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Source: Acta Chiropterologica, 22(1) : 135-146

Published By: Museum and Institute of Zoology, Polish Academy of Sciences

URL: https://doi.org/10.3161/15081109ACC2020.22.1.012

Acta Chiropterologica, 22(1): 135–146, 2020
PL ISSN 1508-1109 © Museum and Institute of Zoology PAS
doi: 10.3161/15081109ACC2020.22.1.012

Bat activity rates do not predict bat fatality rates at wind energy facilities

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Bats are found as fatalities at most wind energy facilities around the world, creating a challenge for wind developers to predict risk to bats in an area before building a new facility. Bat echolocation activity surveys are the standard method for assessing risk, but their effectiveness has not been demonstrated. Sites with relatively low pre-construction bat activity rates are predicted to yield relatively low post-construction fatality rates (i.e., low risk), and vice-versa. To test this hypothesis, we ran simple linear regressions on bat activity rates and fatality rates from 49 paired pre- and post-construction studies across the United States and Canada. Bat activity rates did not predict bat fatality rates at wind energy facilities by detector height, by call frequency category of bats, or by season ($P > 0.10$). One possible explanation for the lack of a predictive relationship is that bat activity patterns may change between the pre- and post-construction periods if bats are attracted to turbines. Indeed, we found support that bat activity rates increased across call frequency category and season at four wind facilities that had measured bat activity rates before ($\bar{x}$ = 1.89 bat passes/detector-night) and after turbines were built ($\bar{x}$ = 4.84 bat passes/detector-night). However, simple linear regressions of post-construction activity rates and fatality rates from 25 studies found no correlation between activity and fatality rates collected concurrently by detector height (ground, raised, nacelle) or by call frequency category ($P > 0.05$). We conclude that the current pre-construction survey methods of collecting bat activity rates at proposed wind energy facilities do not provide reliable information on how many bat fatalities there may be once the facility is built, and advocate exploring other methods for assessing risk to bats prior to wind development.

Key words: bats, wind energy, acoustic monitoring, collision risk, United States, Canada, fatality rate

Introduction

Bats are found as fatalities at most wind energy facilities around the world (Arnett and Baerwald, 2013; EUROBATS, 2014; Arnett *et al*., 2015). The cause of bat fatalities is primarily collision with moving turbine blades (Grodsky *et al*., 2011; Rollins *et al*., 2012), though the underlying reasons for why bats come near turbines are still largely unknown (Cryan and Barclay, 2009; Barclay *et al*., 2017; Bennett and Hale, 2018). The number of bats killed at turbines ranges widely across facilities, and is typically expressed as the number of bat fatalities per megawatt (MW) per year for comparison amongst wind facilities with different numbers and sizes of turbines. In the U.S., a summary of 202 studies at 137 wind energy facilities found that bat fatality rates ranged between 0 and 49.7 bat fatalities/MW/year (AWWI, 2018), and a wind facility in Iowa had a fatality rate of 60.62 bats/MW/year (MidAmerican Energy Company, 2018). The factors driving this wide variation in bat fatality rates are currently unknown, yet assessing risk to bats in an area before building a new facility is important for evaluating potential wildlife impacts for a wind energy project (Lintott *et al*., 2016; Thaxter *et al*., 2017).

Acoustic monitoring has been the main tool used during pre-construction surveys to assess risk to bats (USFWS, 2012; Lintott *et al*., 2016). The earliest studies of operating wind energy facility impacts on bats found a general, positive association between overall bat echolocation activity rates recorded by ultrasonic detectors and fatality rates estimated from carcass surveys at turbines. Studies that recorded comparatively low bat activity rates had comparatively low fatality rates (Gruver, 2002; Johnson *et al*., 2004), and vice-versa (Fiedler, 2004; Arnett *et al*., 2005). Therefore, it was assumed that a predictive relationship might exist between bat activity recorded prior to construction and the number of fatalities found after turbines were built (Kunz *et al*., 2007).

Bat activity surveys subsequently became a standard component of baseline wildlife surveys at wind energy facilities (USFWS, 2012). Yet, as more studies were completed and became publicly available, this relationship was called into doubt. Hein *et al*. (2013) fit a linear regression model for 12 paired studies that had measured bat activity and fatality rates, and found no significant relationship between activity rates and fatality rates. However, data from relatively few studies were used and different research groups collected those data using different sampling protocols. Due to the relatively low number of available studies, Hein *et al*. (2013) only considered overall bat activity in their model, regardless of the height of detectors used, the species composition of bat calls, or the time of year that bat activity was recorded.

Activity rates recorded at 'raised' microphones placed between 30 and 50 meters (m) are assumed to be a better predictor of fatality than activity recorded at 'ground' microphones placed between 0 and 10 m (Roemer *et al*., 2017), given their proximity to the rotor-swept zone where the majority of bat fatalities at wind facilities occur (Horn *et al*., 2008; Cryan *et al*., 2014). Indeed, across five wind facilities in southern Alberta, 31% of the variation in fatality rates was explained by bat activity rates recorded at 30 m (Baerwald and Barclay, 2009). The majority of bat fatalities in the U.S. and Canada are composed of species that emit echolocation calls with minimum frequencies of less than 30 kilohertz (kHz; e.g., hoary bat *Lasiurus cinereus*, silver-haired bat *Lasionycteris noctivagans*, Brazilian free-tailed bat *Tadarida brasiliensis* — AWWI, 2018), and are sometimes categorized as 'low frequency' (LF) species during bat activity surveys (e.g., Good *et al*., 2012; Stantec Consulting Inc. and Western EcoSystems Technology Inc., in litt.). Since at least 63.0% of bats killed by wind turbines in the U.S. belong to LF species (AWWI, 2018), activity rates by LF bats may be a better predictor of bat fatality rates than activity rates by 'high-frequency' species (HF — e.g., eastern red bat *Lasiurus borealis*, many *Myotis* species). Lastly, the majority of bat fatalities in the U.S. occur during the fall (generally from July 1 to October 15 depending on latitude — Kerns *et al*., 2005; Arnett *et al*., 2008), so activity rates recorded during the fall season may be a better predictor of bat fatality rates than activity recorded throughout the overall study period, which can range from a single season (e.g., fall), to multiple seasons (e.g., summer and fall), to a full year.

Conducting pre-construction bat activity surveys costs tens of thousands of dollars for every proposed wind facility, and after more than a decade of studies the actual value of this work for estimating impacts to bats remains unknown. Therefore, the goal of our research was to revisit the activity-fatality relationship with a more comprehensive, standardized data set and determine whether a sufficient relationship exists to justify continued use of pre-construction activity surveys. We hypothesized that a positive relationship exists between bat activity rates measured prior to construction and bat fatality rates estimated after turbines become operational. We predicted this relationship would be strongest for activity rates recorded 1) by raised microphones near the rotor-swept zone of turbines, 2) for LF bats that are more frequently found as fatalities, and 3) during the fall season when most bat fatalities are found.

It has been suggested that bats are attracted to turbines, either because edge habitat created by clearing trees for turbines is attractive to foraging bats (Kunz *et al*., 2007), and/or because the turbines themselves are inherently desirable to bats as potential places to forage, roost, or mate (Cryan and Barclay, 2009; Jameson and Willis, 2014; Bennett *et al*., 2017; Foo *et al*., 2017; Reimer and Baerwald, 2018). Migratory tree bats in particular may perceive turbines as tall trees on the landscape that may be suitable for roosting, navigating (Cryan and Brown, 2007), or attracting mates (Cryan, 2008). If bats are attracted to turbines, then pre-construction activity rates may not be representative of bat activity at operational turbines and could confound any predictive relationship between pre-construction activity rates and post-construction fatality rates. To examine the hypothesis of turbine attraction, we compared bat activity rates measured before and after construction of turbines at a subset of facilities where these data have been collected. We then examined the relationship between activity and fatality rates measured concurrently at operational wind energy facilities and predicted a stronger correlation among these post-construction studies because activity data and fatality events were measured over the same time period.

Materials and Methods

To determine whether bat activity rates measured prior to construction were a good predictor of bat fatality rates once wind energy facilities were built, we compiled pre-construction bat activity rates and post-construction bat fatality rates for 52 wind energy facilities that were collected between 2006 and 2018. WEST, Inc. field crews collected data for 46 wind facilities, which provided some consistency in study methodology. We included data collected for another six facilities by different organizations to increase sample size and geographic coverage, and because these organizations used similar study design and analyses. For post-construction monitoring studies that ran multiple years, fatality rates were averaged to pair pre-construction bat activity rates to a single fatality rate at a study and avoid pseudoreplication in the data. Bat activity rates ranged between 0.1 and 15.1 passes/detector-night, and bat fatality rates ranged from zero to 24.6 bats/MW/study period. The duration of the overall study period varied among survey types, ranging from 45 to 669 nights ($\bar{x}$ = 146.3 days) for pre-construction surveys, and from 56 to 523 nights ($\bar{x}$ = 165.3 nights) for post-construction surveys. The duration of the fall season varied by latitude and by study design. Fall never began earlier than June 26 or went later than November 15 for a survey, and most fall periods occurred between mid-July and mid-October.

Four wind facilities in our dataset measured bat activity before and after turbines were built. To evaluate whether bat activity rates changed once turbines were built at these facilities, we compared bat activity rates between the final year of pre-construction surveys and the first year of post-construction surveys.

To determine whether bat activity rates were a good predictor for bat fatality rates once turbines were operating, we compiled post-construction bat activity and fatality rates for 31 wind facilities that were studied between 2000 and 2018. For studies that conducted activity and fatality monitoring concurrently for multiple years, we treated each year of study as an independent data point for this analysis. Bat activity rates ranged between 0.1 and 45.9 bat passes/detector-night, and bat fatality estimates ranged between 0.7 and 23.6 bats/MW/study period.

We evaluated all datasets for outliers using DFBETAS, DFFITS, covariance ratios, and Cook's distances to identify observations that strongly influenced the fitted values of the model (Fox, 1997; Belsley *et al*., 1980; Cook and Weisberg, 1982). We used data from 49 of 52 wind facilities in our main analysis of pre-construction activity rates and post-construction fatality rates, and included 25 of 31 wind facilities in our analysis of post-construction activity rates and fatality rates (Fig. 1). Excluded studies either exclusively sampled habitat that concentrated bat activity (n = 3 studies), measured fatality rates before activity rates (n = 2), included operational curtailment (i.e., limiting blade rotation by feathering turbine blades up to wind speeds higher than the manufacture cut-in speed; n = 2), or were located in a region of the country not included in this study (n = 1).

Activity Monitoring

All studies collected bat activity data with Anabat ultrasonic detectors (models II, SD1, and SD2 — Titley Scientific™, Columbia, Missouri, USA). Between two and 14 detectors ($\bar{x}$ = 4.5, median = 4) were used for each study, and microphones were calibrated to standardize activity data collection within and across studies. During pre-construction surveys, we placed microphones for detectors at two different height categories: 'ground' (approximately 0 to 10 m above ground level [AGL]) and 'raised' (approximately 30−50 m AGL). Post-construction activity surveys included an additional category for microphones placed on the nacelles of operational turbines ('nacelle'; approximately 80 m AGL). Twenty-one pre-construction studies used just ground microphones, while 28 studies used ground and raised microphones. Of the post-construction studies, six used just ground microphones, one used just raised microphones, one used just nacelle microphones, eight used ground and raised microphones, six used ground and nacelle microphones, one used raised and nacelle microphones, and two used ground, raised, and nacelle microphones. The precise methods and materials used for deployment varied among studies, but in general, detectors were enclosed within a plastic weather-tight container and microphones were protected within a 45° angle polyvinyl chloride (PVC) tube positioned at the desired sampling height. We placed all microphones in locations with vegetation that was representative of future turbine placement and lacked features that would concentrate bat activity, such as edge habitat, foraging/drinking areas, or known roost locations.

Echolocation calls were digitally processed and stored on high-capacity compact flash cards. We visually examined the resulting files in AnalookW software (Titley Scientific) as frequency versus time sonograms to separate bat calls from other types of ultrasonic noise (e.g., wind, insects) and to determine the call frequency category of the bat that generated the calls. A bat pass was defined as a sequence of at least two echolocation calls (pulses) produced by an individual bat with no pause between calls of more than one second (Fenton, 1980; Gannon *et al*., 2003). For each study, we identified and sorted bat passes into HF and LF call frequency categories based on the minimum call frequency. 'All bats' refers to all bat passes recorded for HF and LF bats. The metric used for measuring bat activity was the number of bat passes/detector-night. In this study, we used the terms 'detector' and 'microphone' interchangeably. A detector-night was defined as one detector (and its microphone) operating for one entire night. Across all studies used for these analyses, bat detectors operated for 84.6% of the time the detectors were deployed, on average (range = 55–100%). We calculated bat passes per detector-night for all bats, HF bats, and LF bats. Bat pass rates represent indices of bat activity and do not represent numbers of individuals. To estimate the number of bat passes per detector-night when multiple detectors were used, 1) the average number of bat passes per detector-night was calculated for each detector by taking the sum of the total bat passes divided by the total number of nights detectors were operating (i.e., detector-nights); and 2) the multi-detector bat passes per detector-night were calculated by taking the average number of bat passes per detector-night by detector and averaging across detectors for detectors at similar sampling heights.

Fatality Monitoring

The wind energy facilities used in this study ranged in size from 6 to 420 turbines ($\bar{x}$ = 132.2, median = 100). The height of wind turbines ranged from 70 to 101 m at hub height, with a rotor diameter of 38 to 56 m. We assumed that wind energy facilities used in this analysis are representative of the range of wind energy facilities in the U.S. and Canada. We collected data on bat fatalities using standardized carcass surveys. Searchers would survey a subset of turbines every 1 to 14 days depending on the study, and would record all bat fatalities found within search areas. Search areas were turbine pads and access roads out to a maximum distance of 100 m from turbines (n = 17), or were square (length of one side = 60−280 m, n = 46) or circular (radius = 40−160 m, n = 22) plots centered on the turbine and cleared of vegetation. The bat fatality rates were estimated by adjusting for search frequency, carcass persistence bias (length of time a carcass remained in the field), searcher efficiency bias (proportion of carcasses found during trials), and search area if applicable (e.g., adjustment for carcasses that fell outside of searched areas if turbine pads and access roads were searched). We conducted bias trials throughout the study periods at each facility.

We calculated fatality rates as the number of bat fatalities/MW/study period using either Huso ($n = 33$ studies), Shoenfeld (33), Smallwood (3), Jain (3), Erickson (2), empirical (2), naive (2), or unknown (5) estimators (Shoenfeld, 2004; Smallwood, 2007; Good *et al*., 2011; Huso, 2011; Huso *et al*., 2015). Fatality rates tend to be biased, and the level of bias associated with each estimate depends on the estimator used, the number of fatalities found, the search interval, the searcher efficiency rates, and the carcass persistence rates (Huso, 2011). We did not account for the level of bias associated with each estimate in this analysis. For studies that used both the Huso and Shoenfeld estimators ($n = 7$), we used the Huso (2011) estimator because it is generally less biased than the Shoenfeld estimator. We calculated fatality rates for the overall study period for all 74 studies used in our analyses, 17 of which contained data for just the fall period.

Bat Activity and Bat Fatality Analysis

We used simple linear regression analyses to test our hypothesis that sites with low bat activity rates would be associated with low post-construction fatality rates and vice versa. Ideally, the response and explanatory variables would be recorded in the same fall season (e.g. bat activity rates in the fall would be compared to fatality rates in the fall). However, fall-specific bat fatality rates were not available for 57 studies. To increase the sample size, we evaluated if fatality rates from the fall season were associated with the fatality rates from the overall study period using a Spearman's rank test. Results from this test indicated that there is a strong positive relationship between these fatality rates ($r_S = 0.89$, $n = 17$, $P < 0.001$). Therefore, we used the bat fatality rates during the overall study period as the response variable in all analyses.

For the analysis that compared pre-construction bat activity rates to bat fatality rates, 49 paired studies were retained for analysis after evaluating the pre-construction and post-construction datasets for outliers, 43 of which used the same data collection methods. Facilities were located in five of the seven U.S. Fish and Wildlife Service regions in the continental U.S. (Fig. 1). The number of studies within each geographic region was relatively limited, and we therefore did not evaluate the relationship between bat activity rates and bat fatality rates by region.

We used statistical tests ($\alpha = 0.10$) to evaluate if there were differences in bat activity rates by microphone height (ground and raised) and species call category (all bats, HF, and LF). We conducted all statistical analyses in this study using R language and environment (ver. 3.5.3 — R Core Team, 2019). We used a paired *t*-test to determine if the dataset should be

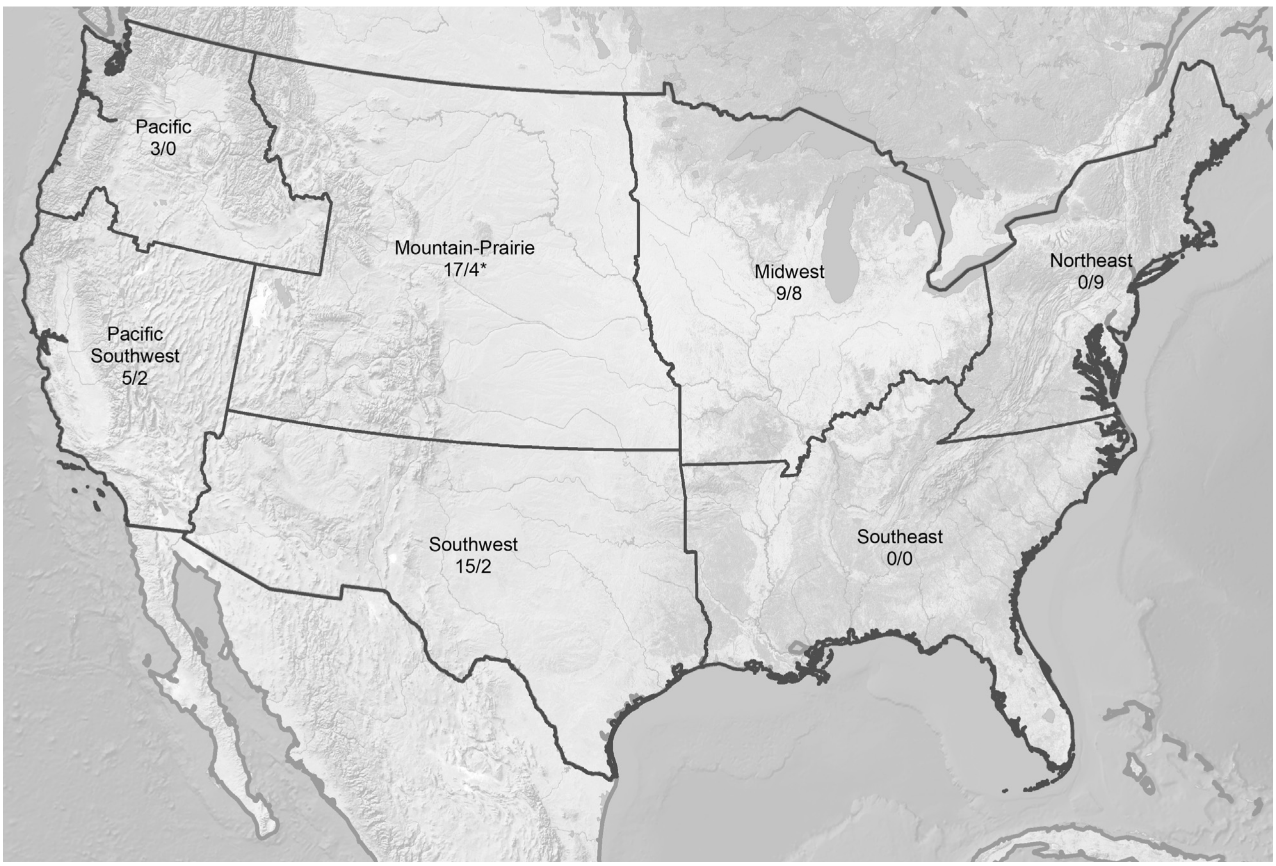

FIG. 1. The number of paired pre-construction bat activity and post-construction bat fatality studies (first number) and paired post-construction bat activity and post-construction bat fatality studies (second number) used for regression analyses, organized by U.S. Fish and Wildlife Service region. The Mountain-Prairie region includes five studies from southern Alberta, Canada

split by ground and raised microphone heights and we used a Wilcoxon matched-pairs signed-ranks test (Wilcoxon, 1945) to compare HF and LF species call categories. If the statistical tests determined there were differences in bat activity rates by microphone height or species call category the data were analyzed separately by category. Conversely, if the statistical tests determined that there were not differences in bat activity rate by microphone height or species call category, then the combined data were analyzed. Nonparametric tests were used if the sample size was small (i.e., less than 10), whereas parametric tests were used when the sample size was sufficiently large (i.e., greater than or equal to 10) and the data met the assumptions of the tests.

To examine whether bat activity rates changed once turbines were built, we compared bat activity rates measured during the final year of pre-construction surveys and the first year of post-construction surveys for each call frequency category (HF and LF) during each season (fall, winter, spring, and summer) from studies that had these data ($n = 4$). Due to the limited sample size for this comparison, we used descriptive statistics to summarize bat activity rate data collected prior to and after construction.

For the analysis that compared post-construction bat activity rates to bat fatality rates, we then used a Wilcoxon matched-pairs signed-ranks test (Wilcoxon, 1945) to compare HF and LF species call categories. We used the results from this test to determine if there should be separate simple linear regression models based on the bat call frequency category. Since the sample size for this analysis was limited (25 projects), the decisions from the analysis that compared pre-construction bat activity rates to fatality rates were also used for selecting the response and explanatory variables in these models. Therefore, we analyzed the activity data collected at turbines separately by microphone height (i.e., ground, raised, nacelle).

Results

Pre-Construction Bat Activity and Post-Construction Bat Fatality Rates

For studies that used both ground and raised microphones ($n = 27$), bat activity rates were significantly lower for raised microphones ($\bar{x} = 1.09$ bat passes/detector-night), standard deviation [SD] = 1.95) than for ground microphones ($\bar{x} = 2.37$ bat passes/detector-night, SD = 4.28; $t_{262} = 6.66$, $P < 0.01$). Therefore, we separated data by microphone height for all subsequent analyses. Mean bat activity rates by HF and LF bats were not statistically different at ground microphones (HF, $\bar{x} = 2.37$ bat passes/detector-night, SD = 3.93; LF, $\bar{x} = 1.46$ bat passes/detector-night, SD = 2.33; Wilcoxon matched-pairs signed-ranks test: $V = 1160.5$, $n = 77$, $P = 0.12$). Therefore, we conducted a simple linear regression analysis for ground microphone data using all measured activity rates for all bats. The analysis found that pre-construction bat activity rates recorded by ground microphones ($n = 47$) did not explain the variation in bat fatality rates ($P = 0.20$ — Table 1 and Fig. 2). Bat activity rates measured by ground microphones only accounted for 3.7% ($r^2 = 0.037$ — Table 1) of the variation in bat fatality rates.

At raised microphones, activity rates by HF bats ($\bar{x} = 0.23$ bat passes/detector-night, SD = 0.45; Wilcoxon matched-pairs signed-ranks test: $V = 56$, $n = 43$, $P < 0.01$) were significantly lower than LF bats ($\bar{x} = 1.34$ bat passes/detector-night, SD = 1.90). Simple linear regression analyses were therefore fit for each call category. Activity for either HF and LF bats did not explain variation in bat fatality rates when recorded by raised microphones (HF, $P = 0.43$; LF, $P = 0.65$ — Table 1 and Fig. 3). In addition, we found no relationship between bat activity rates measured during the fall season and overall study period fatality rates for all bats at ground

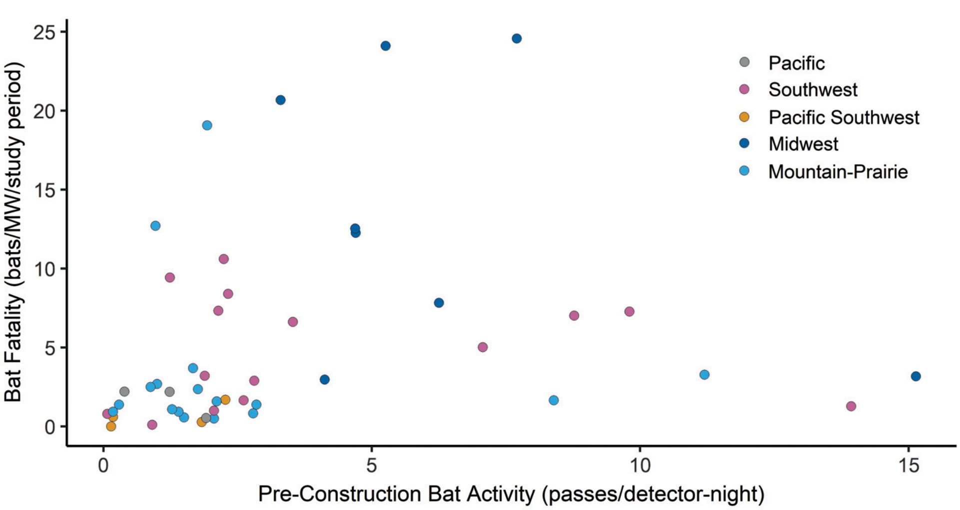

Fig. 2. Regression analysis for overall bat activity rates recorded by ground microphones ($n = 47$) versus overall bat fatality rates at paired pre-construction and post-construction studies, grouped by U.S. Fish and Wildlife Service region

TABLE 1. Regression analysis for bat activity rates versus overall bat fatality rates at both (A) paired pre-construction and post-construction study sites and at (B) paired post-construction study sites. 90% CI: 90% confidence interval; HF = high frequency bats; LF = low frequency bats

A. Paired pre-construction and post-construction studies

Variable	All frequency bats	HF bats	LF bats
Overall bat activity rates versus overall bat fatality rates		Microphone	
	Ground (n = 47)	Raised (n = 23)	Raised (n = 24)
Bat Activity Coefficient	0.341	2.380	-0.304
90% CI	-0.094, 0.776	-2.681, 7.440	-1.453, 0.844
r^2	0.037	0.030	0.009
Fall bat activity rates versus overall bat fatality rates	Ground (n = 42)	Raised (n = 18)	Raised (n = 17)
Bat Activity Coefficient	0.319	1.372	-0.432
90% CI	-0.124, 0.762	-3.654, 6.397	-2.526, 1.662
r^2	0.035	0.014	0.009

B. Paired post-construction studies

Variable	All frequency bats	HF bats	LF bats
All frequency overall bat activity rates versus overall bat fatality rates		Microphone	
	Ground (n = 29)	Raised (n = 13)	Nacelle (n = 13)
Bat Activity Coefficient	0.040	0.963	0.817
90% CI	-0.138, 0.218	0.121, 1.805	-0.515, 2.148
r^2	0.005	0.277	0.099
High-frequency fall bat activity rates versus overall bat fatality rates	Ground (n = 26)	Raised (n = 13)	Nacelle (n = 12)
Bat Activity Coefficient	0.242	3.687	2.445
90% CI	-0.044, 0.528	0.065, 7.308	-1.104, 5.994
r^2	0.080	0.233	0.135
Low-frequency fall bat activity rates versus overall bat fatality rates	Ground (n = 25)	Raised (n = 13)	Nacelle (n = 12)
Bat Activity Coefficient	-0.017	1.165	0.007
90% CI	-0.186, 0.152	0.205, 2.216	-2.055, 2.069
r^2	0.001	0.301	0

microphones ($r^2 = 0.035$, $P = 0.23$) or for HF and LF bats at raised microphones (HF, $r^2 = 0.014$, $P = 0.64$; LF, $r^2 = 0.009$, $P = 0.72$ — Table 1).

Post-Construction Bat Activity and Bat Fatality Rates

Bat activity rates increased between the final year of pre-construction surveys and the first year of post-construction surveys for HF and LF bats during individual seasons at all four wind facilities that had measured bat activity rates before ($\bar{x}$ = 1.89 bat passes/detector-night, n = 12) and after turbines were built ($\bar{x}$ = 4.84 bat passes/detector-night, n = 12 — Table 2). Bat activity rates for all 12 combinations of call frequency category and season increased between pre- and post-construction (Fig. 4).

Due to the limited number of studies with reported fall bat activity rates, overall bat activity rates were used to evaluate the relationship between post-construction bat activity rates and overall fatality rates by microphone height. Overall bat activity rates recorded by ground and nacelle microphones at operational wind facilities did not predict overall bat fatality rates (ground, $r^2 = 0.005$, $P = 0.71$; nacelle, $r^2 = 0.099$, $P = 0.29$). At raised microphones, a weak relationship between bat activity and fatality rates was detected ($P = 0.065$). Activity rates recorded by raised microphones only accounted for 27.7% of the variation in fatality rates ($r^2 = 0.277$). Activity by LF bats was significantly higher than activity by HF bats at all three microphone heights (ground: Wilcoxon matched-pairs signed-ranks test, $V = 232$, $n = 38$, $P < 0.05$; raised: $V = 0$, $n = 19$, $P < 0.01$; nacelle: $V = 0$, $n = 13$, $P < 0.01$). However, activity by HF and LF bats recorded at ground, raised, and nacelle microphones was not predictive of overall bat fatality rates measured during the same time period (Table 1).

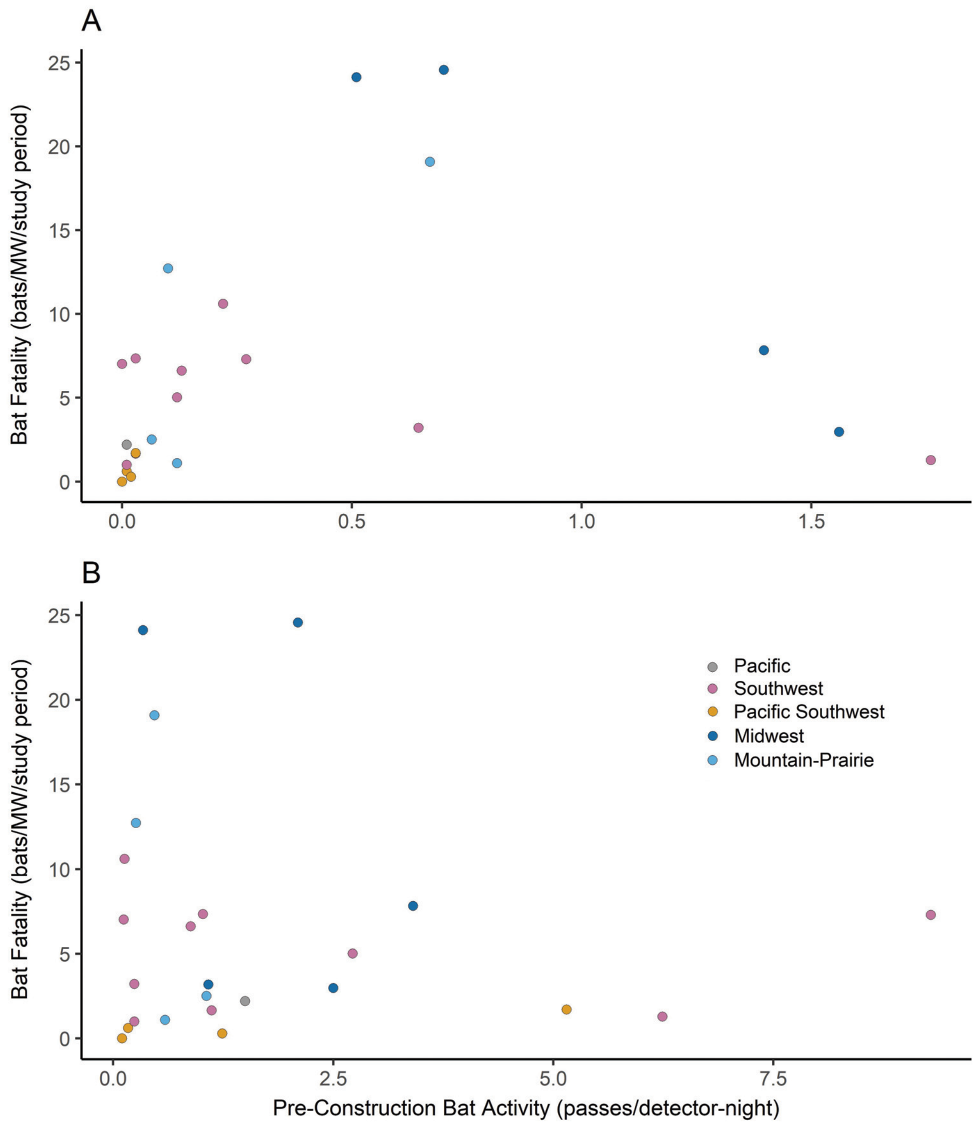

FIG. 3. Regression analysis for high-frequency bat activity rates (Panel A, n = 23) and low-frequency bat activity rates (Panel B, n = 24) recorded by raised microphones versus overall bat fatality rates at paired pre-construction and post-construction studies, grouped by U.S. Fish and Wildlife Service region

DISCUSSION

Bat activity rates recorded by bat detectors prior to wind development did not predict bat fatality rates at wind energy facilities across the U.S. and southern Alberta, Canada. Hein *et al*. (2013) found no significant relationship between activity and fatality rates among 12 studies that varied in study methodology. Our sample size was more than four times greater, and our sampling methodology was standardized across most studies, yet we also found no relationship between measured bat activity rates and bat fatality rates.

The majority of studies in our analysis reported fewer than five bat fatalities/MW/year (Figs. 2 and 3), consistent with a recent summary of bat fatalities by AWWI (2018) that found the majority of 202 studies across the U.S. also reported fewer than five bat fatalities/MW/year. If bat activity rate was a reliable predictor of bat fatality rate, we might expect most of these facilities to have recorded relatively low bat activity rates (i.e., < five bat passes per detector-night). However, bat activity rates for the 'low-fatality' facilities in our study ranged widely, between 0 and 15 bat passes per detector-night. Likewise, a relatively high number of 'low-activity' facilities reported fatality rates between five and 20 bat fatalities/MW/year (Figs. 2 and 3), further diluting this relationship. Activity by temperate-zone insectivorous bats can vary for a variety of reasons, including habitat (macro- and micro-habitat —

TABLE 2. Pre- and post-construction bat activity rates (passes/detector-night)) for paired studies by species call category and by season. HF = high frequency bats; LF = low frequency bats; SD = standard deviation

Paired study	Species call category	Season	Bat activity rate	
			Pre-construction	Post-construction
A	HF	Spring, Summer, and Fall	1.10	2.88
A	LF	Spring, Summer, and Fall	3.17	6.95
B	HF	Fall	0.53	1.52
B	HF	Spring	0.62	0.81
B	HF	Summer	2.33	4.88
B	LF	Fall	1.19	10.02
B	LF	Spring	0.74	1.44
B	LF	Summer	1.49	8.71
C	HF	Fall	6.27	6.33
C	LF	Fall	0.49	3.45
D	HF	Fall	2.30	5.20
D	LF	Fall	2.40	5.85
$\bar{x}$ (SD)			1.89 (1.64)	4.84 (2.93)

Patriquin and Barlcay, 2003; Gehrt and Chelsvig, 2003), reproduction (Dietz and Kalko, 2007), climate and weather (Erickson and West, 2002), bat species composition (Ciechanowski, 2002), insect concentrations (Kunz, 1973), light availability (Speakman *et al*., 2000), and vertical distribution for many of these same factors (Kalcounis *et al*., 1999). We argue that bat activity rates are inherently too variable to serve as a reliable predictor for bat fatality rates at wind facilities.

The height of microphones used to record bat activity did not affect this relationship. Raised microphones recorded significantly fewer bat passes per detector-night than ground-based microphones, likely because fewer bats are active at heights between 30−50 m (Collins and Jones, 2009). Bats flying at these heights are likely more at risk of collision with turbine blades (Roemer *et al*., 2017), but fatality rates still varied widely across facilities irrespective of activity rates at raised detectors.

Most bat fatalities at U.S. wind energy facilities occur during the fall migration period (Arnett *et al*., 2008; AWWI, 2018). However, we found that bat activity rates recorded during the fall do not predict overall bat fatality rates at a facility. Because fall fatality rates were directly related to overall fatality rate, we extrapolate that fall activity rates do not predict fall fatality rates. These results are unexpected, given the comparatively high correlation between the timing of peak bat activity rates and peak

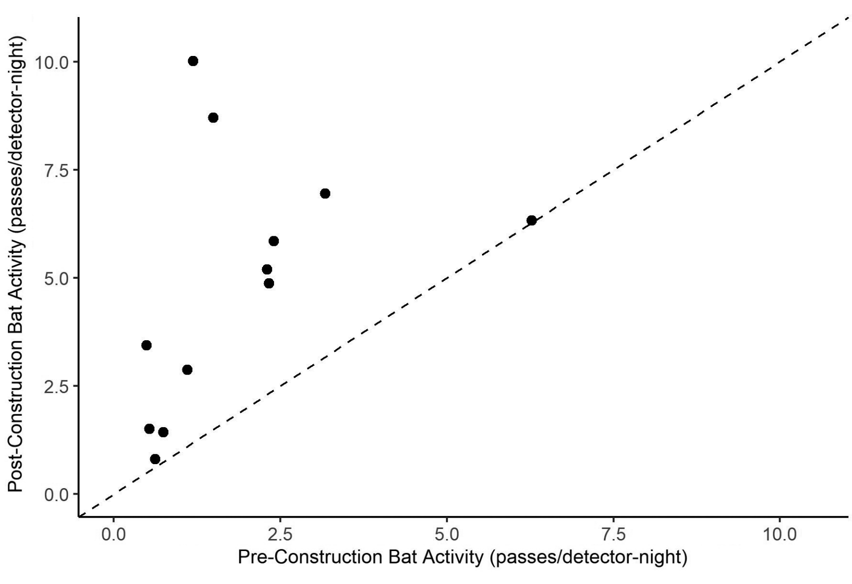

FIG. 4. Bat activity rates measured before and after turbines were built at four wind energy facilities for high- and low-frequency bats during individual seasons. The dashed line indicates a 1:1 relationship between pre- and post-construction activity rates

fatality rates that occur during the fall (Arnett *et al*., 2008; Barclay *et al*., 2017). A possible reason for the lack of a correlation in our study is that bat activity rates and fatality rates can have a wide range of values across facilities, which could clutter a predictive relationship between activity and fatality rates even if the timing of these events coincide. Measures of relative bat activity may therefore tell us when bats are likely to be killed at wind turbines, but are not predictive of the magnitude of fatality.

An explanation for why bat activity rates do not predict bat fatality rates is that the species found most often as fatalities at wind energy facilities are not the most frequent acoustically detected species. For example, at the Foote Creek Wind Farm in southeast Wyoming, hoary bats were found during carcass searches more frequently than other species, representing 88% of fatalities, but were only recorded on detectors 8% of the time (Gruver, 2002). It is possible that hoary bats, and other species most commonly found as fatalities, do not consistently echolocate during flight (Corcoran and Weller, 2018). In northern California, only half of hoary bat flights captured on infrared video produced echolocation calls that were recorded on time-synchronized ultrasonic microphones, and over 40% of those detections were inconspicuous 'micro' calls that had not been previously documented for bats (Corcoran and Weller, 2018).

Hoary bats, silver-haired bats, and Brazilian free-tailed bats are among the most numerous of the species found as fatalities at U.S. wind facilities (AWWI, 2018), and all three species belong to the LF group. Eastern red bats are another species killed by wind turbines in relatively large numbers (AWWI, 2018), and belong to the HF group. However, our results indicate that activity categorized in either frequency group was not predictive of overall bat fatality rates. A potential next step would be to examine specific relationships between LF/HF activity rates and LF/HF fatality rates, or for individual species' activity rates and fatality rates. Correlating individual species' activity rates (e.g., hoary bats) with that species' fatality rates may reveal species-specific relationships that are obscured by the inclusion of other species.

A second explanation for why pre-construction bat activity rates do not predict post-construction bat fatality rates is that some species of bats may be attracted to turbines (Cryan and Barclay, 2009), and bat activity patterns may change once turbines are built. Indeed, we found that bat activity rates increased across all 12 call category and season combinations at four wind facilities that had measured pre- and post-construction bat activity rates, providing some limited support for the turbine attraction hypothesis. Bat activity rates could increase after wind energy development for a number of reasons, including attraction to altered habitat (e.g., edge habitat created by clearing trees — Kunz *et al*., 2007), increased foraging if insects are also attracted to turbines (Valdez and Cryan, 2013; Foo *et al*., 2017; Reimer and Baerwald, 2018), use of turbines as navigation landmarks during migration (Cryan and Brown, 2007), investigation of turbines as potential roost trees (Jameson and Willis, 2014; Bennett *et al*., 2017) or rendezvous points for mating (Cryan, 2008), or due to curiosity as turbines are novel structures on the landscape (Cryan and Barclay, 2009). Since bat activity rates increased for both call categories and for all seasons, this may suggest that attraction to turbines is a broad effect not limited to specific species groups (e.g., migratory tree bats) or periods of time (e.g., fall). An expanded analysis including additional covariates, such as landscape features, could help shed light on why bats might be attracted to wind turbines.

Regardless, the greater activity rates recorded at operational wind facilities did not predict bat fatality rates that occurred during the same period. This is unexpected, given the success of operational mitigation strategies ('smart curtailment') that selectively shut down turbines when the risk to bats is deemed greatest, reducing bat fatalities by 70–90% where it has been tested (Electrical Power Research Institute, 2017; Hayes *et al*., 2019). Smart curtailment strategies vary, but are generally based on weather information (e.g., wind speed), time of year, and bat activity rates (Hayes *et al*., 2019). Weather data and time of night are finer-scaled variables that we were unable to include in our models. It is likely that incorporating weather variables measured at the time of bat activity data collection into our models may improve the ability of measured bat activity rates to predict bat fatality rates.

Wind facilities are built across a wide gradient of environmental conditions. It is possible that bat activity rates are a better predictor of bat fatality rates in some regions of the country, particularly where environmental conditions are more homogenous. However, it does not appear that activity is a better predictor of fatality rates for any of the regions in our study (Figs. 1−3).

Our results indicate that the current pre-construction survey methods of collecting bat activity rates at a proposed facility for four to 12 months does not provide reliable information on how many bat fatalities there may be once the facility is built. We advocate that the current bat activity monitoring methods be refined to obtain the most valuable information and that the scope of impact be broadened to a regional or national scale. For example, bat activity surveys can be used to identify and provide relative activity rates of species that are protected (e.g., Indiana bat *Myotis sodalis* — USFWS, 2019) or might be otherwise adversely affected by wind energy at a particular facility. On a broader scale, echolocation data could be used to monitor the activity patterns of individual species at landscape-level scales to help track the long-term viability of bat populations (Rodhouse *et al*., 2019) and movements across continents.

Acknowledgements

We are grateful to the Wind Wildlife Research Fund for providing financial support to make this work possible. The American Wind and Wildlife Institute provided valuable feedback on earlier drafts of this manuscript, and D. Young also provided a helpful review. K. Nordyke, F. Hornsby, and S. Decker developed and managed the database; M. Bartosh, H. Crow, and C. Goodman populated the database with activity and fatality data; and S. Howlin and L. Jeroue provided valuable statistical assistance. T. Peterson, E. Baerwald, and K. Russell contributed ideas and data for this work. D. Klein and A. Palochak provided excellent technical editing. Many thanks to WEST, Inc. for encouraging this study, helping to gather many years' worth of data, and providing professional and financial support throughout the process.

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Received 02 October 2019, accepted 18 April 2020

Associate Editor: Wiesław Bogdanowicz