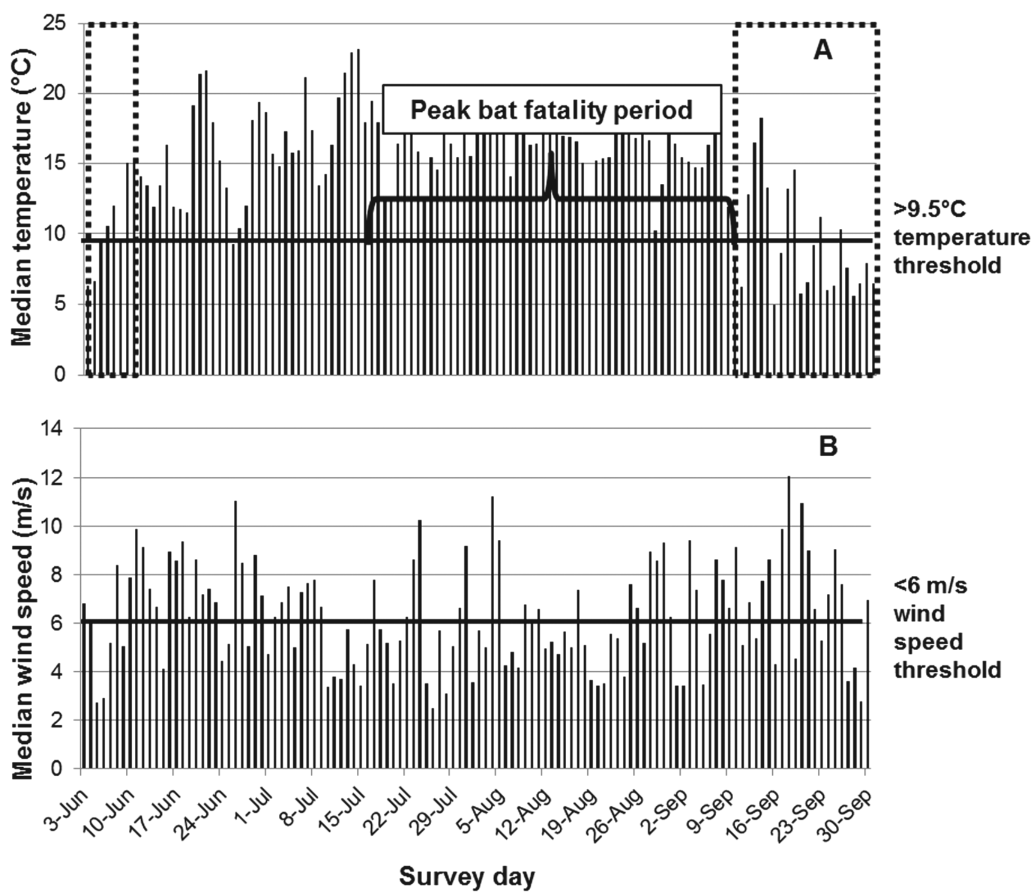

Fig. 2.—A) Median nightly temperature (where temperature threshold was > 9.5°C), peak period of bat fatality (when 85% of fatalities occurred; mid-July to mid-September), and time periods during the study season when the temperature variable dropped below the > 9.5°C threshold (shown in dotted-line boxes); and B) median nightly wind speed (when wind speed threshold was < 6 m/s) during the operational mitigation study at the Sheffield Wind Facility, Caledonia County, Vermont, 3 June to 30 September 2012.

to decreased revenue from energy lost due to operational mitigation, there were minor costs resulting from time First Wind staff spent implementing the study, including programming the operational mitigation design into the SCADA system, attending meetings associated with the project, and addressing any questions or issues that the research crew had while working at SWF.

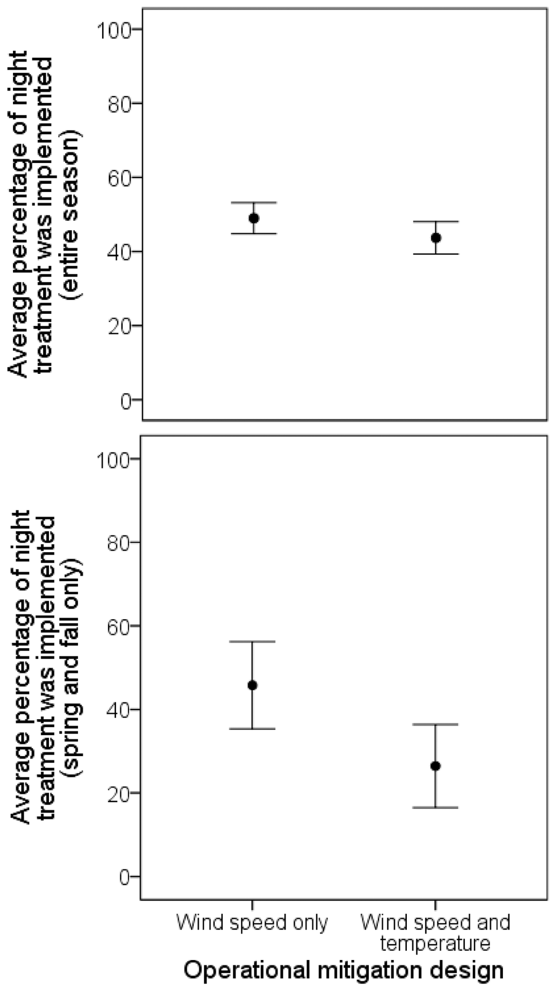

Fig. 3.—Hypothetical percentage of night when treatment would have been implemented for a wind speed-temperature and wind speed-only design for A) the entire operational mitigation season, and B) the spring and fall seasons only based on weather data from the Sheffield Wind Facility, Caledonia County, Vermont, 3 June to 30 September 2012 and 2013. Error bars: 95% *CI*. A) $F_{1,478} = 2.95$, $P = 0.09$; B) $F_{1,102} = 7.27$, $P \leq 0.01$.

Discussion

Raising cut-in speed of turbines in our study reduced bat fatalities by 34–78%, corroborating other research conducted in both the United States (Baerwald et al. 2009; Arnett et al. 2011; Arnett et al. 2013) and Europe (Behr and von Helversen 2006). Although studies vary in design, such as assigned cut-in speed, sample size, treatment assignment, and fatality search methodology, most report at least 50% fewer and as high as 93% fewer bats killed (Arnett et al. 2013); these studies report means and *CI*s similar to ours.

Incorporating a second variable into our operational mitigation design meant that 2 threshold requirements had to be met before the turbine went into "standby," thus increasing the amount of time blades could spin compared to a wind speed-only design. This could either result in no difference in bat fatalities or an increase in bat fatalities, depending on a number of factors, including weather conditions and bat activity in the area. Because our study was designed so that both weather conditions had to be met before a turbine would become non-operational, there was no way to isolate the effect that temperature alone had on bat fatalities, nor was there any way to determine how many bats would have died had the design been wind speed-only. However, by examining weather data and assessing the number of fatalities, we infer possible effects incorporating temperature had on bat fatalities. Temperature dropped below the threshold on only 15% of nights, primarily in early June and late September, when few bat fatalities were found, indicating that for the rest of the study season our temperature requirement was always met. Therefore, wind speed was the driving factor in determining when treatments were implemented during the period of high bat fatality at our site. Consequently, under the conditions of our study, we do not believe incorporating temperature as a variable contributed to increased bat fatalities.

Our exploratory analyses of weather data indicated that incorporating temperature into an operational mitigation design significantly decreased the amount of energy lost from implementing treatments on nights when bats were presumably not active, particularly during late spring and early fall

Table 1.—Estimated energy loss due to the operational mitigation study at the Sheffield Wind Facility, Caledonia County, Vermont, 3 June to 30 September 2012 and 2013. MWh: megawatt hours; POI: Point of Interconnect.

Year	Expected energy at POI (MWh)	8 turbines		16 turbines[a]	
		Energy loss at POI (MWh)	Percent loss	Energy loss at POI (MWh)	Percent loss
Field season only (3 June–30 September)					
2012	23,520	656	2.79%	1,098	4.67%
2013	22,319	601	2.69%	1,191	5.34%
Entire year					
2012	97,375	656	0.67%	1,098	1.13%
2013	99,651	601	0.60%	1,191	1.20%

[a]Values for all 16 turbines are estimates. It was necessary to assume that sunset was at 18:00 and sunrise was at 6:00 for all months, which could overestimate loss of power.

when temperatures in the northeast normally drop below 9.5°C. This finding is a promising step toward optimizing operational mitigation and increasing economic efficiency while maintaining biological effectiveness. These cost savings would likely be even greater if implemented at wind facilities in areas where nightly temperature regularly drops below our designated threshold rather than only at the beginning and end of the migration season, as occurred at our study site. In northern latitudes in North America (e.g., Alberta, Canada) and Europe (e.g., Denmark, United Kingdom, northern Germany), nightly temperature during the fall migration season is regularly below 9.5°C (Environment Canada 2015; WU 2016). Wind companies in these regions may benefit from optimized operational mitigation as wind installations are abundant in many of these countries (CanWEA 2016; EWEA 2016). However, bats remain active in lower temperatures at higher latitudes (Lausen and Barclay 2006; Hope and Jones 2012; Zahn and Kriner 2014) and temperature thresholds should be set at levels appropriate for the region to maintain biological effectiveness of operational mitigation.

While other studies have monitored bat fatalities and environmental conditions and shown that fatality is influenced by variables other than wind speed and temperature, our study incorporates temperature and wind speed into an operational mitigation design. Bat fatality also may be correlated with lunar illumination (Baerwald and Barclay 2011), falling barometric pressure (Baerwald and Barclay 2011), decreasing relative humidity (Amorim et al. 2012), and wind direction (Fiedler 2004; Baerwald and Barclay 2011; Amorim et al. 2012). In addition, bat activity is lower during periods of precipitation (Erickson and West 2002; Johnson et al. 2011). Future research should focus on improving predictability of high-risk periods and incorporating other variables (combined with wind speed) into operational mitigation designs that we did not test. This may reduce energy loss while maintaining or improving biological effectiveness. Weller and Baldwin (2012) found improved model performance (based on ΔAIC) when variables such as lunar illumination and date were included in addition to wind speed and temperature. Additionally, operational mitigation studies should be designed to fit the location. If an area experiences regular changes in wind direction or it rains frequently, wind direction or precipitation could be a reasonable variable to include. Also, the relationship between some environmental conditions and bat activity can depend on location. Wolbert et al. (2014) found a stronger relationship between temperature and bat activity at higher elevations. Bats remain active at lower temperatures in some areas, including higher latitudes in North America (Lausen and Barclay 2006; Nagorsen et al. 2014) and Europe (Krzanowski 1959; Hope and Jones 2012; Zahn and Kriner 2014). As such, different variables and threshold settings, combined with wind speed, may be more appropriate and effective at reducing bat fatalities than others depending on where a wind facility is located. The best variable(s) and threshold(s) for a site could be determined by either reviewing literature on bat activity and weather in the region or by monitoring pre-construction activity and weather conditions.

Observed energy loss from operational mitigation during our study season (2.79% in 2012 and 2.69% in 2013) was slightly higher than that reported in a similarly designed study (2%—Arnett et al. 2011), likely because treatments included cut-in speeds at both 5.0 and 6.5 m/s and their season was a month shorter than ours. Both studies demonstrated ≤ 1% energy loss for the year as a result of operational mitigation. Our cost estimates may be biased in 2 ways. First, our assumption of set times for sunset and sunrise meant that our analysis was based on longer nighttime periods than actually occurred (i.e., amount of time turbines would have been non-operational). Secondly, energy losses were estimated by dividing the amount of time a turbine was non-operational by total nightly hours of the study. This potentially skewed our estimates upward because periods when nightly wind speeds were low, and thus turbines would have been non-operational regardless of our study, were included in our estimates. As such, it is likely that observed energy losses were even less than we reported. Although financial losses are rarely reported, we believe existing data demonstrate that raising cut-in speed is an effective mitigation strategy for reducing bat fatalities with marginal costs (≤ 1% yearly energy loss) to wind companies. Also, predicted energy loss can easily be modeled from pre-construction wind data and factored into the design and economic models of the facility to account for anticipated financial costs of mitigation.

At present, mitigation is not usually mandated by government agencies in many countries, including the United States (AFWA 2007). Thus, in many cases it is up to the wind companies' discretion to adopt mitigation strategies. Given that 1) bat fatalities have been documented at wind facilities worldwide (Kunz et al. 2007; Arnett and Baerwald 2013; Arnett et al. 2016), 2) development of wind facilities is projected to increase (CanWEA 2008; DOE 2008; WWEA 2014), and 3) cumulative effects to bat populations are expected (Kunz et al. 2007; Arnett and Baerwald 2013; Erickson et al. 2015), we recommend operational mitigation be implemented broadly during high-risk periods at wind facilities to reduce bat fatalities and lessen potential effects to bat populations. Our findings may encourage wind companies to implement operational mitigation at facilities during peak fatality periods by improving economic efficiency and reducing costs incurred from non-operational turbines when bats would not be active. Operational mitigation is not always possible or logistically feasible to implement, but many SCADA systems allow for easy employment and management of mitigation designs. Turbine manufacturers should continue to work closely with wind energy developers and operators and researchers to determine logistically feasible and cost-efficient approaches to operational mitigation at wind facilities, such as incorporating other conditions in addition to wind speed into the design. With greater coordination between manufacturers, researchers, and wind companies in designing new turbines with SCADA systems and updating older turbines, operational mitigation could become a more accessible technology that effectively reduces bat fatalities while being cost-efficient for broad implementation by the wind industry.

Acknowledgments

Funding for this project was provided by Bat Conservation International (BCI), First Wind, National Renewable Energy Laboratory, U.S. Fish and Wildlife Service (USFWS), and Vermont Department of Fish and Wildlife (VDFW). We thank BCI, Clipper, First Wind, USFWS, and VDFW employees for their assistance and support throughout this project. C. Hein and M. Schirmacher, BCI, provided helpful feedback throughout the project, for which we are very grateful. We also thank the First Wind employees in the Distributed Asset Control Center for providing the weather data and their assistance in the operational mitigation study and financial cost assessment. Our crew worked tirelessly in the field to collect the data for this research; we thank A. Bouton, Z. Bryant, K. Friedman, G. Furr, M. Iachetta, K. Pollander, G. Sandoval, L. Sherman, J. Trudeau, and M. VanderLinden. We are inordinately grateful to M. Huso, U.S. Geological Survey, and L. Ganio, Oregon State University, for their assistance with analyses of the data. We thank M. Huso, 6 anonymous reviewers, and the Associate Editor whose comments greatly improved this manuscript.

Literature Cited

AFWA (Association of Fish and Wildlife Agencies). 2007. Wind power siting, incentives, and wildlife guidelines in the United States. www.fishwildlife.org/files/AFWAWindPowerFinalReport.pdf. Accessed 18 April 2016.

Altringham, J. D. 1996. Bats: biology and behaviour. Oxford University Press, New York.

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

Arnett, E. B., and E. F. Baerwald. 2013. Impacts of wind energy development on bats: implications for conservation. Pp. 435–456 in Bat evolution, ecology, and conservation (R. A. Adams and S. C. Pederson, eds.). 1st ed. Springer Science+Business Media, New York.

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

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

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

Arnett, E. B., et al. 2016. Impacts of wind energy development on bats: a global perspective. Pp. 295–323 in Bats in the Anthropocene: conservation of bats in a changing world (C. C. Voigt and T. Kingston, eds.). Springer International Publishing AG, Cham, Switzerland.

AWEA (American Wind Energy Association). 2015. U.S. wind industry fourth quarter 2014 market report. www.awea.org. Accessed 3 March 2015.

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

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

Baerwald, E. F., W. P. Patterson, and R. M. R. Barclay. 2014. Origins and migratory patterns of bats killed by wind turbines in southern Alberta: evidence from stable isotopes. Echosphere 5:1–17.

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

Behr, O., and O. von Helversen. 2006. Gutachten zur Beeinträchtigung im freien Luftraum jagender und ziehender Fledermäuse durch bestehende Windkraftanlagen – Wirkungskontrolle zum Windpark 'Roßkopf'. Freiburg im Breisgau, Erlangen, Germany.

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

CanWEA (Canadian Wind Energy Association). 2008. Wind vision 2025. www.canwea.ca. Accessed 19 February 2012.

CanWEA (Canadian Wind Energy Association). 2015. Installed capacity. www.canwea.ca. Accessed 3 March 2015.

CanWEA (Canadian Wind Energy Association). 2016. Wind energy in Alberta, Saskatchewan, and Manitoba. www.canwea.ca. Accessed 18 April 2016.

Cryan, P. M., C. A. Stricker, and M. B. Wunder. 2014. Continental-scale, seasonal movements of a heterothermic migratory tree bat. Ecological Applications 24:602–616.

DOE (Department of Energy). 2008. 20% wind energy by 2030 – increasing wind energy's contribution to U.S. electricity supply. U.S. Department of Energy, Oak Ridge, Tennessee.

Drake, D., C. S. Jennelle, J. Liu, S. M. Grodsky, S. Schumacher, and M. Sponsler. 2015. Regional analysis of wind turbine-caused bat mortality. Acta Chiropterologica 17:179–188.

Environment Canada. 2015. Historical climate data. www.climate.weather.gc.ca. Accessed 4 April 2016.

Erickson, R. H., E. A. Eager, J. C. Stanton, J. A. Beston, J. E. Diffendorfer, and W. E. Thogmartin. 2015. Assessing local population vulnerability with branching process models: an application to wind energy development. Ecosphere 6:1–14.

Erickson, J. L., and S. D. West. 2002. The influence of regional climate and nightly weather conditions on activity patterns of insectivorous bats. Acta Chiropterologica 4:17–24.

EUROBATS. 2015. Report of the IWG on wind turbines and bat populations. 20th Meeting of the Advisory Committee, Budva, Montenegro. Doc.EUROBATS.AC20.5.

EWEA (European Wind Energy Association). 2016. Wind in power, 2015 European statistics. www.ewea.org/statistics. Accessed 4 April 2016.

Fiedler, J. K. 2004. Assessment of bat mortality and activity at Buffalo Mountain Windfarm, eastern Tennessee. M.S. thesis, University of Tennessee, Knoxville.

Good, R. E., et al. 2011. Bat monitoring studies at the Fowler Ridge Wind Energy Facility, Benton County, Indiana. Western EcoSystems Technology, Inc., Cheyenne, Wyoming.

Hope, P. R., and Jones, G. 2012. Warming up for dinner: torpor and arousal in hibernating natterer's bats (*Myotis nattereri*) studied by radio telemetry. Journal of Comparative Physiology 182:569–578.

Hurlbert, S. H. 1984. Pseudoreplication and the design of ecological field experiments. Ecological Monographs 54:187–211.

IBM Corp. 2013. IBM SPSS statistics for Windows. Ver. 22.0. IBM Corp., Armonk, New York.

Johnson, J. B., Gates, J. E., and Zegre, N. P. 2011. Monitoring seasonal bat activity on a coastal barrier island in Maryland, USA. Environmental Monitoring and Assessment 173:685–699.

Krzanowski, A. 1959. Some major aspects of population turnover in wintering bats in the cave at Pulawy (Poland). Acta Theriologica 3:27–43.

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

Lausen, C. L., and R. M. R. Barclay. 2006. Winter bat activity in the Canadian prairies. Canadian Journal of Zoology 84:1079–1086.

Lehnert, L. S., Kramer-Schadt, S., Schönborn, S., Lindecke, O., Niermann, I., and Voigt, C. C. 2014. Wind farm facilities in Germany kill noctule bats from near and far. PLoS One 9:e103106.

Martin, C. M. 2015. Effectiveness of operational mitigation in reducing bat mortality and an assessment of bat and avian fatalities at Sheffield Wind Facility, Vermont. M.S. thesis, Texas Tech University, Lubbock.

MathWorks Inc. 2014. MATLAB R2014b. Ver. 8.4. The MathWorks, Inc., Natick, Massachusetts.

Nagorsen, D. W., I. Robertson, and M. Sarell. 2014. Preconstruction bat activity at four wind energy sites in northeastern British Columbia. Northwestern Naturalist 95:300–311.

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

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

SAS Institute Inc. 2008. SAS/STAT user's guide. Release 9.2. SAS Institute, Inc., Cary, North Carolina.

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

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

Thompson, E. H. 2002. Vermont's natural heritage: conserving biodiversity in the Green Mountain State. Vermont Biodiversity Project, Burlington.

Voigt, C. C., L. S. Lehnert, G. Petersons, F. Adorf, and L. Bach. 2015. Wildlife and renewable energy: German politics cross migratory bats. European Journal of Wildlife Research 61:213–219.

Voigt, C. C., A. G. Popa-Lisseanu, I. Niermann, and S. Kramer-Schadt. 2012. The catchment area of wind farms for European bats: a plea for international regulations. Biological Conservation 153:80–86.

Weller, T. J., and J. A. Baldwin. 2012. Using echolocation monitoring to model bat occupancy and inform mitigations at wind energy facilities. Journal of Wildlife Management 76:619–631.

Wolbert, S. J., A. S. Zellner, and H. P. Whidden. 2014. Bat activity, insect biomass, and temperature along an elevational gradient. Northeastern Naturalist 21:72–85.

WU (Weather Underground). 2016. Historical weather. https://www.wunderground.com/history. Accessed 4 April 2016.

WWEA (World Wind Energy Association). 2014. World wind resource assessment report. www.wwindea.org/wwea-publishes-world-wind-resource-assessment-report. Accessed 22 March 2016.

WWEA (World Wind Energy Association). 2015. Press releases statistics. www.wwindea.org/hyr2015. Accessed 22 March 2016.

Zahn, A., and E. Kriner. 2014. Winter foraging activity of central European Vespertilionid bats. Mammalian Biology 81:40–45.

Submitted 11 December 2015. Accepted 18 January 2017.

Associate Editor was John Scheibe.