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ARTICLE

Methods, Tools, and Technologies

Acoustic exposure reveals variation in curtailment effectiveness at reducing bat fatality at wind turbines

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Abstract

As the global transition to renewable energy generation continues, so does the need to reduce wind turbine-related bat mortality. Curtailing turbine operation to prevent rotor movement at low wind speeds not only lowers risk but also decreases renewable energy production. Adjusting curtailment criteria according to seasonal patterns in bat activity could reduce energy loss, but determining whether the resulting curtailment alternative sufficiently lowered risk to bats would require a more sensitive measure of bat mortality than carcass counts can provide. We deployed turbine-mounted acoustic bat detectors at two wind energy facilities to (1) explore seasonal and spatial variation in bat activity in and near the rotor-swept zone of turbines, (2) confirm the efficacy of acoustic exposure to turbine operation as a measure of bat fatality risk, and (3) evaluate seasonal variation in reduction in acoustic exposure among curtailment alternatives with varying cut-in wind speeds. Biweekly distribution of acoustic bat activity was similar among facilities, and acoustic exposure to rotating turbine blades was closely correlated with bat fatality estimates, corroborating previous studies. Curtailment strategies with higher cut-in speeds reduced the percentage of acoustic exposure by a consistent margin across biweekly intervals, but differences in the rate of acoustic exposure among strategies were far greater during late summer and early fall, when bat activity levels were highest. In other words, the relative protectiveness of curtailment strategies did not vary greatly throughout the year, but the choice of curtailment strategy during periods of high bat activity could substantially affect bat fatality rates. Small changes in cut-in speed (e.g., 0.5 m/s) resulted in clear reductions in acoustic exposure that were measurable at biweekly intervals, providing sensitive feedback on curtailment effectiveness. Site-specific data from turbine-mounted acoustic detectors could therefore provide more sensitive feedback on curtailment effectiveness than carcass searches, which cannot typically detect differences in fatality rates among curtailment strategies with similar cut-in speeds. Acoustic exposure also provides useful practical feedback for wind energy facility operators on how best to design curtailment strategies around site-specific patterns in bat activity and balance the simultaneous goals of generating renewable energy and protecting bats.

KEYWORDS
acoustic exposure, bat detectors, bat mortality, Missouri, turbine curtailment, wind energy

INTRODUCTION

As the global transition to renewable energy generation and associated expansion of the wind energy industry continues, so does the need for broader adoption of measures to reduce turbine-related bat fatalities. Bats are long-lived and slow to reproduce, and cumulative impacts at wind energy facilities may threaten populations of some bat species in North America (Arnett et al., 2008; Friedenberg & Frick, 2021) and Europe (Arnett et al., 2016; Voigt et al., 2022). Turbine-related bat fatalities have also been documented in Asia, New Zealand and Australia, Africa, Central and South America, and the Caribbean, suggesting the potential for population impacts to bats at a global scale (Arnett et al., 2016). Bat fatalities are thought to occur only when turbine rotors are spinning (Horn et al., 2008); curtailing turbine operation to limit turbine rotor movement, whether by feathering turbine blades parallel to the wind or applying a mechanical rotor brake, is currently considered the most reliable method to reduce the number of turbine-related bat fatalities (Adams et al., 2021; Arnett et al., 2011; Baerwald et al., 2009).

Turbines do not generate energy when curtailed, and the associated amount of energy loss increases as a function of the cut-in speed, the speed at which the blades begin rotating and generating energy (Hayes et al., 2023). The cost of curtailment is largely a function of lost energy generation potential and depends on the amount of time turbines are curtailed (Arnett et al., 2013; Thurber et al., 2023); cost varies among sites based on wind patterns, curtailment parameters, and the energy market and could threaten the financial viability of wind energy in certain regions (Maclaurin et al., 2022). Curtailment therefore represents a tradeoff between decreasing renewable energy production and protecting bats (Hayes et al., 2019). Balancing the expansion of renewable energy capacity with the simultaneous goal of maintaining bat fatalities at a sustainable level depends on accurate feedback on how effectively curtailment strategies prevent turbine operation when bats are more active and enabling energy to be produced when bats are less active.

Curtailment effectiveness has traditionally been evaluated by comparing bat fatality estimates derived from standardized carcass searches at subsets of curtailed and uncurtailed turbines, as first reported by Baerwald et al. (2009) and Arnett et al. (2011). More recent meta-analyses have continued to demonstrate the efficacy of curtailment at reducing bat fatality rates but have also highlighted the difficulty of detecting the effect of curtailment cut-in speed on fatality reduction using carcass searches (Adams et al., 2021; Whitby et al., 2024). Carcass counts are typically low due, in part, to sampling challenges such as imperfect carcass detection and removal by scavengers (Arnett et al., 2008), and the number of carcasses expected to be found further decreases when turbines are curtailed. This further reduction in sample size compounds the difficulty of differentiating fatality rates from subsets of turbines operating under curtailment strategies with similar cut-in wind speeds (e.g., 6.0 vs. 6.5 m/s). In addition to challenges in comparing curtailment strategies, the temporal resolution of carcass data is seldom finer than the search interval, so carcass counts provide limited information on conditions associated with a higher risk of turbine-related bat fatalities and therefore cannot be used to determine appropriate wind speeds below which turbine operation should be curtailed.

Alternatively, acoustic bat activity may serve as a more sensitive metric for assessing fatality risk and offers several important advantages over carcass searches in evaluating how well curtailment strategies align with patterns in bat activity. Acoustic monitoring requires substantially less labor than carcass counts and is commonly used to characterize the relationship between bat activity and fatality risk near wind turbines (Amorim et al., 2012; Behr et al., 2023; Johnson et al., 2004; Peterson et al., 2021). The risk of turbine-related impacts to bats depends on bat presence during turbine operation; acoustic exposure, the subset of bat passes occurring when rotor blades are spinning, was positively correlated with bat fatality per curtailment treatment, per turbine, and per turbine search (Peterson et al., 2021). Bat passes, here defined as a file containing two or more ultrasonic pulses with characteristics of bats recorded during a period of 15 s or less, represent the presence of one or more bats within the airspace sampled by the detector during a distinct moment (Fenton, 1970; Gannon et al., 2004).

In the context of monitoring risk using nacelle-mounted bat detectors, acoustic exposure refers to the subset of bat passes recorded during 10-min intervals when turbine rotor speed exceeds 1 rotation per minute (rpm) and can be expressed as a rate (e.g., exposed bat passes per detector night) or a percent (Peterson et al., 2021). When calculated as a rate of exposed bat passes per detector night, acoustic exposure should indicate the number of interactions between bats and moving turbine blades and correlate positively with turbine-related bat fatalities. When expressed as a percentage (e.g., number of exposed passes divided by the total number of bat passes), acoustic exposure indicates the relative portion of bat activity exposed to risk and can be used to evaluate the protectiveness of curtailment strategies. Acoustic exposure can be measured based on turbine rotor speed only for curtailment strategies as implemented when acoustic data were collected, but since detectors record bat activity regardless of the operational state of turbines, acoustic exposure can be calculated as though turbines had been operating under different curtailment scenarios. Calculating acoustic exposure in this manner enables detailed comparisons of how adjusting curtailment criteria such as cut-in wind speed would change acoustic exposure and the associated risk of turbine-related impacts to bats. Acoustic exposure can therefore be used to select cut-in speeds that tailor the intensity of curtailment to patterns in risk at whatever temporal scale is appropriate given operational constraints and the consistency of site-specific bat activity patterns. Improved understanding of when and how to curtail wind turbines to protect bats and more sensitive quantitative measures of curtailment effectiveness are both essential to balancing the simultaneous needs to reduce turbine-related bat fatalities and rapidly expand the global capacity for renewable energy generation.

In this study, we used data from turbine-mounted acoustic bat detectors and standardized carcass counts to (1) explore seasonal and spatial variation in bat activity in and near the rotor-swept zone of turbines, (2) confirm the efficacy of acoustic exposure as a measure of bat fatality risk, and (3) evaluate seasonal variation in the reduction in acoustic exposure among curtailment alternatives with varying cut-in wind speeds. By comparing patterns in acoustic exposure among curtailment strategies across multiple turbines and facilities, we were thus able to evaluate variation in the effectiveness of curtailment according to seasonal, spatial, and temporal patterns in bat activity near turbines. We demonstrated how site-specific data from turbine-mounted acoustic detectors could therefore generate more sensitive feedback on curtailment effectiveness than carcass searches can typically provide. Such information could also help wind energy facility operators tailor curtailment strategies around site-specific patterns in bat activity and balance the simultaneous goals of generating renewable energy and protecting bats.

METHODS

Study area

This study occurred at two wind energy facilities, Kings Point and North Fork Ridge, each with a nameplate capacity of 149.4 MW and consisting of 12 Vestas V-110 (2.0 MW) turbines, 57 V-120 (2.2 MW) turbines, and an associated substation, access roads, and underground electrical collection system (Figure 1). Both facilities are within the Springfield Plateau ecoregion in southwest Missouri, USA, characterized by flat to rolling topography with karst features and rocky soils (Chapman et al., 2002). Kings Point encompasses 140.8 km^2 of pasture/hay (~49%), cultivated crops (~42%), deciduous forest (~5%), and developed land (~4%), and North Fork Ridge encompasses 95.6 km^2 of cultivated crops (~51%), pasture/hay (~35%), deciduous forest (~7%), and developed land (~4%; Dewitz, 2021). Topography at both facilities is generally flat with some slight elevation changes associated with riparian areas. Several large, perennial streams are present within each project, which provide season-long foraging and traveling habitat for bats. Known gray bat (*Myotis grisescens*) maternity colonies occur approximately 9 km east of Kings Point and 10 km west of North Fork Ridge.

Carcass monitoring

Between March 1 and October 31, 2021 and from April 4 to October 31, 2022, we conducted standardized carcass searches for all 69 turbines at each facility. Searches consisted of turbine pads and access roads out to 100 m ($N_{2021} = 45$ and $N_{2022} = 41$ turbines per facility), cleared plots out to 60 m from the base of the turbine ($N_{2021} = 20$ and $N_{2022} = 24$ turbines per facility), and cleared plots out to 100 m from the turbines ($N = 4$ turbines per facility). Cleared plots were mowed periodically to maintain a vegetation height of ~13 cm (5 inches) or less to facilitate visual searches. Approximately every 2–3 days, trained searchers walked the plots and visually scanned 3 m to each side of alternately marked transects spaced at 6-m intervals to identify carcasses. Prior to collecting carcasses, searchers recorded carcass locations using a sub-meter accuracy global navigation satellite system (GNSS; Arrow 100). Searcher efficiency trials, carcass

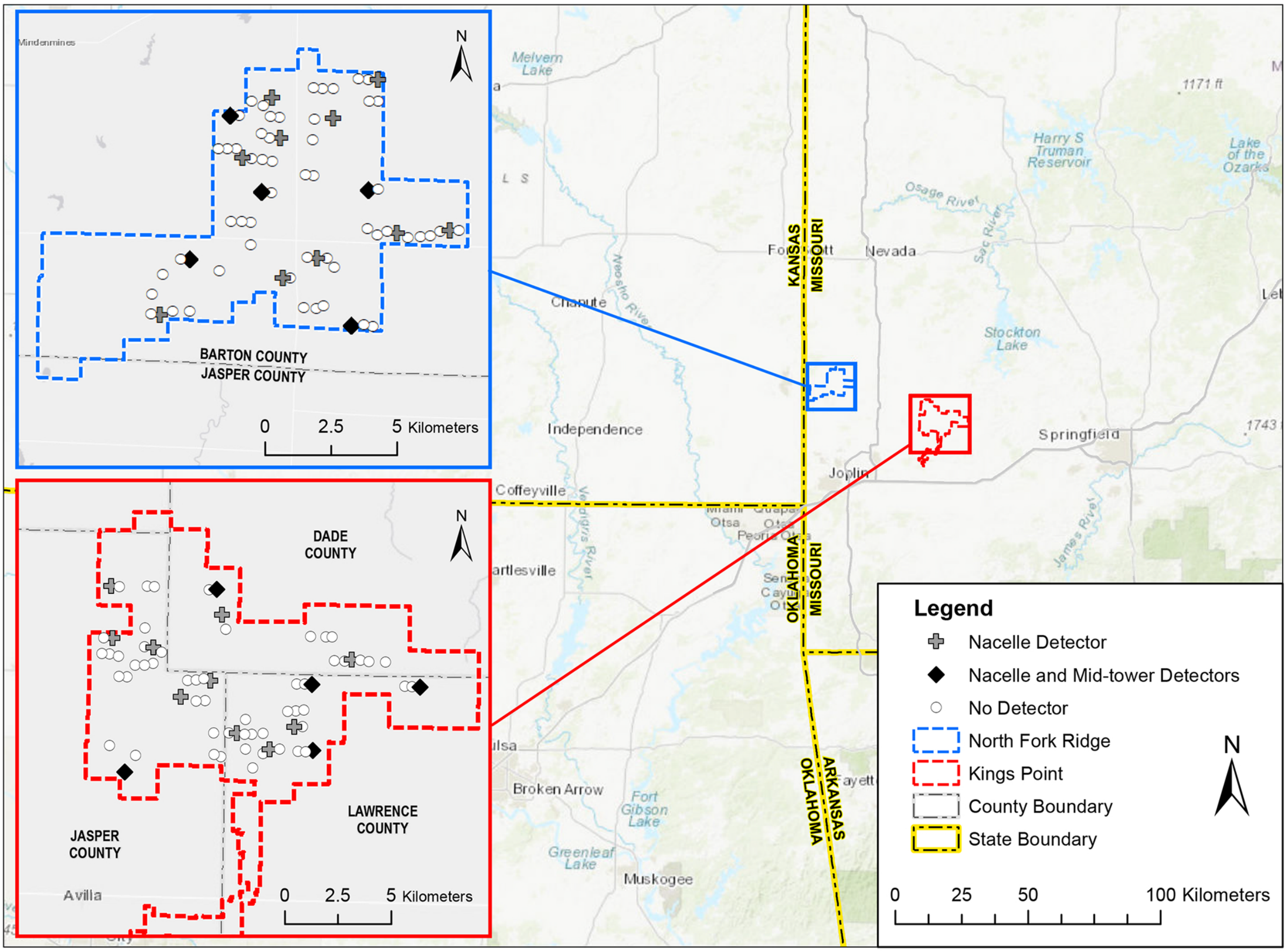

FIGURE 1 Map of Kings Point and North Fork Ridge wind facilities with turbines used for acoustic analysis highlighted.

persistence trials, and density-weighted proportion (DWP) calculations for each wind facility were also conducted as described in methods by Stantec (2022, 2023).

Acoustic data collection and turbine operation

We conducted bat acoustic activity monitoring using SM4BAT-FS acoustic detectors (Wildlife Acoustics, Maynard, MA) at 15 turbines per wind facility. Acoustic monitoring spanned from August 3 to December 31, 2021, and from February 19 to December 6, 2022. We deployed 15 detectors per wind facility atop the nacelle, approximately 120 m above the ground, powered by 12-V batteries charged by a 10-W solar panel (2021) or 120-V AC power inside the turbine nacelle (2022). However, in 2021, a detector failure at Kings Point resulted in one fewer nacelle detector deployed. For 5 of the turbines, acoustic detectors were also attached to the monopole, positioned 20 m above the ground (referred to as "mid-tower"), and powered by alkaline batteries (Figure 2). While we deployed mid-tower detectors at the same time as nacelle detectors in 2021, we deployed mid-tower detectors approximately 2 months later than nacelle detectors in 2022. Detectors functioned for 0–249 nights in 2021 ($\bar{x} = 105.0$ detector nights) and 19–282 nights in 2022 ($\bar{x} = 173.6$ detector nights). Equipment malfunctions resulted primarily from power supply failure and led to 16 detectors functioning for less than 50% of the deployment time ($N_{2021} = 4$ detectors and $N_{2022} = 12$ detectors). We equipped acoustic detectors with SMM-U1 omnidirectional microphones and oriented the microphones away from the rotor at the opposite end of the nacelle (downwind when turbines were pointed into the wind) to standardize the sampled airspace among turbines, minimize interfering noise from wind or turbine noise, and avoid potential microphone damage from wind-driven rain. Detectors could record bats within a range of approximately 30 m and were programmed to operate from 45 min before sunset to

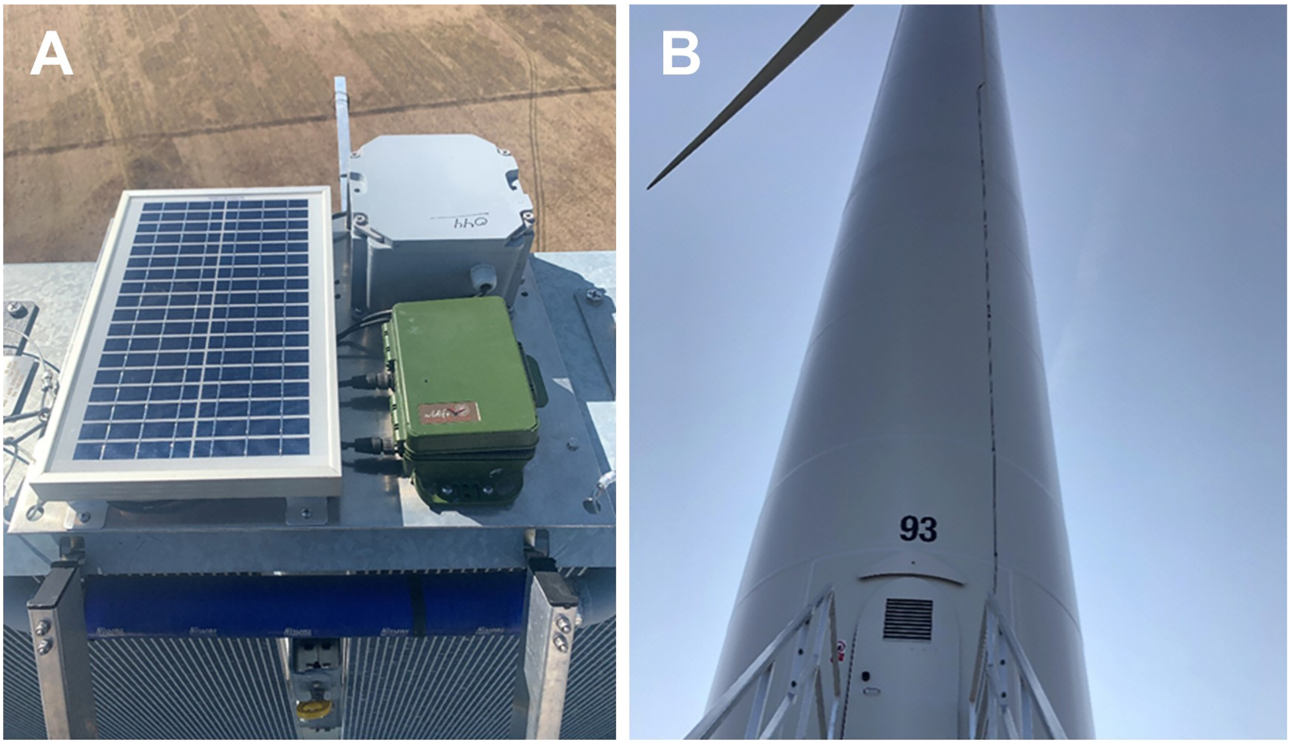

FIGURE 2 Image of acoustic detector (A) mounted atop a turbine nacelle at Kings Point and (B) at the mid-tower position on a turbine monopole at North Fork Ridge. Photo credit: (A) Vestas and (B) Stantec.

45 min after sunrise each night based on the latitude and longitude of the center of each facility. We programmed detectors to record in a compressed audio format ("WV4-6") using manufacturer's default audio settings.

Throughout acoustic monitoring, turbines operated under several curtailment treatments. Curtailment at both facilities was triggered 30 min before sunset when temperatures exceeded 10°C and wind speed was below the prescribed cut-in speed. During 2021, an 8-m/s cut-in speed was applied to all 15 turbines with acoustic detectors from the start of data collection until September 6 at Kings Point and until August 29 at North Fork Ridge. For the remainder of 2021, seven turbines operated under a 3 m/s cut-in speed, while eight operated with a 5 m/s cut-in speed. The 8 m/s treatment was discontinued after 2021. During 2022, seven turbines operated with a 3 m/s cut-in speed, while eight operated with a 5 m/s cut-in speed, and operational treatments did not differ throughout the year. Treatments were reassigned between 2021 and 2022.

Acoustic data analysis and alignment with turbine operations data

We first processed full-spectrum acoustic recordings with Kaleidoscope Pro (version 5.4.0, Wildlife Acoustics, Maynard, MA, USA) to remove noise, convert the remaining files to zero-crossing format, and auto-classify files to species according to the list of species potentially occurring within one county of Kings Point and North Fork Ridge. We manually vetted all zero-cross files in AnalookW to confirm the presence of bat passes, defined as a file containing at least 2 echolocation call pulses with characteristics of bats recorded within a period of up to 15 s (Fenton, 1970; Gannon et al., 2004; Kunz et al., 2007).

We obtained turbine operational data and weather recordings collected by nacelle-mounted anemometers to determine bat exposure to turbine operation and verify turbine curtailment in the corresponding conditions. For each turbine equipped with acoustic detectors, blade rotor speed (rotations per minute, rpm), temperature in degrees Celsius (°C), and wind speed (in meters per second, m/s) were reported as averages over 10-min intervals. We screened weather information for discernable measurement errors, such as erroneous windspeed (e.g., <0 or >40 m/s) or temperature readings (e.g., <−30 or >40°C). We adjusted time stamps to reflect the correct time zone and used the R package suncalc (version 0.5.1, Thieurmel & Elmarhraoui, 2019) to calculate the time 30 min before sunset and 30 min after sunrise to determine when curtailment treatments would be active. We rounded the timestamps of each bat acoustic recording to the nearest 10-min interval and paired them with the associated temperature, wind speed, and rotor speed to assess exposure to turbine operation.

Calculating total bat activity rates

We aggregated the number of bat passes recorded for each detector height at every turbine, organizing nightly passes into biweekly intervals that spanned the 1st to the 14th day and the 15th to the final day of each month during the study period. We grouped data by wind facility and year of data collection and calculated total bat activity rates by dividing the number of detected bat passes regardless of turbine operation by the number of operational detector nights in each biweekly interval. To analyze trends in total activity rates across the year and variations between years, facilities, and detector heights, we employed a generalized additive mixed model (GAMM) from the mgcv library (version 1.9.1, Wood, 2011) in R. The total bat activity rate per turbine was estimated as a function of biweekly intervals as well as factor variables of collection year, wind facility, and the random effect of each turbine. Because of bias toward values near zero in our dataset, we modeled our data using a Tweedie distribution with an estimated power parameter. The model was assessed using outputs from gam.check in the R package mgcv (Appendix S1: Figure S1), and the model exhibited no strong evidence of improper fit (e.g., non-normal distribution or non-random distribution of residuals; $R^2 = 0.92$, 91.7% deviance explained). We evaluated the effect of detector height, collection year, and wind facility based on their significance in the model. We then estimated total activity rates with the model from the start to the end of the data collection period using the R package ggeffects (version 1.5.0, Lüdecke, 2018) and visualized the estimated activity rates to observe seasonal trends at each detector height.

Comparing acoustic exposure and bat fatalities

Bats recorded by turbine-mounted acoustic detectors do not necessarily fly through the rotor-swept zone of turbines; bats detected by mid-tower detectors are likely below the rotor-swept zone, and much of the sampled airspace for nacelle-mounted detectors was downwind of the nacelle in the opposite direction of the rotor. Nevertheless, the presence of bats near the rotor-swept zone during intervals when turbines are operational indicates the risk of turbine-related impacts, and we therefore categorized passes detected when turbine rotor speed was 1 rpm or greater as exposed to turbine operation, following the same methods used by Peterson et al. (2021).

We calculated the acoustic exposure rate by pooling data across all turbines for each wind facility, year, and detector height in the same biweekly intervals using the previously described method. To provide sufficient numbers of carcasses for fatality estimates, we aggregated fatality and acoustic data across treatments, with analysis focusing on variation among biweekly intervals. We used carcass monitoring data from all turbines, including those without acoustic monitoring, to estimate bat fatality at each wind facility with "GenEst" (Generalized Mortality Estimator, version 1.4.9, Dalthorp et al., 2023) in RStudio. GenEst incorporates other measurements, such as searcher efficiency and carcass persistence, which account for imperfect carcass detection to more accurately estimate fatality (Simonis et al., 2018). Using 1000 bootstraps and 90% CIs, we generated biweekly fatality estimates splitting data by search schedules aligned with the same biweekly acoustic monitoring intervals described earlier. Search season (i.e., April 1 to May 31, June 1 to August 31, September 1 to October 31) and plot type (i.e., road and pad, full plot) were included as possible independent variables for search efficiency and carcass persistence models. Because searcher efficiency and carcass persistence trials were conducted across longer seasonal periods, we assumed that estimates of these variables did not vary largely across the biweekly intervals within a search season. For all variables, the model with the lowest Akaike information criterion was selected for fatality estimates (Appendix S1: Table S1). Site-wide bat fatality estimates from GenEst were converted to per-turbine estimates by dividing by the estimated number of bat fatalities by the number of total wind turbines at each facility ($N = 69$).

We generated linear models for each detector height using lm in R (R Core Team, 2023) to measure the relationship between biweekly exposure and estimated fatality. We did not include wind facility as a factor in the model due to similarity in activity trends and carcass detection between both locations. Additionally, operational treatment was excluded as an independent factor from the model structure because of seasonal variation in curtailment treatment groups.

Comparing acoustic exposure based on rotor speed and curtailment criteria

We determined that acoustic exposure would occur in any 10-min interval for which we had acoustic data and corresponding wind speed, temperature, and rotor speed data if (1) rotor speed exceeded 1 rpm or (2) wind speed and temperature criteria of the associated curtailment strategy were not met. Comparing acoustic exposure rates according to these two distinct methods therefore tested whether curtailment was implemented properly and how well curtailment criteria represented actual turbine operation. We compared the rate of acoustic exposure based on turbine rotor speed versus curtailment criteria being met, both calculated per turbine per year at nacelle-mounted and mid-tower detectors, using lm in R (R Core Team, 2023). We did not include wind facility or operational treatment in the model because of the similarity between facilities and seasonal variation in operational treatment.

Evaluating curtailment alternatives

We created a set of curtailment alternatives with cut-in speeds ranging from 4 to 7 m/s at 0.5 m/s increments and determined whether turbines would have been curtailed in each 10-min interval based on associated wind speed and temperature readings. Using the method based on curtailment criteria, we calculated the rate and proportion of exposed bat passes under each curtailment alternative within biweekly periods per turbine to examine seasonal and spatial differences in how effectively curtailment alternatives would have reduced risk to bats. We plotted mean biweekly acoustic exposure and associated 95% CIs per detector position for each curtailment alternative and qualitatively compared their relative protectiveness in relation to seasonal and spatial patterns in bat activity.

RESULTS

Total bat activity

Acoustic bat detectors recorded 158,296 bat passes with corresponding weather and turbine operational data across two wind facilities ($N_{\text{Kings Point}} = 75{,}221$; $N_{\text{North Fork Ridge}} = 83{,}075$) and two different heights ($N_{\text{nacelle}} = 29{,}333$; $N_{\text{mid-tower}} = 128{,}963$). Bats were detected during 20 out of 22 biweekly intervals throughout the period acoustic detectors were active, spanning August 3 to December 31 in 2021 and February 19 to December 6 in 2022 (Table 1). Bat activity rates varied significantly by date ($p < 0.001$, $F = 441.3$, $\text{df} = 8.9$; Figure 3), year (estimate = 0.11, $p = 0.01$, $t = 2.52$), and detector height (estimate = 1.99, $p < 0.001$, $t = 35.8$), regardless of wind facility (estimate = 0.0, $p = 0.95$, $t = 0.06$). Outside of peak bat activity during summer, between July 1 and September 15, bat activity was minimal at both heights. At its peak in early August, estimated activity was approximately 7.3 times higher at mid-tower height (Kings Point, 174.3 bat passes per detector night; North Fork Ridge, 175.5 bat passes per detector night) than at nacelle height (Kings Point, 23.7 bat passes per detector night; North Fork Ridge, 23.9 bat passes per detector night).

Acoustic exposure and bat fatalities

During the 20 biweekly intervals when bats were detected, 15,548 carcass searches were conducted across all 69 turbines, including those without detectors, at both wind facilities (Kings Point, $N = 7690$; North Fork Ridge, $N = 7722$) yielding 617 carcasses (Kings Point, $N = 314$; North Fork Ridge, $N = 303$). Acoustic exposure was available for 39 turbines operating under three curtailment treatments in 2021 (nacelle, $N = 29$ detectors; mid-tower, $N = 10$ detectors) and 40 turbines representing two curtailment treatments in 2022 (nacelle, $N = 30$ detectors; mid-tower, $N = 10$ detectors). Detectors recorded 97,295 passes exposed to turbine blade rotor speeds above 1 rpm during this period with a mean exposure rate of 8.73 passes per detector night (nacelle, $\bar{x} = 2.08$; mid-tower, $\bar{x} = 25.8$). We pooled data across all turbines by facility within each biweekly interval when calculating measured acoustic exposure because curtailment treatments varied seasonally for individual turbines in 2021. More bat fatalities were estimated during biweekly intervals with higher acoustic exposure ($p < 0.001$; Figure 4). While this relationship was similar at both nacelle (estimate = 1.88; $t = 14.9$; $p < 0.001$) and mid-tower detectors (estimate = 0.22; $t = 9.52$; $p < 0.001$), it was stronger at nacelle height ($R^2 = 0.86$; $F_{1,37} = 223.4$) than mid-tower ($R^2 = 0.72$; $F_{1,39} = 90.71$).

Acoustic exposure for curtailment alternatives

The rate of acoustic bat passes detected when turbine rotor speed exceeded a threshold of 1 rpm was highly correlated with the rate of bat passes detected during intervals when curtailment conditions were not met at both nacelle detectors (estimate = 0.97, $p < 0.001$, $F_{1,57} = 2912$, $R^2 = 0.98$; Figure 5) and mid-tower detectors (estimate = 1.01, $F_{1,18} = 4221$, $p < 0.001$, $R^2 = 0.99$; Figure 5) at Kings Point and North Fork Ridge. At both sites, acoustic exposure rates were substantially higher at mid-tower detectors than at nacelle detectors and varied considerably among turbines at

TABLE 1 Summary of the rate of total bat activity and exposed bat activity (total number of bat passes with nightly rate in parentheses) recorded by facility (Kings Point and North Fork Ridge), treatment group, and detector height.

Operational group	Detector position	Start–end date	No. turbines	Total no. bat passes	Bat passes when rotor speed >1 rpm	Bat passes when curtailment criteria not met
2021						
Kings Point						
8.0 m/s cut-in wind speed	Nacelle	08/12–09/06	14	3756 (17.3)	867 (4.0)	833 (3.8)
	Mid-tower	08/04–09/06	5	21,173 (124.5)	10,005 (58.9)	9891 (58.2)
5.0 m/s cut-in wind speed	Nacelle	09/07–12/20	8	1004 (1.7)	540 (0.9)	489 (0.8)
	Mid-tower	09/07–12/02	3	2606 (10.6)	1479 (6.0)	1375 (5.6)
Control (3 m/s cut-in wind speed)	Nacelle	09/07–12/20	6	594 (1.3)	487 (1.1)	492 (1.1)
	Mid-tower	09/07–12/03	2	1865 (11.1)	1587 (9.4)	1555 (9.3)
North Fork Ridge						
8.0 m/s cut-in wind speed	Nacelle	08/16–08/29	15	3274 (22.1)	462 (3.1)	493 (3.3)
	Mid-tower	08/03–08/29	5	18,793 (143.5)	6473 (49.4)	6712 (51.2)
5.0 m/s cut-in wind speed	Nacelle	08/30–12/31	8	1834 (2.2)	1239 (1.5)	1041 (1.3)
	Mid-tower	08/30–11/28	3	3824 (14.2)	2634 (9.8)	2407 (8.9)
Control (3 m/s cut-in wind speed)	Nacelle	08/30–12/31	7	1441 (1.8)	1257 (1. 6)	1243 (1.5)
	Mid-tower	08/30–12/04	2	2633 (14.3)	2290 (12.4)	2171 (11.8)
2022						
Kings Point						
5.0 m/s cut-in wind speed	Nacelle	02/20–11/27	8	5965 (4.9)	3230 (2.6)	3035 (2.5)
	Mid-tower	04/19–11/09	3	21,008 (35.9)	13,218 (22.6)	12,773 (21.8)
Control (3 m/s cut-in wind speed)	Nacelle	02/19–11/27	7	3723 (3)	2878 (2.4)	2876 (2.3)
	Mid-tower	04/19–11/08	2	15,568 (38.8)	12,894 (32.2)	13,077 (32.6)
North Fork Ridge						
5.0 m/s cut-in wind speed	Nacelle	02/28–12/06	8	2634 (2.5)	1167 (1.1)	1253 (1.2)
	Mid-tower	04/19–11/12	3	24,257 (42.9)	12,026 (21.2)	11,689 (20.7)
Control (3 m/s cut-in wind speed)	Nacelle	02/28–12/06	7	6343 (4.3)	4559 (3.1)	4510 (3.0)
	Mid-tower	04/19–11/10	2	22,615 (56)	18,003 (44.6)	17,978 (44.5)

Note: Values in parentheses are rates.

both detector positions. For each detector position, variation in acoustic exposure among turbines was largely attributable to the curtailment treatment to which turbines were assigned.

Had curtailment strategies with cut-in wind speeds ranging from 4 to 7 m/s been implemented, the rate of acoustic exposure would have varied substantially among treatments during the seasonal peak in bat activity from July 15 to August 15. Outside of this peak activity period, acoustic exposure remained low for all curtailment alternatives, with higher rates of exposure and a slightly longer seasonal peak observed at mid-tower height than at nacelle height. Within the peak of bat activity in late summer, acoustic exposure declined rapidly as a function of increasing cut-in wind speed (Figure 6).

In contrast to the rate of exposed bat activity, the proportion of exposed bat passes was less variable among biweekly intervals throughout the study period. Curtailment alternatives reduced exposure by a similar margin among biweekly intervals regardless of the underlying rate of activity (Figure 7). Pooling data among turbines across seasons, facilities, and years, the percent of acoustic exposure was lower at nacelle height than at mid-tower detectors for all curtailment alternatives (Table 2).

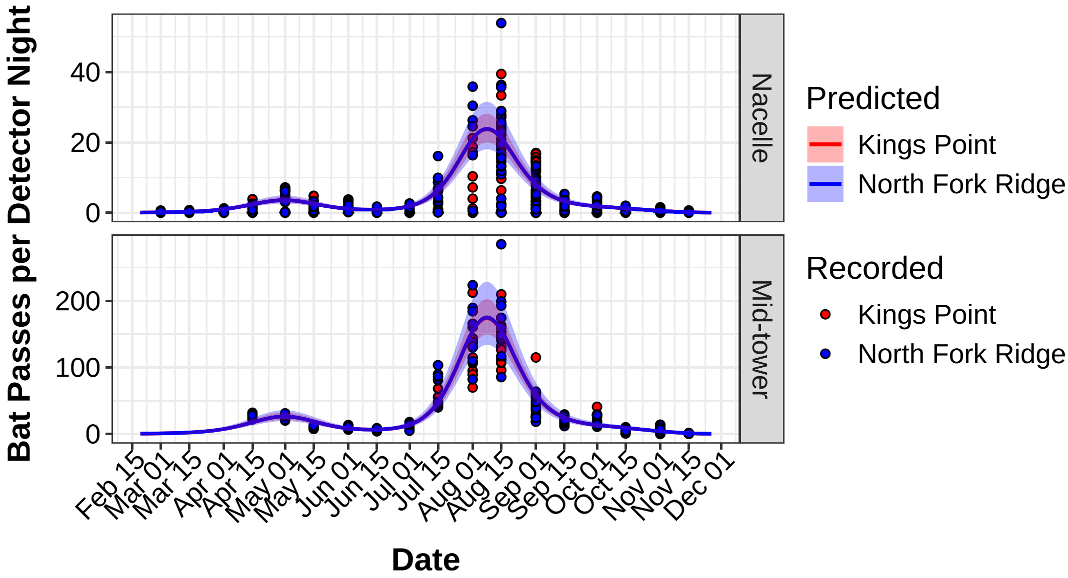

FIGURE 3 Estimated bat activity rates by date as modeled by biweekly bat activity at each turbine ($R^2 = 0.92$, 91.7% deviance explained, $N = 819$ biweekly intervals). Shaded lines indicate 95% CIs of the model.

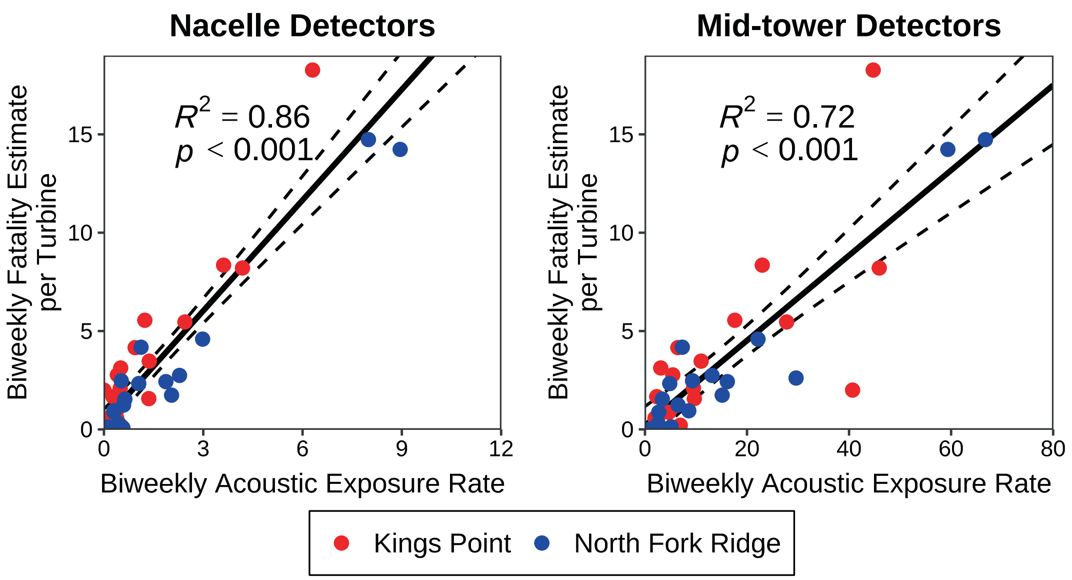

FIGURE 4 Biweekly bat fatality estimates from GenEst as a function of the rate of acoustic exposure (exposed bat passes per detector night) based on mean rotor speed exceeding 1 rpm at nacelle detectors and mid-tower detectors. Dashed lines indicate 95% CIs of the regression line.

DISCUSSION

Alongside the global expansion of wind energy are growing concerns about potential unsustainable declines in bat populations resulting from turbine-related bat fatalities (Arnett et al., 2008; Friedenberg & Frick, 2021; Voigt et al., 2015, 2019). While curtailment is the most reliable method for preventing bat fatalities, it could contribute to unsustainable energy losses (Maclaurin et al., 2022) and work against achieving renewable energy production targets. Effective deployment of curtailment strategies could reduce bat fatality rates, but without a more sensitive metric than carcass counts for assessing fatality risk, it is difficult to assess similar curtailment strategies and justify their use. While carcass counts have been the standard for assessing fatality risk (Adams et al., 2021; Arnett et al., 2011; Baerwald et al., 2009; Whitby et al., 2024), our results provide further evidence that acoustic exposure can serve as an alternative metric.

We found support that acoustic exposure is strongly correlated to bat fatalities at turbines. Strong correlation between biweekly acoustic exposure and bat fatality

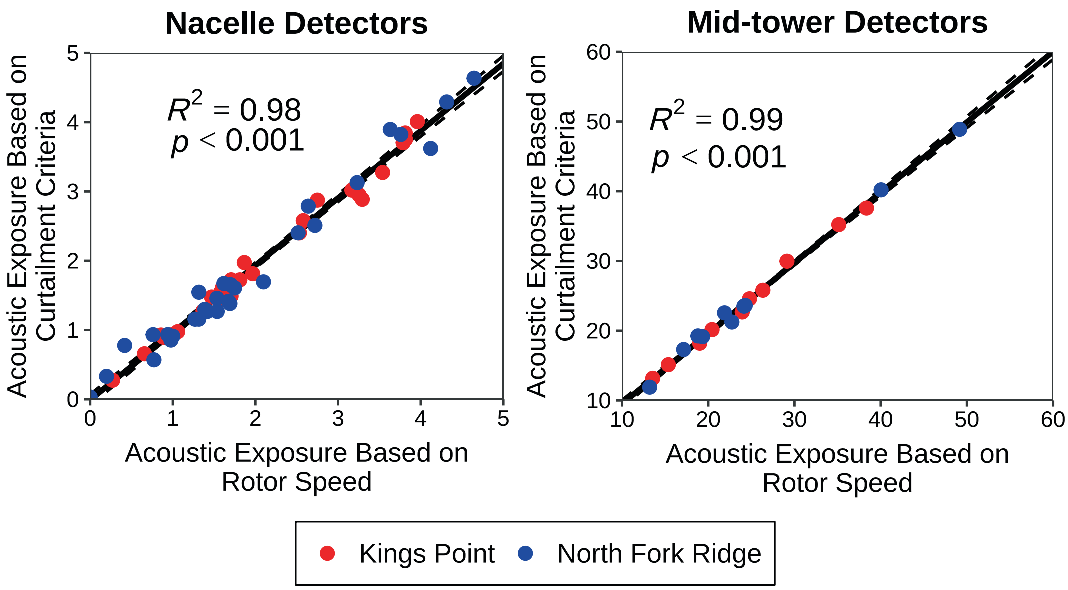

FIGURE 5 Estimated rate of acoustic exposure (exposed bat passes per detector night) based on curtailment criteria not being met versus mean rotor speed exceeding 1 rpm at nacelle detectors and mid-tower detectors at Kings Point and North Fork Ridge. Dashed lines indicate 95% CIs of the regression line.

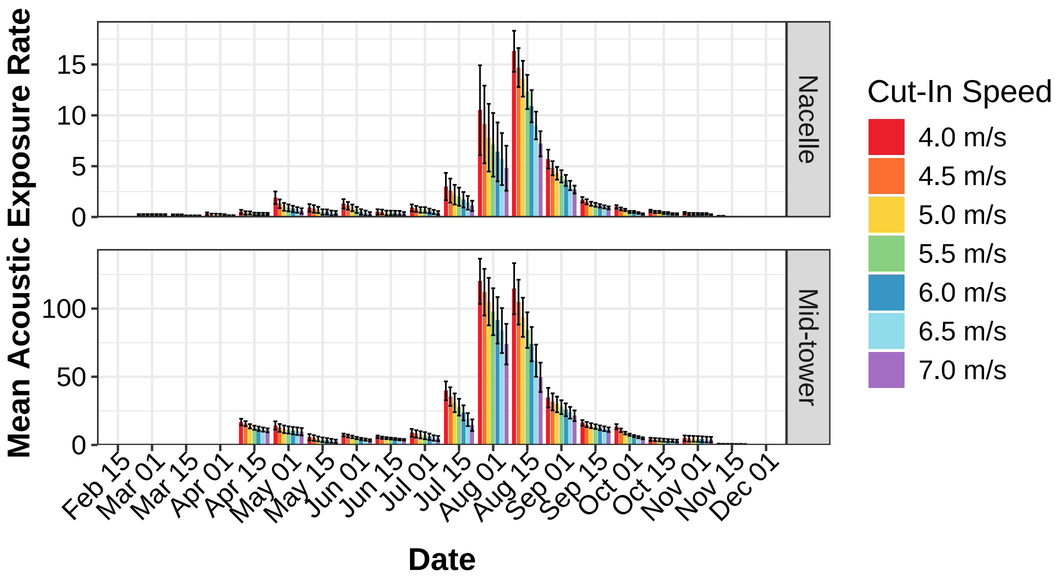

FIGURE 6 Biweekly distribution of acoustic exposure for curtailment alternatives with cut-in wind speeds ranging from 4.0 to 7.0 m/s (N = 843 biweekly intervals). Error bars represent 95% CIs based on variation observed across facilities, turbines, and years.

estimates was apparent regardless of spatial variation in detector height. These findings are in alignment with Peterson et al. (2021), who found that acoustic exposure was positively correlated to bat fatality estimates and the number of carcasses found per turbine. Notably, we observed that the relationship between acoustic exposure and fatality risk was stronger for nacelle detectors. Because the detection range of mid-tower detectors reached from ground level to approximately 10 m below the lowest point of the rotor-swept zone, it is likely that not all passes detected were at risk of collision. Conversely, all passes recorded by nacelle detectors occurred within altitudes reached by the rotor blades, which could explain why they were more strongly linked to fatality risk.

We found evidence of distinct variation in bat activity rates between detector heights, which were mirrored by distributions of acoustic exposure. Mid-tower detectors recorded significantly more bat activity than nacelle detectors, suggesting that bat activity decreases with

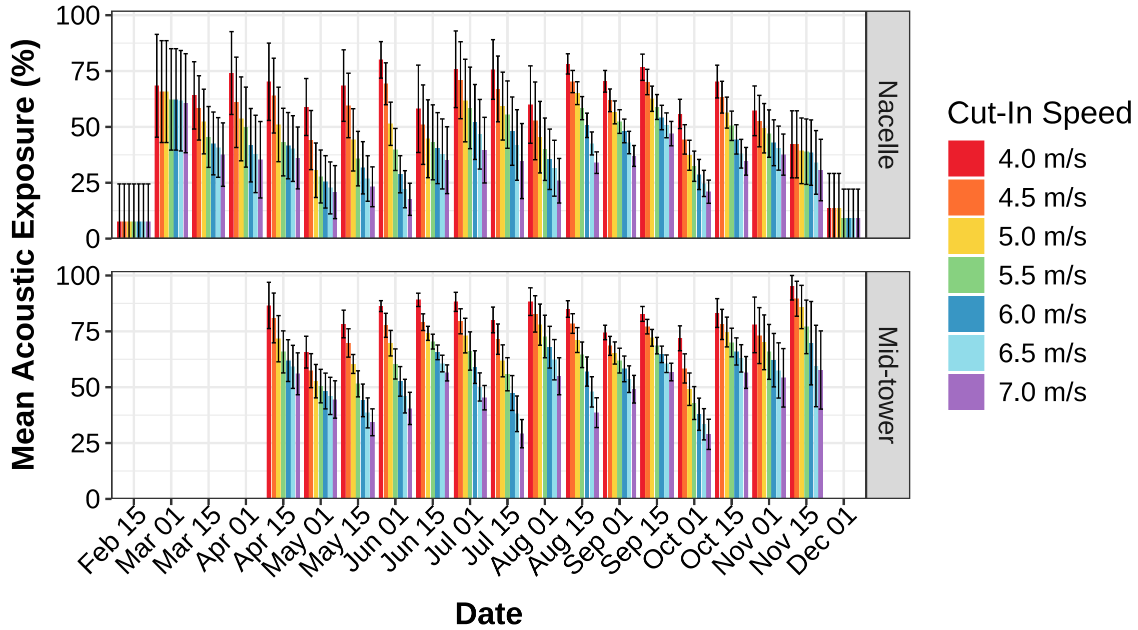

FIGURE 7 Distribution of the percent of exposed passes among turbines for curtailment alternatives with cut-in wind speeds ranging from 4.0 to 7.0 m/s ($N = 843$ biweekly intervals). Error bars represent 95% CIs based on variation observed across facilities, turbines, and years.

TABLE 2 Mean biweekly percent acoustic exposure for curtailment alternatives with varying cut-in speeds.

Detector position	Cut-in speed (m/s)	Mean biweekly acoustic exposure (%)
Nacelle	4.0	76.3
	4.5	68.0
	5.0	60.3
	5.5	55.1
	6.0	49.8
	6.5	44.7
	7.0	39.6
Mid-tower	4.0	81.9
	4.5	74.8
	5.0	69.0
	5.5	63.5
	6.0	58.3
	6.5	52.7
	7.0	47.5

increasing altitude. While the link between acoustic exposure and fatality rates was weaker at mid-tower height, activity biased toward low altitude could suggest that fatality risk is higher in the lower rotor-swept area. In other acoustic studies, bat pass rates collected near the ground were typically higher than pass rates at mid-tower heights (Redell et al., 2006) and near nacelle height (Roemer et al., 2017). While there is little information about spatial variation within the rotor-swept area, a more detailed vertical activity profile using detectors suspended in 10-m intervals from a construction crane found that total bat activity decreased approaching lower altitudes covered by the rotor-swept area of commercial wind turbines (Wellig et al., 2018). However, activity differences could be driven by species-related flight ecology, as certain species, such as *Tadarida teniotis* in Europe (Wellig et al., 2018), are more likely to be detected at heights in the rotor-swept area. Therefore, it is important to consider species-specific flight patterns when assessing spatial differences in fatality risk in the rotor-swept area.

Bat activity also varied seasonally, with minimal activity occurring outside of peak activity levels in mid- to late summer. This relationship was consistent across detector heights and wind facilities, although there was some variation in the magnitude of activity across years. The difference in seasonal distribution of bat activity across years was minimal and potentially attributable to the shortened deployment season in 2021, which led to few passes being detected at nacelle height in certain biweekly intervals. The seasonality of bat fatality risk for migratory species most often killed by turbines is well established in temperate regions (Arnett et al., 2016), and our findings align with known migratory bat activity patterns at turbines (Goldenberg et al., 2021;

Johnson et al., 2004) and other sites (Gorman et al., 2021; Johnson et al., 2011) in North America.

While wind speed is known to affect overall bat activity near wind turbines (Amorim et al., 2012; Arnett et al., 2008; Cryan et al., 2014; Horn et al., 2008), there is also evidence that relationships between bat activity and wind speed vary on a species level. For example, *Pipistrellus pipistrellus*, the most commonly killed species in Europe (EUROBATS, 2023), ceased most activity in an open area cited for turbine construction at a lower wind speed compared to total bat activity (Wellig et al., 2018). Species-specific exposure as a function of cut-in speed could be a necessary factor in determining whether cut-in parameters are appropriately protecting species with the highest fatality risk. Species-specific flight patterns may also affect spatial, seasonal, and wind speed-related fatality risk. Future studies seeking to assess curtailment effectiveness should take into consideration species differences, which can better inform decisions about the timing and parameters of a given strategy.

Similar to Peterson et al. (2021), we found that calculations of acoustic exposure based on rotor speed and curtailment criteria were highly correlated; in our study, this relationship was equally strong at both nacelle-height and mid-tower detectors. This result indicated that turbine operation was closely aligned with the criteria of curtailment strategies, enabling comparison of acoustic exposure among curtailment alternatives with different curtailment criteria such as cut-in wind speed. By comparing acoustic exposure among curtailment alternatives with cut-in speeds ranging from 4 to 7 m/s, we documented seasonal and spatial variation in curtailment effectiveness at reducing risk to bats. While incremental increases in cut-in wind speeds resulted in consistent reductions in the proportion of bat passes exposed to risk across biweekly intervals, increasing cut-in speed had the greatest impact in reducing the number of exposed bats when rates of bat activity were highest. Therefore, the relative protectiveness of curtailment strategies does not vary greatly throughout the year, but the choice of curtailment strategy during periods of high bat activity could substantially affect associated fatality risk.

Determining acoustic exposure based on curtailment criteria rather than rotor speed allowed the use of acoustic data from all turbines equipped with detectors when comparing curtailment alternatives. This approach improved the ability to detect differences in risk among alternatives with similar criteria and removes the need for an uncurtailed control treatment. Small changes in cut-in speed (e.g., 0.5 m/s) resulted in clear reductions in acoustic exposure that were measurable at biweekly intervals, providing sensitive feedback on curtailment effectiveness. By contrast, carcass searches can typically detect changes in fatality estimates among curtailment treatments only if the cut-in speed is adjusted by more than 1 m/s (Adams et al., 2021; Whitby et al., 2024), and comparisons among curtailment strategies require many turbines to be operated according to each strategy and an operational control treatment. Implementing multiple curtailment treatments substantially increases the cost and complexity of studies and may not be possible for smaller facilities, and operating a subset of turbines as an operational control group increases risk to bats.

Interpreting variation in acoustic exposure among curtailment alternatives based on their criteria as opposed to turbine rotor speed assumes that turbine motion itself does not affect bat presence in the rotor-swept zone and/or the process of acoustic detection. This study did not document substantial differences in the rate of total bat acoustic activity at turbines with 3.0 versus 5.0 m/s cut-in speeds; the 8.0 m/s treatment could not be compared directly as it was not implemented at the same time as other treatments. Future studies could directly test this assumption by incorporating additional tools such as thermal video data or cross-comparing acoustic exposure calculations based on rotor speed and curtailment criteria among groups of turbines curtailed below a wider range of cut-in speeds. Aggregating data from turbine-mounted acoustic detectors across wind energy facilities operating across a wider geographic range will help identify additional factors affecting patterns in acoustic exposure and the transferability of relationships between acoustic exposure and fatality risk among regions and sites.

Our study provided additional support for using acoustic exposure as an alternative metric of fatality risk capable of fine-grain assessment of curtailment strategies. We demonstrated that acoustic exposure varied spatially and seasonally as a function of wind speed, but that such variation was consistent between sites and years. The relative protectiveness of curtailment did not vary seasonally, but consistent reductions in the magnitude of exposure, and therefore fatality risk, were apparent for a range of curtailment strategies with incrementally higher cut-in wind speeds applied throughout the season. Our results demonstrate how acoustic exposure could serve as a suitable metric for determining how to adjust curtailment parameters to meet seasonal changes in fatality risk and provide feedback on how effectively these changes prevent exposure. We conclude that using acoustic exposure to understand relative differences in risk across time and wind speeds can provide quantitative evidence needed to justify which curtailment strategy is most appropriate to minimize risk while reducing associated energy losses.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Analysis code and supporting data, summarized at biweekly intervals (Peterson et al., 2025), are available on Zenodo: https://doi.org/10.5281/zenodo.14714816.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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