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Original Article

Bat Mortality at a Wind-Energy Facility in Southeastern Wisconsin

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ABSTRACT The wind-energy industry is rapidly developing worldwide as a viable renewable power option to offset high economic and environmental costs of fossil fuel consumption and nuclear power generation. Evidence suggests bats are more likely to be negatively affected by wind facilities than are birds. Studies have shown that significant bat mortality occurs at wind facilities, yet our understanding of the concomitant drivers of these events is limited. Our objectives were to assess the impact of a wind facility in southeastern Wisconsin, USA, on migratory and non-migratory and/or short-distance migrant bats by 1) estimating mortality, 2) recording species composition of mortality cases, and 3) determining the correlative variables associated with bat mortality events. We estimated 4,454 total bats, 3,019 migratory and 912 non-migratory and/or short-distance migrant bats were killed, respectively, over 277 search days during two spring and two autumn study periods, 2008–2010. We found bat mortality was strongly linked to migration. Approximately one-quarter of all bat mortality consisted of non-migratory big brown bats (*Eptesicus fuscus*) and short-distance migrant little brown bats (*Myotis lucifugus*), which is higher than many previous studies, supported by similar studies in the Midwest, and of concern due to these species' susceptibility to white-nose syndrome. We determined weanling mice were suitable surrogates for bat carcasses in scavenger removal trials. We found temperature was positively related to bat mortality, which indicates a possible link with prey availability. We encourage standardization in search and statistical methods across studies and acknowledgment of migratory and non-migratory and/or short-distance migrant bat mortality at wind facilities in agricultural landscapes.

KEY WORDS bat fatalities, mortality estimation, white-nose syndrome, wind facilities.

The wind-energy industry is rapidly developing worldwide because it offers a viable renewable power option to offset high economic and environmental costs of fossil fuel consumption and nuclear power generation. Wind facilities generally do not release toxic emissions, and they incur limited air or water pollution (Hoogwijk 2004). Furthermore, the environmental impacts tend to be local, while other forms of energy (e.g., fossil fuels, coal) can have environmental impacts throughout the fuel cycle and more globally (Pasqueletti 2004). However, wind facilities can have negative direct (e.g., mortality) impacts on bats and, to a lesser extent, birds (Kunz et al. 2007*a*, *b*, Kuvlesky et al. 2007, Arnett et al. 2008). The growth of the wind energy industry is currently outpacing research related to the impact wind facilities have on bats and birds (Garvin et al. 2011).

The detrimental effects wind facilities have on bats were first recognized in 2003, more than a decade after similar studies began on birds (i.e., raptors at Altamont Pass; Orloff and Flannery 1992), when an estimated 1,400–4,000 bats were killed in West Virginia, USA (Kerns and Kerlinger 2004). Other studies in the eastern United States validated numbers of bat fatalities, with similar findings in Pennsylvania and Tennessee (Fiedler 2004, Arnett 2005). Although the aforementioned facilities were situated on forested ridge-tops in the eastern United States, most studies of bat mortality have been in agricultural landscapes (Arnett et al. 2008). Studies in the mid-western United States (e.g., Howe et al. 2002, Johnson et al. 2003, Jain et al. 2011) recorded lower mortality rates compared with those in the eastern United States, but significant variation occurred (Arnett et al. 2008). Despite regional differences in US studies, species composition generally was skewed toward

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lasiurine bats (migratory, tree bats; Griffin 1970) including hoary bat (*Lasiurus cinereus*), eastern red bat (*L. borealis*), and silver-haired bat (*Lasionycteris noctivagans*; Arnett et al. 2008). However, recent studies suggest that bat mortality in agricultural landscapes of the mid-western United States is higher than previously estimated; short-distance migrant and non-migratory bats, such as little brown (*Myotis lucifugus*; Barbour and Davis 1969, Griffin 1970) and big brown bats (*Eptesicus fuscus*), respectively, are experiencing higher rates of mortality than previously had been recorded (Gruver et al. 2009, Grodsky 2010, Jain et al. 2011).

Our objectives were to assess the impact of a wind facility in southeastern Wisconsin, USA, on bats by 1) estimating bat mortality, both migratory and non-migratory and/or short-distance migrant; 2) recording the species composition of collected bats; and 3) determining the correlative variables associated with bat mortality. In addition to addressing these objectives, we discuss the management implications for bat species in agricultural regions such as the Midwest and make suggestions for future research.

STUDY AREA

The western boundary of the study area was set back 3.2 km from the eastern edge of Horicon Marsh National Wildlife Refuge (Horicon Marsh) as a condition of the operating permit issued by the Wisconsin Public Service Commission (WPSC), with guidance from the Wisconsin Department of Natural Resources (WDNR) and US Fish and Wildlife Service (USFWS). The remaining boundary lines encompassed all turbine locations at the Forward Energy Center (Center). The Center was in northern Dodge and southern Fond du Lac counties in southeastern Wisconsin and covered 13,110 ha. The Center became commercially operational on 14 May 2008 and consisted of 86 General Electric 1.5sle (1.5-MW) wind turbines. General Electric model 1.5sle wind turbines were 80 m high at the hub, with a maximum height of 118 m above ground level at the apex of the rotor-tip revolution and a rotor-sweep area of 77 m across. Roughly 97% of the project area was agricultural land (primarily corn and soybean rotation) and approximately 2% of the land area was deciduous woodland (i.e., fencerows, isolated woodlots). The Center was approximately 5 km east of Horicon Marsh, 16 km north of Neda Mine State Natural Area and hibernaculum (Neda Mine), 56 km west of Lake Michigan, and 21 km south of Lake Winnebago.

METHODS

We collected data within two study periods over 2 years. Most mortality occurs during peak migration periods for bats, so we concentrated our searches around these times (Howe et al. 2002, Johnson 2005, Kunz et al. 2007*b*, Arnett et al. 2008). We searched turbines during autumn study periods from 15 July to 15 October 2008 and 2009 and spring study periods from 15 April to 31 May 2009 and 2010.

Study Design

We used an experimental design adapted from previous bat mortality studies that shared similar ecological attributes to our study area (Jain et al. 2007, 2011; Kerlinger et al. 2007). Our sampling methods were consistent with protocols from California, USA, and Canada (Canadian Wildlife Service 2007), as well as standards for post-construction monitoring at terrestrial wind facilities in Wisconsin recommended by the USFWS, WDNR, and WPSC.

We randomly selected 29 of 86 (34%) wind turbines at which to search for bat carcasses. We divided the Center into three north–south-oriented sections, each approximately 3.22 km wide, which allowed establishment of an impact gradient as distance increased eastward from Horicon Marsh and northward from Neda Mine (Fig. 1). Number of selected turbines in each section was proportional to the total number of turbines in each section. Because the western, central, and eastern strata contained 48%, 38%, and 14% of the total number of turbines at the Center, respectively, we searched 14, 11, and 4 turbines within each respective section.

Study Plots

We defined total search area identically for all 29 study plots, with each plot consisting of a 160-m × 160-m square (2.5 ha) centered on the wind turbine. For 26 of the 29 searched turbines, we monitored only 19% (0.5 ha) of the total searchable area to minimize impacts on landowner crops because the Center was situated among private agricultural land. For each of the 26 turbines, we randomly selected five parallel 160-m × 5-m transects from a grid superimposed upon the total searchable area. The five parallel transects were perpendicular to the turbine access road. The access road itself plus an extension and the pad of the turbine served as a sixth search transect.

At the remaining three turbines, we monitored the entire searchable area, which allowed us to determine the number of carcasses potentially missed within plots where we only searched a subset of the total searchable area. Additionally, we searched three 0.5-ha control sites to measure background mortality. Control plots replicated search plots in terms of land use and cover to the extent possible. One control site and one fully cleared study plot were present within each of the three, north–south-oriented sections of the study area, but we located each control site outside of Center boundaries (*see* Fig. 1).

All of the turbines monitored during our study were located in active agricultural fields; the searchable areas of study plots primarily passed through corn and soybean crops. However, other crop types present included alfalfa, wheat, timothy grass, and hay, in addition to Conservation Reserve Program habitat. We marked transects with posts and flagging for the duration of our 2-year study. A hired crew cleared search transects of vegetation by mowing with a tractor; at all plots, mowing ensured adequate visibility (i.e., low, uniform vegetation levels or bare soil; see Supporting Information for visual example: available online at www.onlinelibrary.wiley.com). Variation in visibility between crop types was captured in searcher efficiency trials (see Searcher Efficiency below).

Carcass Searches

Carcass searches were consistent across all study plots. We searched the 0.5-ha plots by walking up one side of the

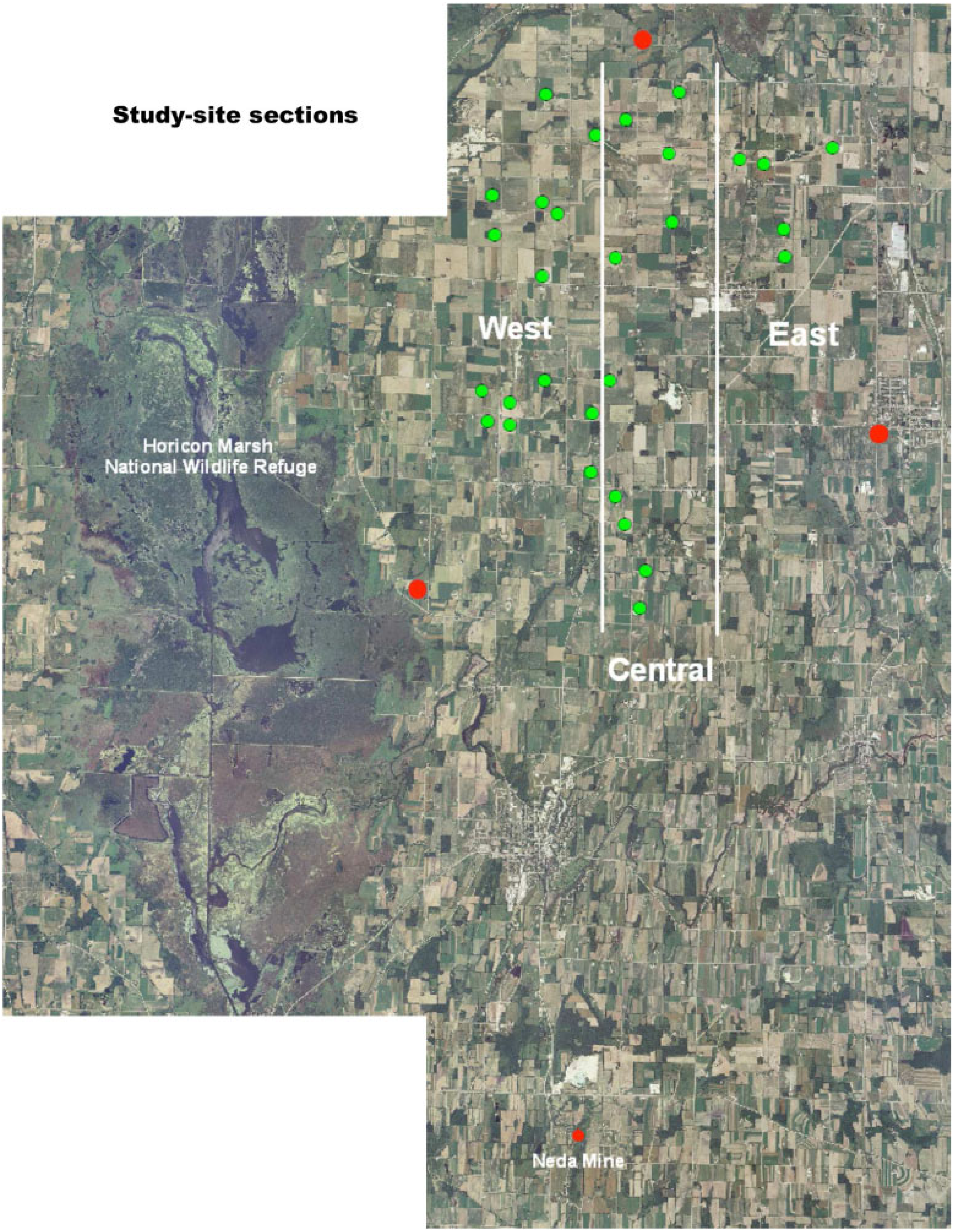

Figure 1. Map of Forward Energy Center, Wisconsin, USA, and impact gradient with study turbines (green dots) in their respective project sections and control plots (large red dots) outside of the Center boundaries, 2008–2010. The exact location of Neda mine is indicated by a small red dot (bottom of map); this dot does not represent another control plot.

transect and then down the other side. We searched the 2.5-ha plots by walking parallel transects 5 m apart in a zigzag pattern and scanned approximately 2.5 m to each side of the search line. For all 29 study plots, we also searched the entire gravel and cement areas of the turbine pad. Prior to searches, we recorded weather conditions and vegetation height. We cleared all plots of any carcasses prior to beginning the first search of each season.

When found, we assigned carcasses to a unique carcass identification number that included turbine number and date, placed them in a re-sealable bag, and scored them for level of decomposition based on the following scale:

Freshly killed—unaltered by scavenging animals, no signs of fly larva infestation (approx. 1–2 days on the landscape);
Partially scavenged—signs of insect infestation, partially degraded and/or scavenged (approx. 2–5 days on the landscape); or
Decomposed—severely decomposed and/or scavenged (>5 days on the landscape).

We estimated distance of the carcass from the base of the turbine using the same grid system from which we randomly chose the search transects. We recorded additional information on the appearance of the carcass and its location (e.g., cover type in which it was found), and photographed the carcass. The lead author identified carcasses to species (in hand).

We froze and saved all collected bats for future use in searcher efficiency and scavenger removal trials, except for bats found during the autumn 2009 study period. These bats were refrigerated and transported to the Wisconsin Veterinary Diagnostic Laboratory (WVDL) for post-mortem analysis (see Grodsky et al. 2011). We assigned age and sex to a subset of carcasses either at the University of Wisconsin Zoology Museum (Museum) by gonadic development or the WVDL by gonadic development and the degree of physeal fusion of the wing joints (Brunet-Rossinni and Wilkinson 2009). P. Holohan of the Museum identified bat carcasses found in advanced states of decomposition by using skull morphology. We considered bat carcasses found outside of designated searchable areas or discovered at turbines outside of the study area (e.g., reported by Center technicians) as incidentals. We excluded incidental carcasses from mortality estimates. We obtained required collection and salvage permits for the transport and possession of deceased wildlife from the WDNR and the USFWS. Our research was exempt from University of Wisconsin—Madison's Animal Care Use Committee approval.

Search Intervals

To minimize the potential for carcass removal by diurnal scavenging animals, we began searches approximately 30 min before sunrise. We generally concluded searches prior to 1200 hours. We randomly selected searched turbines for one of three search schedules during the study periods: 11 (38%) turbines were searched every day, 9 (31%) were searched every 3 days, and 9 (31%) were searched every 5 days. We randomly assigned these search intervals to turbines throughout the three study sections. We searched one each of the three fully cleared sites and control sites every day, every 3 days, and every 5 days. We randomized the order in which turbines were searched during the day to prevent bias from time of day effects.

Searcher Efficiency

We conducted searcher efficiency trials to estimate the percentage of carcasses not seen and recovered by individual searchers. We calculated a searcher's efficiency as the percentage of trial bat carcasses found and recorded by the searcher relative to the total number of carcasses placed within the search area for that particular searcher. Trials coincided with actual mortality searches, and we used bat carcasses (varying from 1 to 4/trial) placed at randomly selected locations within the searchable area of the study plot prior to each day's searches. Timing and carcass placement was unknown to the searchers. We did not physically mark the trial carcasses, but we explicitly mapped them on a grid and notated identifying attributes (e.g., species, appearance, condition of carcass) to differentiate the trial carcasses from actual fatality events. A field technician returned after searches were completed for the day to determine whether searchers had successfully located trial carcasses. Although we implemented trials at randomly selected turbines, every searched turbine was used for searcher efficiency trials throughout the duration of each field season. We set out approximately 100 bats during each study period to test for searcher efficiency. We used bats collected during mortality searches and from the Wisconsin State Laboratory of Hygiene (post-rabies testing—opened brain case) as trial carcasses. We conducted searcher efficiency trials throughout the duration of each field season to account for any temporal variation in searcher efficiency. We averaged each searcher's ($\bar{x} = 5.5$ searchers/study period) efficiency/turbine/study period using results from approximately 18 searcher efficiency trials/searcher/study period and included these rates in the corrected mortality estimator (see Supporting Information for searcher efficiency trial results: available online at www.onlinelibrary.wiley.com).

Scavenger Removal Rate

We designed scavenger removal trials to account for carcass removal by scavenging animals before searchers encountered them. These trials also accounted for removal due to other sources, such as tilling, plowing, mowing, and manure spreading, and weather-mediated events, such as the flooding of study transects. Because retrieved bat carcasses were needed to determine cause of death in a separate study (see Grodsky et al. 2011), we used black and gray weanling mice (20–25 days old; Rodentpro®.com, Inglefield, Indiana) as surrogates for bat carcasses in some cases. We used 1–3 bats or surrogate mice for each trial and performed 100 trials during each study period. Similar to searcher efficiency trials, we evenly distributed the scavenger removal trials throughout the entire study period to account for temporal variation in scavenger abundance and composition. We randomly selected the turbine, date, and placement of trial carcasses and mapped each carcass using the same methods as described for searcher efficiency trials. We checked trial carcasses every day to determine whether a scavenging event occurred, but the duration of scavenger removal trials matched the search interval for the selected turbine (i.e., 1 day, 3 day[s], or 5 day[s]). We set out the scavenger removal-trial carcasses prior to 1200 hours. Unlike with searcher efficiency trials, each searcher and field technician had a copy of the mapped locations for each scavenger removal carcass at each study plot to prevent searchers from removing carcasses used for scavenger removal trials before the trial concluded (see Supporting Information for scavenger removal-trial results: available online at www.onlinelibrary.wiley.com).

Mortality Estimation

We estimated mortality using data collected from four study periods (summer–autumn 2008 and 2009, and spring 2009 and 2010). Because carcass searches did not occur throughout the calendar year, we conditioned the results on sampling periods, which primarily coincided with migratory periods for bats. We used a slightly modified version of a mortality estimator proposed by Huso (2010), which accounts for searcher efficiency, scavenger removal, search interval, density-weighted area searched, and visibility within search transects. Because we shortened the amount of time during which we left trial carcasses on the landscape for scavengers to find, we modified Huso's (2010) estimator by not using the exponential component for scavenger removal and instead, substituted the 2-year average for the 1-day, 3-day, and 5-day scavenger removal rates of bats (1-day = 0.18, 3-day = 0.5, and 5-day = 0.65). Our estimates, along with 95% confidence intervals, were based on 3,000 bootstrap samples with replacement from the original data and calculated using a program developed for the purposes of this paper (see Supporting Information for code: available online at www.onlinelibrary.wiley.com) in SAS (Version 9.2; SAS Institute Inc., Cary, North Carolina).

None of the incidental mortalities or carcasses found on non-search plots were included in mortality estimates. We estimated mortality for three categories, including total bats, non-migratory and/or short-distance migrant bats, and migratory bats. For each group, we estimated mortality/turbine and mortality/MW (hourly power; see Arnett et al. 2008) for each study period and the entire study (i.e., 277 search days in four study periods). We assumed delayed lethal effects or crippling bias to be low (but see Grodsky et al. 2011, Rollins et al. 2012), and we did not account for them in our mortality estimates.

Covariates

We obtained post-construction weather data, including hourly records of visibility, temperature, ceiling height, relative humidity, dew point, barometric pressure, precipitation, altimeter, and wind speed from the National Oceanic and Atmospheric Administration station at the Fond du Lac, Wisconsin, airport, located 17 km from the project area. We obtained turbine operating status data, including hourly power (MW) and revolutions per minute of the rotor, from Invenergy, LLC via a General Electric data-logger. We averaged all of the hourly data over a 12-hour period from 1900 hours to 0700 hours each night, which encompassed times of peak bat activity. We measured distances of each study plot from Horicon Marsh and Neda Mine using spatial analyst tools in ArcMap software.

Statistical Analysis

We analyzed bat mortality recorded at the Center with respect to select landscape, weather, and turbine status covariates. All statistical analyses were performed using SAS software (Version 9.2; SAS Institute Inc.). To evaluate use of mice as surrogates for bats in scavenger removal trials, we used 99 records from the spring 2010 study period, which included a random mixture of mice and bats. We used a Cox proportional hazards model (after verifying assumptions) with PROC PHREG using type of carcass (bat or mouse) as a fixed effect. We also evaluated a generalized linear mixed model (GLMM), which allowed for fixed and random effects. We used PROC GLIMMIX to construct a predictive model evaluating the relationship between covariates and a response variable: bat mortality. The unit of analysis was the occurrence (1 = carcass present; 0 = no carcass present) of a bat carcass per turbine per search day. We did not independently model migratory and non-migratory and/or short-distance migrant bat mortality because the numbers were too small. We evaluated covariates for co-linearity using Pearson's correlation coefficients, and when correlated variables were encountered ($r \geq 0.5$ or $r < 0.5$ and $P \leq 0.10$), we randomly excluded one from further consideration in the model. We accounted for spatial and temporal variation by including the natural log of the time spent searching a given site, which is a proxy for the area searched (e.g., 0.5 ha vs. 2.5 ha), as an offset in our model. In the GLMM, random effects included searcher nested within season and visit (i.e., search day) nested within turbine and season. We used a logit link for the response variable to analyze differences in the odds of a fatality event occurring as a function of selected covariates. Degrees of freedom were derived using the approximation of Kenward and Roger (1997). We performed parameter estimation using the Restricted Maximum Subject-Specific Pseudo-Likelihood approach, which sufficiently accounts for random effects (Molenberghs and Verbeke 2006). We conducted *post hoc* analyses on least-square means using a Bonferroni adjustment to evaluate differences between study periods with respect to bat mortality.

RESULTS

Carcass Searches

We searched for 277 days. We searched 93 days for each autumn study period, and 47 and 44 days for the spring 2009 and spring 2010 study periods, respectively. We completed 3,763 carcass searches throughout the duration of our 2-year study. By search interval, we did 2,562 carcass searches ($\bar{x}$ = 232.91/turbine) for turbines searched daily, 724 carcass searches ($\bar{x}$ = 80.44/turbine) for turbines searched every 3 days, and 477 carcass searches ($\bar{x}$ = 53/turbine) for turbines searched every 5 days. We completed 135, 43, and 29 carcass searches at the control sites searched daily, every 3 days, and every 5 days, respectively, for a total of 207 carcass searches at all control sites.

Bat Mortality

We found 122 bat carcasses during scheduled carcass searches, with none recorded as incidental finds. We mostly found fresh bat carcasses (61%), while 26% and 13% of the bats were partially scavenged and decomposed, respectively.

Table 1. Summary of bat species found during mortality searches at the Forward Energy Center, Wisconsin, USA, 2008–2010.

Common name	Autumn 2008		Spring 2009		Autumn 2009		Spring 2010		Grand total	
	N	%	*N*	%	*N*	%	*N*	%	*N*	%
Silver-haired bat	23	29.9	2	100	10	24.4	0	0	35	28.7
Hoary bat	18	23.4	0	0	16	39.0	1	50	35	28.7
Little brown bat	11	14.3	0	0	1	2.4	1	50	13	10.7
Eastern red bat	8	10.4	0	0	6	14.6	0	0	14	11.5
Big brown bat	7	9.1	0	0	4	9.8	0	0	11	9.0
Unidentified *Myotis* spp.	6	7.8	0	0	0	0	0	0	6	4.9
Unidentified bat	4	5.1	0	0	4	9.8	0	0	8	6.6
Total	77	100	2	100	41	100	2	100	122	100

We found mortalities from five unique bat species (Table 1). Additionally, we identified a group of bats in the autumn 2008 study period to the genus *Myotis*; however, we did not record the species of these bats because they were used as searcher efficiency trial carcasses before they could be identified to species. Hoary bats ($n = 35$; 29%) and silver-haired bats ($n = 35$; 29%) collectively composed over half of the bat mortalities. With the inclusion of eastern red bat ($n = 14$; 12%) carcasses, the migratory tree bats (i.e., hoary bat, silver-haired bat, and eastern red bat) accounted for 69% of bat mortality. Non-migratory or short-distance migrants included little brown bats ($n = 13$; 11%), big brown bats ($n = 11$; 9%), and unidentified species of the genus *Myotis* ($n = 6$; 5%). These bats accounted for approximately 25% of total bat mortality. Unidentified bat carcasses made up the remaining 7% of the total recorded bat mortality. Of the bats we found, little brown and big brown bats are listed as state threatened in Wisconsin. We assumed federally endangered Indiana bats (*M. sodalis*) did not occur as residents, migrants, or vagrants in our study area due their rarity in Wisconsin and the fact that our study area was north of their known range. We found no bat carcasses at control sites during the study. Of the bat carcasses retrieved, we sexed and aged a subset ($n = 48$) at the Museum and the WVDL. Most bats were adults ($n = 39$; 81%), while the age could not be determined for nine (19%) bats due to decomposition. Females ($n = 22$; 46%) outnumbered males ($n = 16$; 33%). We could not determine sex for 10 (21%) bats. Bat mortality was relatively evenly distributed throughout the Center. The 2.5-ha plots accounted for 21% of the total bat mortality. We found approximately 80% of bat carcasses ($n = 89$) within 40 m of the base of the turbine (Table 2). Given our search area, the proportion of carcasses found at each distance class may not have exactly reflected the actual distribution of all fatalities but likely reflected virtually all of the quick-kill fatalities that occurred.

Our model results suggested that increasing temperature ($F = 8.96$, $P = 0.003$) and study period ($F = 5.30$, $P = 0.004$) were significantly associated with bat mortality and distance to Horicon Marsh ($F = 3.72$; $P = 0.054$) was marginally significant. As distance from Horicon Marsh increased (i.e., moving eastward), the chances of observing a bat fatality increased when controlling for other factors in the model (Odds Ratio = 1.100; 95% CI = 0.998–1.211). All other covariates did not influence bat mortality in our model (Table 3).

Estimates

Averaged over all study periods, we estimated total bat mortality was 0.19 bats/turbine/day and 0.13 bats/MW/day; migratory bat mortality was 0.13 bats/turbine/day and 0.08 bats/MW/day; and non-migratory and/or short-distance migrant bat mortality was 0.04 bats/turbine/day and 0.03 bats/MW/day. Migratory and non-migratory and/or short-distance migrant bat mortality estimates do not equal total bat mortality estimates because a small subset of bats could not be ascribed to species (hence, migratory status) due to decomposition state. We estimated an average of 4,454 total bat, 3,019 migratory bat, and 912 non-migratory and/or short-distance migrant bat fatalities, respectively, during the two spring and two autumn study periods or 277 search days (see Supporting Information for breakdown of bat mortality by study period: available online at www.onlinelibrary.wiley.com). The persistence (survival) distribution of mice was no different from bats in scavenger removal trials ($\chi^2 = 1.49$, $P = 0.22$).

Temporal and Spatial Distribution

Most bat mortality occurred from late August through the second week of September for both autumn study periods (Fig. 2). Bat mortality in the spring study periods peaked in late April through early May and again in mid-May;

Table 2. Summary of the distances bat carcasses were found from searched turbines at the Forward Energy Center, Wisconsin, USA, 2008–2010. Excludes incidentals.

Distance range[a] (m)	% Bat carcasses found				
	Autumn 2008	Spring 2009	Autumn 2009	Spring 2010	Total %
0–10	24	0	29	0	25.89
10–20	19	0	21	50	17.85
20–30	20	50	21	50	22.32
30–40	14	0	13	0	13.40
40–50	7	50	11	0	7.14
50–60	7	0	0	0	4.46
60–70	7	0	5	0	6.25
70–80	1	0	0	0	1.79
80–90	0	0	0	0	0
90–100	0	0	0	0	0
100–110	1	0	0	0	0.90

[a] Given our search area, the proportion of carcasses found at each distance class may not exactly reflect the actual distribution of all mortalities, but likely reflects virtually all of the quick-kill fatalities that occurred.

Table 3. Evaluation of fixed effects from GLMM of bat mortality at the Forward Energy Center, Wisconsin, USA.

Model effects	Numerator degrees of freedom	Denominator degrees of freedom	*F* value	*P* value
Study period	3	41.19	5.30	0.004
Power	1	3,049	1.82	0.178
Temperature	1	2,243	8.96	0.003
Relative humidity	1	3,208	1.07	0.300
Wind speed	1	2,966	0.83	0.363
Precipitation	1	3,298	0.90	0.342
Distance to mine	1	1,348	0.06	0.801
Distance to marsh	1	1,312	3.72	0.054

however, the sample sizes for bat mortality during spring study periods were low ($n = 4$). Migratory bat mortality peaked from 15 August to 15 September both years, while non-migratory and/or short-distance migrant bat mortality remained relatively constant through time (Fig. 3). Bat mortality was lower in the second year of the study when compared with the first, despite consistent searcher efficiency and scavenger removal rates. There was a significant difference in mortality between the summer–autumn of 2008 and both spring study periods, respectively (Bonferroni; $P = 0.017$; $P = 0.038$). However, no difference was detected between both summer–autumn study periods or between both spring study periods (Table 4).

DISCUSSION

Current estimates of bat mortality in agricultural landscapes suggest that, in some cases, bats are experiencing similarly high mortality rates at wind facilities both on forested ridge-tops and in agricultural regions. Previous studies in forested regions of the eastern United States recorded mortality rates that ranged from 14.9 to 53.3 bat fatalities/MW, during an undisclosed time interval (Arnett et al. 2008). Wind-facility mortality rates in forested regions of the eastern United States were highest in comparison with other regions (e.g., agricultural Midwest, Rocky Mountain, Pacific Northwest). These high mortality rates may be correlated with fragmented, linear landscapes on forested ridge-tops (areas used by bats for travel and feeding) created by the development of wind facilities in the eastern United States and food availability. Our average bat mortality estimate, transformed to match reporting standards for other studies, was 17.5 bat mortalities/MW/year (34.63 bat fatalities/MW/span of study, 51.80 bat fatalities/turbine/span of study) and falls within the lower spectrum of mortality rates recorded in the eastern United States. Although methodologies differ, Blue Sky Green Field (BSGF; Gruver et al. 2009), and Cedar Ridge (CR; BHE Environmental, Inc. 2010) wind-facility studies, both located in Wisconsin, USA, are most comparable to ours in design, land use, timing of searches, and cover types. BSGF estimated 21.6 bat fatalities/MW/year excluding incidentals and CR estimated 50.5 bat fatalities/turbine/entire study excluding incidentals (per MW not provided). Outside of Wisconsin, recent studies in agricultural landscapes in Alberta, Canada (Baerwald and Barclay 2011) and the Top of Iowa (TOI) wind facility (Jain et al. 2011) estimated slightly lower mortality rates (11.42 bats/MW/yr and 7.94 bats/MW/Mar–Dec, respectively). Comparisons using the same units are difficult to make due to differences in reporting standards and methodologies among studies (Piorkowski et al. 2012). Additionally, geographic variation and differences in migration routes may induce disparity in mortality rates among studies, even in similar landscapes. Agricultural landscapes, such as those found in the mid-western United States, are likely cover types for future wind facilities worldwide (Garvin et al.

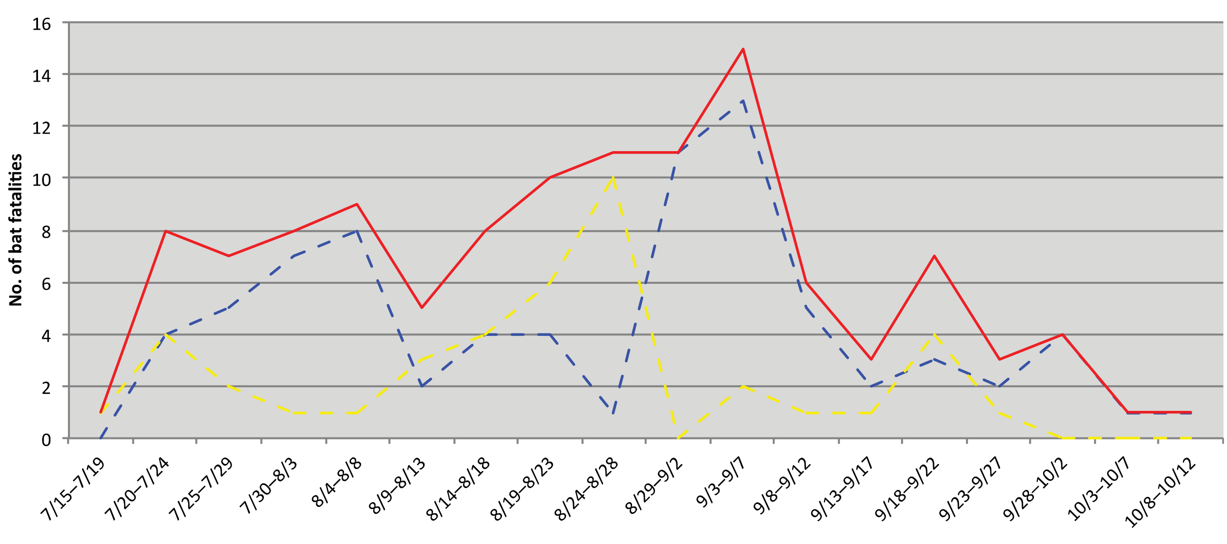

Figure 2. Temporal variation in observed bat fatalities at 29 wind turbines at the Forward Energy Center, Wisconsin, USA, during the autumn 2008–2009 study periods. Excludes incidentals. The solid red line is total bat mortality (i.e., both summer–autumn study periods); the dashed blue line is bat mortality in summer–autumn 2008; and the dashed yellow line is bat mortality in summer–autumn 2009. Time of year includes pooled mortality data from 2008 and 2009 summer–autumn study periods.

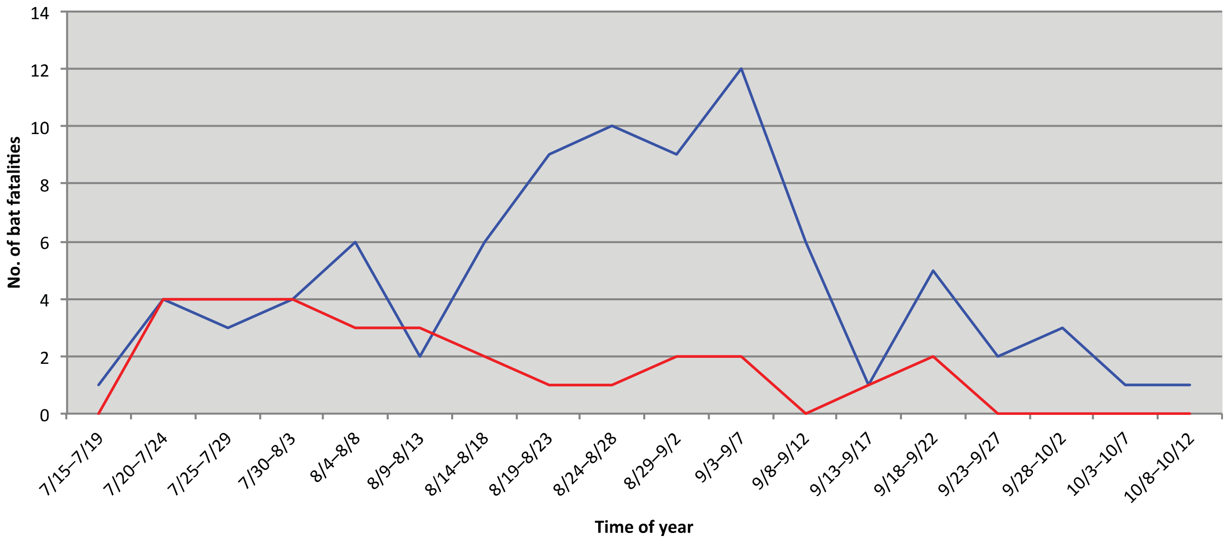

Figure 3. Temporal variation in observed bat mortality at 29 wind turbines at the Forward Energy Center, Wisconsin, USA, between migratory and non-migratory and/or short-distance migrants during 2008–2009 summer–autumn study periods. The blue line is migratory bat mortality; the red line is non-migratory and/or short-distance migrant bat mortality. Time of year includes pooled mortality data from 2008 and 2009 summer–autumn study periods.

2011) and already hold most of the wind facilities at which mortality studies have been done (Arnett et al. 2008); therefore, it is important to acknowledge higher than anticipated bat mortality rates in agricultural regions.

Another major management concern based on our data is the relatively high rate of non-migratory and short-distant migrant bat mortality. Although in most previous studies little brown and big brown bats comprised <13.5% of overall bat mortality (Arnett et al. 2008), our study found that little brown and big brown bats comprised approximately 25% of the total bat mortality. Neighboring studies in agricultural regions, including BSGF (Gruver et al. 2009), CR (BHE Environmental, Inc. 2010), and TOI (Jain et al. 2011), recorded similarly high rates (47.5%, 32%, and 33%, respectively). The Center is north of TOI and south of BSGF and CR, but is closest to Neda Mine, where little brown and big brown bats are known to hibernate in large numbers (Redell 2005). Despite the Center's proximity to Neda Mine, TOI, BSGF, and CR all recorded greater percentages of little brown and big brown bat mortality, and our model did not find a significant relationship between bat mortality and distance to Neda Mine. Therefore, agricultural landscapes themselves or, in the case of little brown bats, short-distance migration routes (see Barbour and Davis 1969) may play a role in non-migratory and short-distance migrant bat mortality. Studies in Europe found high rates of short-distance migrant bat mortality during the same time of year as did studies in the United States (summarized in Rydell et al. 2010), which may indicate that migration is related to short-distant migrant bat (e.g., little brown bat) mortality. Little brown and big brown bat mortality at wind facilities in the United States is of concern because these species are affected by the fungal pathogen (*Geomyces destructans*) that causes white-nose syndrome, which has led to unprecedented bat mortality since 2006 (Blehert et al. 2009). Population modeling by Frick et al. (2010) predicts that the little brown bat, once the most common species in North America, will experience regional extinction as a result of white-nose syndrome. The state of Wisconsin recently listed northern long-eared bat (*Myotis septentrionalis*) and eastern pipistrelle (*Perimyotis subflavus*), in addition to little and big brown bats, as state threatened due to their susceptibility to white-nose syndrome. Mortality at wind facilities could function as an additive source of mortality to declining populations of little brown bats, and perhaps to big brown bats.

Table 4. *Post hoc* comparison of study period effects on bat mortality at the Forward Energy Center, Wisconsin, USA

Year comparison	Degrees of freedom	*t* value	Adjusted *P* value
Autumn 2008 vs. autumn 2009	15.9	0.84	1.000
Autumn 2008 vs. spring 2009	165.6	3.18	0.017
Autumn 2008 vs. spring 2010	59.74	2.87	0.038
Autumn 2009 vs. spring 2009	141.2	2.64	0.070
Autumn 2009 vs. spring 2010	55.54	2.40	0.127
Spring 2009 vs. spring 2010	116.3	−0.07	1.000

Most bats found as mortalities at the Center were migratory tree-roosting bats (e.g., hoary bat, silver-haired bat, and eastern red bat), which is consistent with most studies in the United States and Canada (Kuvlesky et al. 2007, Arnett et al. 2008). Given the distinct temporal distribution of bat mortalities, particularly during the autumn study periods, mortality at the Center was likely correlated with migratory pulses of bats. Other studies have found both bird and bat migration tightly linked to mortality at wind facilities (Kunz et al. 2007*b*, Arnett et al. 2008, Cryan and Barclay 2009), most likely because wind facilities are often situated along migration routes. Baerwald and Barclay (2009) suggest bat migrations, at least in the autumn, are concentrated on select routes, rather than dispersed amongst the landscape. Therefore, concentrated migratory pulses of bats that are following routes likely to be intercepted by wind facilities may yield high numbers of migratory bat fatalities. Clearly, migratory bats killed during the mating period (i.e., autumn—delayed fertilization in tree bats) will not reproduce the following spring, potentially affecting population dynamics.

Bat mortality was significantly different between the summer–autumn and spring study periods. There were significantly fewer bat fatalities in the spring compared with the autumn, which is consistent with other studies (Johnson 2005, Arnett et al. 2008). Density and routes of autumn and spring bat migration may differ for many migratory species (e.g., hoary and eastern red bat; Johnson et al. 2003) and may potentially drive this pattern. Johnson et al. (2003) also suggest silver-haired bat presence is more stable from spring through summer in the Midwest; we recorded only silver-haired bat mortality in spring, although numbers were low. Agricultural environments surrounded by neighboring wood lots may serve as migratory stopovers for tree-roosting bats because both roosts and food are provided. Our results suggest temperature is associated with bat mortality; higher temperatures may increase insect activity (see Erickson and West 2002), which may in turn increase bat foraging and consequential risk of contact with wind turbines. Similarly, migratory bats may be more likely to stopover in agricultural landscapes during warmer months (i.e., summer–autumn migration when insect emergence, particularly of crop pests, is high), increasing mortality risk at wind turbines. The paucity of resident or short-distance migrant bat mortality in spring may be a result of the coinciding birthing season or variation in short-distance migration routes between autumn and spring for little brown bat.

Several other patterns and relationships emerged from our results. Other studies revealed increased bat mortalities with lower wind speeds (see Arnett et al. 2008, Baerwald et al. 2009), but we did not find any such relationship in our analysis. Bats, like most flying animals, are more active at lower wind speeds; consequently, bat mortality may be higher at low wind speeds due to higher bat activity. Our study may differ in methods, species composition, time scale, and geographic location from similar studies that found wind speed impacted bat mortality. However, our search interval, which was far more frequent than any previously reported study, allowed us to relate fresh bat carcasses to nightly weather covariates, and may offer a more direct measure of relationships between bat mortality and weather variables. Most bats killed at the Center were adults, which is consistent with results from other studies (Arnett et al. 2008). However, there were slightly more female compared with male bats found during mortality searches, which is less commonly reported in the literature, but may have a greater impact on overall population status due to removal of breeders from the population. Our model suggested important regional landscape features such as Neda Mine and Horicon Marsh had little impact on bat mortality, which indicates bat mortality may be more linked to other factors, such as migration and/or agricultural landscapes.

An important issue that hampered direct comparison across studies of bat (or bird) mortality at wind facilities is the lack of standardization in search and statistical methodologies, as well as metrics for reporting mortality (see Piorkowski et al. 2012). Studies use different definitions or methods (e.g., search interval, search frequency, searcher efficiency, and scavenger removal trials), which likely influences resultant mortality estimates making interpretation of study differences difficult. On the other hand, the notion of meta-replication (Johnson 2002) is applicable to this research area; that is, given that general conclusions can be made across multiple studies, should we be so concerned with methodological standardization? This warrants further consideration, but until formal evaluation takes place, we specifically urge researchers to consider reporting standardized mortality metrics and their associated standard errors, which can be easily transformed (e.g., via the Delta method) to facilitate comparison with other studies. For example, we believe that mortality per MW per day is an appropriate reporting measure because it only accounts for the mortality captured in a given study's duration and MW can easily be converted to KwH if necessary, which enables easier comparisons between differing energy sources (Sovacool 2009). Studies that report bat mortality per year do not account for bat behavior, such as migratory movements and hibernation. Currently, there are no mortality estimators that account for delayed lethal effects of wind facilities on bats or studies that have documented delayed lethal effects (Piorkowski et al. 2012). After initial non-lethal contact with wind turbines, bats may experience mortality caused by injuries such as ear or skeletal damage, which have been found to occur more frequently than originally anticipated (see Grodsky et al. 2011, Rollins et al. 2012). However, post-mortem assessment of non-lethal injuries is difficult (Grodsky et al. 2011), and the feasibility of accounting for delayed mortality is questionable.

MANAGEMENT IMPLICATIONS

Our search intervals, frequency, and the proportion of turbines searched daily exceeded those of most published studies, and we accounted for sampling bias (including searcher efficiency and scavenger removal) by abiding by the most updated recommendations, which many studies have not done sufficiently (reviewed in Arnett et al. 2008). Our study is the first to statistically analyze and determine that weanling mice are viable surrogates for bat carcasses in scavenger removal trials. Surrogate mice enable researchers to use bat carcasses collected under wind turbines for concurrent studies without compromising the efficacy of scavenger removal trials. Although our model suggested that proximity of the Center to Horicon Marsh, a National Wildlife Refuge, only marginally affected bat mortality, we recorded relatively high numbers of bat mortalities in agricultural landscapes near Horicon Marsh and the impact of Horicon Marsh, on short- and long-distance bat migration was not studied. Given that we found temperature to be associated with increased bat mortality, the potential drivers of that relationship (e.g., insect activity) should be more fully studied. We found comparatively high numbers of non-migratory and short-distance migrant bat mortalities, and these species are susceptible to white-nose syndrome. Consequently, we encourage management agencies to distinguish wind facilities' impacts on non-migratory and short-distance migrant bats in addition to migratory bats, and to consider study of the determinants of short-distance migration routes of bats (e.g., little brown bat).

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