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Research Article

Acoustic Exposure to Turbine Operation Quantifies Risk to Bats at Commercial Wind Energy Facilities

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ABSTRACT Turbine-related bat mortality at commercial wind energy facilities may threaten populations of migratory tree-roosting bat species in North America. Industry stakeholders and regulatory agencies alike are investigating strategies to reduce risk of population-level consequences as the wind energy industry grows. Bats collide with turbines only when turbine rotors are spinning and curtailing turbine operation at low wind speeds can effectively reduce bat fatality rates. Nonetheless, few quantitative data exist to determine appropriate threshold wind speeds below which turbine operations should be curtailed. Carcass monitoring is labor-intensive and does not provide information on factors linked to bat fatality rates on any scale finer than nightly. We tested whether acoustic bat data recorded at turbine nacelles could provide a more precise and sensitive measure of fatality risk to bats by analyzing acoustics, weather, turbine operation, and carcass data collected at 2 commercial wind energy facilities in West Virginia over 7 years. Each wind facility implemented several distinct curtailment treatments during our study, allowing us to compare fatality rates and acoustic bat activity across multiple operational strategies. We found that bat passes exposed to turbine operation explained close to 80% of the variation in carcass-based estimates of bat fatality rates and accounted for significant variation in raw carcass counts per turbine and probability of finding bat carcasses during individual turbine searches. Conversely, bat activity occurring when turbines were not operating had little or no relationship to fatality rates. We also found that patterns in bat activity exposure could be predicted accurately among turbines and years. Our results demonstrate that measuring exposure of acoustic bat activity provides a quantitative basis for designing, evaluating, and adaptively managing curtailment strategies. This is an important advance towards using curtailment to reduce bat fatality rates strategically while allowing for increased generation of renewable energy. © 2021 The Authors. *Wildlife Society Bulletin* published by Wiley Periodicals LLC on behalf of The Wildlife Society.

KEY WORDS acoustic monitoring, aerosphere, bat mortality, informed curtailment, West Virginia, wind energy.

Many migratory tree-roosting bats die each year at commercial wind energy facilities in North America, with fatalities occurring most often during late summer and fall on nights with relatively low wind speeds and warm temperatures (Kunz et al. 2007*a*, Arnett et al. 2008). Hoary bats (*Lasiurus cinereus*), eastern red bats (*L. borealis*), and silver-haired bats (*Lasionycteris noctivagans*) appear most susceptible to turbine-related impacts and account for most carcasses found during monitoring at wind energy facilities (Arnett and Baerwald 2013, Zimmerling and Francis 2016, Hein and Hale 2019). Fatalities of federally endangered, threatened, and candidate bat species whose populations have been impacted by White-nose Syndrome (e.g., Indiana bats [*Myotis sodalis*], northern long-eared bats [*M. septentrionalis*], and little brown bats [*M. lucifugus*]) also have occurred at low levels at wind energy facilities (Arnett et al. 2016, Hein and Hale 2019). Wind power is a growing source of renewable energy and extrapolating average bat mortality estimates to projected future development yields cumulative estimates high enough to threaten populations of

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vulnerable North American bat species (Arnett and Baerwald 2013, Arnett et al. 2016, Zimmerling and Francis 2016, Hein and Hale 2019). Potential population-level consequences are difficult to assess given the absence of reliable population estimates for long-distance migratory bats, but the relatively long lifespan of bats coupled with slow reproductive rates suggest that declines are likely for vulnerable species such as hoary bats (Frick et al. 2017, Friedenberg and Frick 2021).

Turbine-related bat fatalities occur only when turbine rotors are spinning (Horn et al. 2008, Arnett et al. 2016, Smallwood and Bell 2020), and preventing turbine operation when bats are active has been shown to reduce bat fatality rates (Arnett et al. 2011). The cut-in speed refers to the wind speed at which turbines begin to generate electricity into the power grid and typically ranges from 2.5 to 4 meters per second (m/s) for utility-scale wind turbines (Manwell et al. 2009). Turbine rotors may or may not rotate when wind speed is below the cut-in speed, depending on make and model. In the context of wildlife impacts, turbine curtailment refers to the current practice of simultaneously increasing the cut-in wind speed and feathering turbine blades parallel to the wind to prevent the turbine rotor from spinning below the increased cut-in speed. Turbine curtailment at low wind speeds, when bats are most active, prevents turbine operation and consequently removes fatality risk that would otherwise occur during these conditions. Baerwald et al. (2009) first reported reductions in bat fatality rates resulting from curtailing turbines at low wind speeds, and Arnett et al. (2011) demonstrated effectiveness of curtailment, noting similar reductions at turbines with modified cut-in wind speeds of 5.5 and 6.5 m/s. Subsequent curtailment studies have demonstrated considerable variation in fatality rate reductions for cut-in speeds ranging from 3.5 to 6.9 m/s (Arnett et al. 2013, Martin et al. 2017, American Wind and Wildlife Institute 2018). Although effective at reducing bat fatalities, curtailing turbine operation also eliminates generation of electricity and cost of curtailment increases as an approximately cubic function of wind speed from cut-in up to ~12–15 m/s (Carrillo et al. 2013). Accordingly, wind energy facility operators seek to minimize curtailment but often lack empirical evidence to justify reduced cut-in speeds, shortened periods, or incorporation of parameters other than wind speed to reduce power production losses.

Standardized carcass monitoring by trained observers who walk regularly-spaced transects beneath turbines and search visually for bat carcasses has been the primary method to estimate bat fatality rates and evaluate effectiveness of curtailment (Kunz et al. 2007*b*, Bernardino et al. 2013, Huso et al. 2016). Bat mortality estimates resulting from carcass monitoring often are imprecise due to short carcass persistence times relative to search interval, imperfect searcher efficiency, carcasses falling outside searchable areas, and other factors which prevent surveyors from finding all bat carcasses (Huso and Dalthorp 2014). Although carcass searches can demonstrate effectiveness of curtailment strategies if associated fatality rates are sufficiently different, the abovementioned imprecision of fatality estimates limits distinguishing among curtailment strategies, especially when carcass sample sizes are small or curtailment strategies are similar. More importantly, carcass searches, even if conducted daily at each turbine, cannot determine the precise timing of fatalities and will therefore do little to refine our understanding of how temporally variable factors affect fatality risk. The high cost of standardized carcass monitoring also reduces its suitability as a long-term monitoring strategy.

By contrast, acoustic detectors provide temporally fine-grained data on bat activity within the rotor zone of turbines and can operate autonomously for long periods of time (Kunz et al. 2007*b*, Parsons and Szewczak 2009). Weller and Baldwin (2012) used acoustic monitoring and occupancy models to demonstrate the influence of season and multiple environmental variables on bat activity in the rotor zone and suggested that incorporating additional parameters could improve efficiency of curtailment strategies. Behr et al. (2017) and Korner-Nievergelt et al. (2013) modeled bat activity from 35 wind energy facilities in Germany as a function of wind speed, temperature, and additional factors and used model outputs to predict fatality risk at a finely grained temporal scale. Hayes et al. (2019) incorporated real-time detection of bat activity at nacelle-mounted acoustic detectors into a strategy that also used wind speed to trigger curtailment and estimated a reduction in energy losses of 48% relative to a blanket curtailment strategy with a cut-in wind speed of 6.9 m/s. Collectively, these studies highlight the potential to use acoustic bat data to focus curtailment strategies on high-risk conditions.

We investigated relationships between acoustic bat activity measured on turbine nacelles and fatalities across temporal and spatial scales with an extensive dataset collected at 2 commercial wind energy facilities in West Virginia between 2011 and 2018. We hypothesized that bat activity exposed to turbine operation would be positively correlated with bat fatalities, whereas activity occurring when turbines were curtailed would be irrelevant for assessing risk. We also compared bat activity exposure at individual turbines under various curtailment treatments among turbines and years to evaluate the ability to simulate and predict exposure. As such, we tested whether acoustic bat monitoring at nacelle height could provide an effective methodological framework to predict and evaluate effectiveness of curtailment strategies. Achieving a temporally precise and sensitive metric of fatality risk will improve ability to predict and manage risk to bats and be useful in designing curtailment strategies that are tailored to site-specific patterns in bat activity.

STUDY AREA

Our study took place at 2 commercial wind energy facilities in West Virginia, both located on and characterized by long, linear forested ridges oriented roughly northeast-southwest (Woods et al. 1996; Fig. 1). The Laurel Mountain Wind Facility (Laurel Mountain) was a 97.6-megawatt (MW) wind energy facility spanning approximately 20 km along the ridgeline of Laurel Mountain, which formed the border between Randolph and Barbour counties in northeastern West Virginia. Laurel Mountain consisted of 61, 1.6-MW

GE XLE turbines arranged in a single string at elevations ranging from 780 to 945 m above sea level (ASL). Each turbine had an 82.5-m diameter rotor mounted atop an 80-m tower, with a rotor zone extending from approximately 39 to 122 m above ground level. During normal operation, these turbines rotated at speeds ranging from 10 to 18 revolutions per min (rpm) between a standard cut-in wind speed of 3.5 m/s and maximum wind speed of 25.0 m/s, and often freewheeled at wind speeds <3.5 m/s. The New Creek Wind Project (New Creek) was a 103-MW wind energy facility located on approximately 11 km of forested ridgeline on New Creek Mountain in Grant County, West Virginia (Fig. 1). The ridgeline elevation within New Creek is approximately 900 m ASL, with elevations in surrounding valleys ranging from 400 to 450 m ASL. New Creek included 49 Gamesa turbines (45 model G97 and 4 model G90), each with a 2.0-MW capacity and 78-m hub height. The rotor diameters of the G97 and G90 turbines are 97 m and 90 m, respectively. During normal operation, these turbines rotated at speeds up to 17.8 rpm between a standard cut-in wind speed of 3.0 m/s and maximum wind speed of 25.0 m/s.

Fourteen bat species occurred in West Virginia, including little brown bat, northern long-eared bat, Indiana bat, gray bat (*M. grisescens*), eastern small-footed bat (*M. leibii*), silver-haired bat, tri-colored bat (*Perimyotis subflavus*), big brown bat (*Eptesicus fuscus*), eastern red bat, Seminole bat (*Lasiurus seminolus*), hoary bat, evening bat (*Nycticeius humeralis*), Virginia big-eared bat (*Corynorhinus townsendii virginianus*), and Rafinesque's big-eared bat (*Corynorhinus rafinesquii*). All bats in West Virginia echolocate using ultrasonic frequencies ranging from ~10 to 190 kHz and can be detected acoustically using bat detectors, although species vary in echolocation behavior and characteristics, and not all species are equally detectable (Parsons and Szewczak 2009). Hoary bats, eastern red bats, and silver-haired bats accounted for 72% of carcasses found at commercial wind energy facilities in the region, although fatalities of all species except Virginia big-eared bats and Rafinesque's bats have occurred at facilities in North America (American Wind and Wildlife Institute 2020).

METHODS

Turbine Operation and Curtailment

Subsets of turbines at Laurel Mountain and New Creek were operated under curtailment strategies with cut-in wind speeds from 3.5 to 8.0 m/s and operational control groups without curtailment from 2011 to 2018. Although curtailment treatments were originally applied to compare their effectiveness at reducing bat fatality rates and not selected as part of an *a priori* study design, the diversity of curtailment strategies allowed us to compare acoustic exposure and fatality rates across an unusually large range. At Laurel Mountain, treatments included blanket curtailment strategies with a single cut-in wind speed and temperature threshold and a sliding scale that applied progressively higher cut-in speeds at warmer temperatures (Table 1). All turbine curtailment strategies at Laurel Mountain used real-time data from nacelle-mounted anemometers and temperature sensors at 2 on-site meteorological (met) towers to automatically trigger curtailment of individual turbines during prescribed combinations of temperature and wind speed. When multiple treatments were in place at Laurel Mountain, turbines were divided equally among treatments, which were assigned to turbines at random and reassigned between monitoring periods (e.g., fall 2011 and spring-summer 2012). Curtailment treatments at New Creek included several distinct strategies with seasonally variable cut-in speeds and temperature thresholds, triggered automatically based on temperature and wind speed data recorded by nacelle-mounted anemometers and temperature sensors on each turbine (Table 2). At New Creek, turbines were divided equally among treatments during each monitoring period, and treatments were assigned systematically in a repeating sequence along the single turbine string so that treatments were distributed evenly among turbines. Turbines in operational control groups were operated according to turbine manufacturer's specifications at each site; rotor freewheeling was not prevented below the standard cut-in speed of 3.5 m/s at Laurel Mountain and 3.0 m/s at New Creek.

To document whether turbines were effectively curtailed during appropriate conditions, we obtained 10-min mean rpm and wind speed data from each surveyed turbine and 10-min mean temperature from turbines and on-site met towers during each study period. For Laurel Mountain, we used temperature data averaged between 2 met towers, and for New Creek, we used temperature data recorded externally at each turbine nacelle, as corresponding turbine control systems referenced these same data. We removed implausible wind speed readings (e.g., <0 m/s and >40 m/s) and also omitted wind speed, temperature, and rpm measurements in certain instances where sequences of 6 or more identical values across multiple sensors indicated data gaps

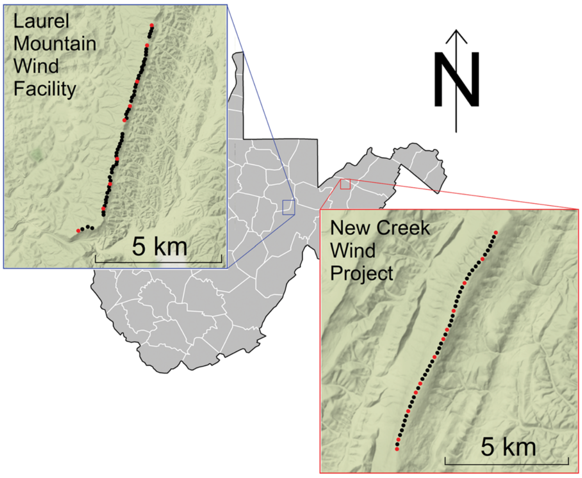

Figure 1. Location of the Laurel Mountain (blue outline) and New Creek (red outline) wind energy facilities in West Virginia. USA, 2011–2018. Red dots identify turbines equipped with acoustic detectors during the study and black dots indicate turbines without acoustic detectors.

Table 1. Cut-in wind speeds (m/s) below which turbine blades were feathered and temperature thresholds of curtailment treatments during each monitoring period at Laurel Mountain wind energy facility, West Virginia, USA, between 2011 and 2015. In 2011–2014, curtailment occurred from 30 min before sunset to 30 min after sunrise and in 2015 curtailment occurred from sunset to sunrise. Blades of turbines in the operational control group were not feathered below the turbine manufacturer's cut-in speed of 3.5 m/s.

	Study period							
	2011–2012[a]	2012		2013	2014	2015		
Temperature	15 Aug–31 Oct 2011; 1 Apr–31 Jul 2012	1 Aug–5 Sep[b]	6 Sep–15 Nov	1 Apr–15 Nov	1 Apr–15 Nov	1–30 Apr	1 May–31 Oct	1–15 Nov
>15°C	control; 3.5; 4.5 m/s	shutdown	8.0 m/s	8.0 m/s	6.9 m/s	4.0 m/s	6.9 m/s	control
12.5–15°C	control; 3.5; 4.5 m/s	shutdown	7.5 m/s	7.5 m/s	6.9 m/s	4.0 m/s	6.9 m/s	control
10.0–12.5°C	control; 3.5; 4.5 m/s	shutdown	6.5 m/s	6.5 m/s	6.5 m/s	4.0 m/s	6.5 m/s	control
7.5–10.0°C	control; 3.5; 4.5 m/s	shutdown	5.5 m/s	5.5 m/s	5.5 m/s	4.0 m/s	5.5 m/s	control
<7.5°C	control; 3.5; 4.5 m/s	shutdown	3.5 m/s	3.5 m/s	3.5 m/s	3.5 m/s	3.5 m/s	control

[a] The 3.5 m/s treatment was implemented only from 1 Aug to 31 Oct 2011.

[b] All turbines were fully curtailed (all wind speeds) from 1 Aug to 5 Sep 2012, during which no carcass searches occurred.

as opposed to valid measurements. We used time-stamped temperature and wind data to categorize every 10-min interval as meeting or not meeting conditions of corresponding curtailment strategies for each turbine, determining sunrise and sunset times for each surveyed night using the suncalc package (v. 0.5.0, Thieurmel and Elmarhraoui 2019) in the R software environment (v. 4.0.1, R Core Team 2020). We further categorized periods as curtailed if conditions were met and turbine rotor speed was <1 rpm.

Standardized Carcass Monitoring and Bat Fatality Estimates

Standardized carcass monitoring occurred seasonally at subsets of turbines at Laurel Mountain in 2011–2015 and at New Creek in 2017–2018 following protocols and levels of effort approved by the West Virginia Division of Natural Resources and U.S. Fish and Wildlife Service, as summarized below. Survey dates varied from year to year and the search intervals for Laurel Mountain and New Creek were 3 days and 7 days, respectively, although field survey protocols were consistent among turbines and years at each site (Table 3). Trained observers visually scanned the ground on either side of marked, linear transects spaced at 5-m intervals at Laurel Mountain (Stantec Consulting Services Inc. [Stantec] 2016) and 4-m intervals at New Creek (Stantec 2019). Plot sizes were defined by the area cleared of forest around each turbine or the limit of searchable terrain up to a maximum square plot, centered on turbines and 90 m on a side. Periodic mowing of search plots occurred at Laurel Mountain to maintain visibility and carcass detection, whereas ground cover at New Creek remained sufficiently sparse during the monitoring periods and mowing was unnecessary.

Bat fatality rates estimated per turbine for each operational treatment were obtained from publicly-available monitoring reports prepared for each site (Table 3). Bat fatality estimates for Laurel Mountain were generated using the Shoenfeld method, as described in Stantec (2016), whereas fatality rates for New Creek were estimated using the Huso estimator (Huso 2010), as described in Stantec (2019). Each estimator applies correction factors based on search interval and proportion of plot area that could be searched and adjusts raw carcass counts by incorporating results of site-specific bias trials to account for imperfect carcass detection and carcass removal by scavengers. The Huso and Shoenfeld estimators are similar and have both been used frequently to estimate bat fatality rates but make different assumptions about carcass detectability, persistence, and other factors (Bernardino et al. 2013). Recalculating fatality estimates using the same estimator for both sites was beyond the scope of this study. Searcher efficiency trials (36–84 per site per monitoring period) and carcass removal trials (27–69 per site per monitoring period) occurred at each site during each monitoring period and used bat carcasses found at each site, supplemented when necessary with carcasses provided by the West Virginia Division of Natural Resources and

Table 2. Cut-in wind speeds (m/s) below which turbine blades were feathered and temperature thresholds of curtailment treatments applied from sunset to sunrise at New Creek wind energy facility, West Virginia, USA, in 2017 and 2018. Cut-in speeds were the same across all treatments during April through June 2017 but otherwise differed among treatments according to temperature and time of year. Blades of turbines in the operational control group were not feathered at wind speeds below the turbine manufacturer's cut-in speed of 3.0 m/s.

	Study period						
	2017			2018			
Temperature	1 Apr–30 Jun	1 Jul–15 Oct	16 Oct–15 Nov	1 Apr–30 Jun	1 Jul–30 Sep	1–31 Oct	1–15 Nov
>10°C	6.9 m/s	6.0 m/s; 6.9 m/s	4.5 m/s; 5.5 m/s; 6.0 m/s; 6.9 m/s	control; 5.5 m/s	control; 6.0 m/s	control; 5.0 m/s	control; 4.0 m/s
5–10°C	6.9 m/s	control; 6.0 m/s; 6.9 m/s	control; 6.0 m/s; 6.9 m/s	control; 5.5 m/s	control; 6.0 m/s	control; 5.0 m/s	control; 4.0 m/s
≤5°C	6.9 m/s	control; 6.0 m/s; 6.9 m/s	control; 6.9 m/s	control	control	control	control

Table 3. Standardized bat carcass monitoring survey effort for Laurel Mountain and New Creek wind energy facilities, West Virginia, USA, 2011–2018.

Site	Year	Dates	Operational group	No. Turbines/Search interval	Estimator	Reference
Laurel	2011	15 Aug–31 Oct	control	8 turbines/3 days	Shoenfeld	Stantec 2013
			3.5	8 turbines/3 days	Shoenfeld	Stantec 2013
			4.5	8 turbines/3 days	Shoenfeld	Stantec 2013
	2012	1 Apr–31 Jul	control	12 turbines/3 days	Shoenfeld	Stantec 2013
			4.5	12 turbines/3 days	Shoenfeld	Stantec 2013
	2012	6 Sep–15 Nov	3.5–8.0 (based on temp)	24 turbines/3 days	Shoenfeld	Stantec 2014
	2013	1 Apr–15 Nov	3.5–8.0 (based on temp)	24 turbines/3 days	Shoenfeld	Stantec 2014
	2014	1 Apr–15 Nov	3.5–6.9 (based on temp)	24 turbines/3 days	Shoenfeld	Stantec 2015
	2015	1 Apr–15 Nov	3.5–6.9 (based on temp)	24 turbines/3 days	Shoenfeld	Stantec 2016
New Creek	2017	1 Apr–15 Nov	6.9	12 turbines/7 days	Huso	Stantec 2018
			6.0–6.9 (by season)	12 turbines/7 days	Huso	Stantec 2018
			5.5–6.9 (by season)	13 turbines/7 days	Huso	Stantec 2018
			4.5–6.9 (by season)	12 turbines/7 days	Huso	Stantec 2018
	2018	7 May–14 Nov	Control	24 turbines/7 days	Huso	Stantec 2019
			4.0–6.9 (by season)	25 turbines/7 days	Huso	Stantec 2019

commercially available brown mouse carcasses as surrogates.

Bat Acoustic Monitoring

Bat acoustic data collection.—Bat acoustic monitoring at Laurel Mountain and New Creek used ultrasonic bat detectors attached to nacelle-mounted anemometers at the downwind end of turbine nacelles (~90 m above ground level), with microphones oriented horizontally, facing away from turbine rotors (Fig. 2). Acoustic detectors were deployed on a subset of turbines where carcass searches took place, such that acoustic metrics were based on data collected at a smaller number of turbines (2–9 turbines per treatment) than bat fatality estimates (12–24 turbines per treatment). At each site, detectors were powered by 12V batteries charged by 10-watt solar panels. We used similar criteria to select turbines for acoustic monitoring from the subset of turbines with standardized carcass searches at each site, deploying detectors on northernmost and southernmost turbines and distributing remaining detectors at turbines spaced approximately equally along each facility. Acoustic detectors were reassigned or replaced between survey years such that each annual turbine-detector pair was a unique combination, and 6–9 detectors were deployed per site during each year of monitoring.

At Laurel Mountain, we used Anabat (Titley Electronics, Queensland, Australia) model SD1 or SD2 zero-crossing echolocation detectors programmed to operate each night between 1800 and 0800 hr. We tested all system microphones using an ultrasonic transmitter (Bat Chirp II, Tony Messina, Las Vegas, NV, USA) prior to and following deployment and manually adjusted the sensitivity to ~6–7, or one unit below the point where constant static was recorded (Peterson et al. 2014). In 2011–2014, GLM1 (Titley Electronics, Queensland, Australia) modems enabled remote data transfer and in 2015, we manually downloaded data from detectors' compact flash memory cards and inspected detector systems on an approximately monthly basis. We replaced malfunctioning system components when possible throughout each monitoring period.

We monitored acoustic bat activity at New Creek using SM4BAT-FS (Wildlife Acoustics, Concord, MA, USA) detectors equipped with omni-directional SMM-U1 microphones and programmed to operate from 30 min before sunset to 30 min after sunset. We operated detectors in

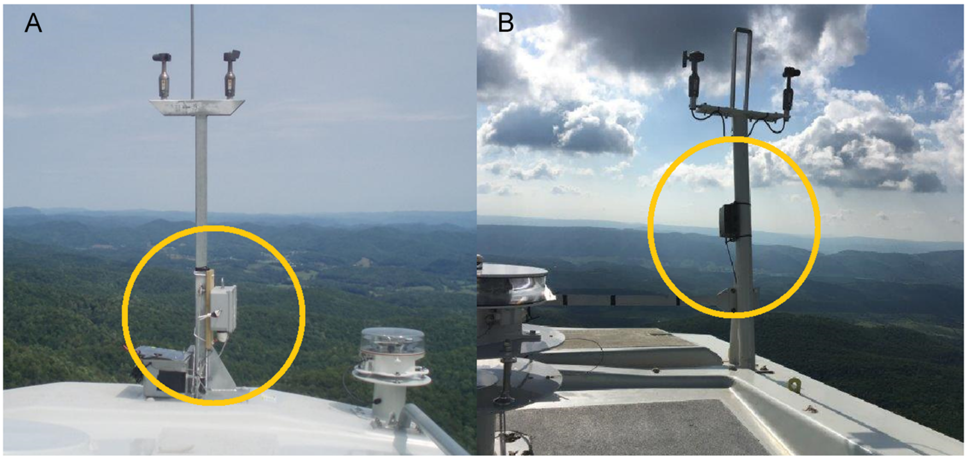

Figure 2. Acoustic bat detectors in weatherproof enclosures (circled in yellow) installed on the nacelle of Turbine 47 at Laurel Mountain A) and Turbine 25 at New Creek B) wind energy facilities, West Virginia, USA, September 2011 and May 2017.

triggered wav mode using default settings recommended by the manufacturer. We performed sensitivity checks on detector microphones prior to deployment using a Wildlife Acoustics Ultrasonic Calibrator (Wildlife Acoustics, Concord, MA, USA) to verify that microphones were operating according to manufacturers' specifications.

Acoustic data analysis.—We converted raw field recordings to zero-crossing format using CFCread software (version 4.3 s, Titley Scientific, Queensland, Australia) for Anabat systems at Laurel Mountain and Kaleidoscope Pro software (v. 3.1.7, Wildlife Acoustics, Concord, MA, USA) for full-spectrum systems at New Creek. Next, we manually generated a nightly status file categorizing each attempted survey night as successful or not successful based on review of recorded data and a system status file generated by each detector. After conversion to the zero-crossing format, we visually inspected each recorded file from Laurel Mountain and New Creek using AnalookW software (v. 3.8 s or later; Titley Scientific, Queensland, Australia) and defined a bat pass as a single file containing 2 or more visually discernable echolocation pulses within a 15-sec file (Kunz et al. 2007*b*).

Comparison of Bat Activity Exposure and Fatality Data

We rounded the time stamp of each bat pass up to 10-min intervals using R package xts (v. 0.12.0, Ryan and Ulrich 2018) and determined wind speed and turbine rotor speed (rpm) from the same turbine nacelle during the corresponding period. To differentiate bat activity in terms of exposure to turbine operation and associated risk of turbine-related mortality, we categorized bat passes detected when rotor speed was 1 rpm or greater as exposed and those detected below 1 rpm as not exposed to turbine operation using R package dplyr (v. 1.0.0, Wickham et al. 2019). We compared metrics of total and exposed bat activity to bat fatality rates at multiple scales including curtailment treatment, turbine, and turbine search. Unlike fatality estimates, which incorporated interturbine variation in carcass counts, metrics of acoustic exposure used in the treatment-level analysis were based on data pooled among detectors in each treatment.

Bat activity and fatality estimates by treatment.—We pooled acoustic data from turbines within operational treatments for which empirical bat fatality estimates were available (Table 3) and calculated, for date ranges represented by the fatality estimates, total numbers of bat passes per detector night. We also calculated acoustic exposure per treatment as a rate (number of exposed passes per detector night) and as a percent of total passes (scaled from 0 to 100). We limited acoustic data summaries to ranges of dates in which treatments were in effect or time periods represented by corresponding carcass-based fatality estimates. We used general linear models to compare bat fatality estimates for each treatment to our 3 metrics of acoustic bat activity. We compared models with and without site as a factor using Wald likelihood ratio tests implemented in R package aod (v. 1.3.1, Lesnoff and Lancelot 2012).

Bat activity and raw carcass counts per turbine.—To compare fatality patterns and acoustic bat activity at a finer spatial and temporal scale, we compared total numbers of bat passes and the subset of exposed bat passes per detector night to raw numbers of bat carcasses found per turbine during standardized carcass searches. We calculated carcass totals and acoustic metrics per turbine per monitoring period, excluding data from the brief fall 2012 carcass monitoring period (Table 3). We assumed acoustic data and carcass totals to be independent among turbines and monitoring periods based on temporal and spatial isolation of our data sets. We modeled raw carcass counts per turbine as a function of total bat activity and exposed bat activity recorded per turbine during the same monitoring period using generalized linear models with a Poisson distribution. Our analysis focused on spatial and temporal patterns in fatality rather than total magnitude of fatality, so we did not adjust carcass counts to account for searcher efficiency and carcass persistence or extrapolate for unsearchable area. Searchable area, number of turbine searches, and ground visibility, each of which can influence raw carcass counts, were similar among turbines at each site but differed between sites. We tested models with and without site as a factor to account for intersite differences in search interval and potential differences in searcher efficiency and carcass persistence, evaluating significance of site using Wald tests.

Bat activity and carcass detection during individual turbine searches.—We calculated the number of total and exposed bat passes per night for the intervals between every standardized carcass search at turbines equipped with acoustic detectors. Typical search intervals were 3 nights for Laurel Mountain and 7 nights for New Creek. We categorized every turbine search as having detected or not detected fresh bat carcasses (e.g., fatalities estimated to have occurred since the previous search) and used logistic regression to compare probability of carcass detection to the rate of acoustic bat activity. As we had done at the treatment and turbine level, we ran separate models for total bat activity and the subset of exposed activity and compared models with and without site using Wald tests.

Simulating, Measuring, and Predicting Bat Activity Exposure

We simulated bat activity exposure associated with each operational group by calculating the rate (per detector night) and percent (per 100 total bat passes) of the subset of bat passes occurring when curtailment conditions were met and turbines would be operating. For operational control groups, we used wind speeds at which rotor speed exceeded 1 rpm for >50% of the time (i.e., 2.0 m/s for New Creek and 3.0 m/s for Laurel Mountain) as thresholds above which simulated exposure would occur. We then measured bat activity exposure for each operational group as a rate and a percent, this time defining exposure as the subset of bat passes recorded when turbine rotor speed exceeded 1 rpm. Comparing simulated and measured exposure indicated how closely actual turbine operation aligned with each curtailment strategy, providing a measure of practical accuracy of curtailment simulations. We calculated simulated and measured exposure per turbine and treatment, pooling acoustic data among turbines in each operational group.

Next, we predicted exposure of bat activity to turbine operation by measuring exposure associated for each turbine and comparing this to simulated exposure for the same treatment and turbine using data recorded during the previous monitoring period (usually the previous year). We compared predicted and measured exposure for individual turbines, limiting analysis to turbines surveyed acoustically in consecutive years. We also tested predictions based on a pooled data set (separated by site) of acoustic data from all turbines except those in the treatment being predicted. We compared predicted versus measured exposure for individual turbines and pooled data using general linear models. To account for bias in our dataset toward curtailment treatments that resulted in low exposure of bat activity to turbine operation, we log-transformed (base 10) simulated and measured exposure from individual turbines. We compared models with and without site using likelihood ratio tests and evaluated the accuracy of predictions based on models using the individual turbine and pooled data sets by calculating the root mean square error (RMSE) and 95% confidence intervals of model residuals.

RESULTS

Bat Activity and Fatalities

Bat activity and fatality estimates by treatment.—Paired nacelle-height acoustic bat activity data and bat fatality estimates were available for 11 distinct operational groups (7 at Laurel Mountain and 4 at New Creek). We excluded the 3.5 m/s treatment at Laurel Mountain from analysis because acoustic data from only a brief period (21 detector-nights) at one detector were available for this treatment. Otherwise, acoustic detectors generated substantial datasets (220–1,874 detector-nights and 2,394–18,666 bat passes per treatment). Empirical bat fatality estimates ranged from 1.4 to 38.2 bats per turbine per monitoring period among operational groups, and associated numbers of bat passes per night ranged from 5.3 to 12.8 (Table 4). Total nightly bat passes (i.e., combined rate of exposed and unexposed passes) measured at turbines within each operational treatment had no discernable relationship with estimated bat fatality rates, but the subset of exposed bat passes explained close to 80% of the variation in estimated bat fatality rates among treatments ($F_{(1,8)} = 26.1$, $R^2 = 0.77$, $P < 0.001$; Fig. 3). Likewise, percent of bat passes exposed to turbine operation was even more closely aligned with estimated fatality rates ($F_{(1,8)} = 67.2$, $R^2 = 0.89$, $P < 0.001$). Site was not a significant factor for any models comparing bat activity and fatality estimates.

Bat activity and raw carcass counts per turbine.—Bat carcass counts and acoustic data were available for 9 turbines at Laurel Mountain and 13 turbines at New Creek (after removing 2 turbines with fewer than one week of acoustic data) during 6 distinct monitoring periods, representing 49 independent carcass totals with corresponding measures of bat activity. The totals do not include an abbreviated fall 2012 monitoring period at Laurel Mountain, which we excluded due to its low number of carcass searches relative to other monitoring periods. More bat carcasses were found at turbines with higher rates of exposed bat activity within

Table 4. Acoustic bat survey effort and metrics of total bat activity (and the subset exposed to turbine operation) by site, year, and treatment with corresponding bat fatality estimates (bats per turbine per monitoring period), for Laurel Mountain and New Creek wind energy facilities, West Virginia, USA, 2011–2018.

Site	Year	Dates surveyed acoustically	Operational group	No. Turbines (detector-nights)	No. Bat passes (exposed)	No. Bat passes per detector-night (exposed rate)	% Passes exposed	Bat fatality estimate (95% confidence intervals)
Laurel Mountain	2011/ 2012[a]	24 Aug–11 Nov; 28 Mar–31 Jul	control	4 (483)	4,708 (2,755)	9.7 (5.7)	58.5	23.4 (17.6–30.2)
	2011	24 Aug–13 Sep	3.5 m/s[b]	1 (21)	260 (133)	12.4 (6.3)	51.2	7.8 (3.5–12.6)
	2011/ 2012[a]	24 Aug–11 Nov; 30 Mar–31 Jul	4.5 m/s	5 (609)	4,252 (1,720)	7.0 (2.8)	40.5	6.6 (4.6–8.8)
	2012	1 Aug–5 Sep	shutdown[c]	6 (198)	3,711 (0)	18.7 (0.0)	0.0	NA
	2012	6 Sep–14 Nov	3.5–8.0 m/s (by temp)	6 (384)	3,636 (381)	9.5 (1.0)	10.5	1.5 (0.8–2.5)
	2013	31 Mar–14 Nov	3.5–8.0 m/s (by temp)	9 (1,741)	18,666 (1,030)	10.7 (0.6)	5.5	1.4 (0.7–2.2)
	2014	9 Apr–15 Nov	3.5–6.9 m/s (by temp)	9 (1,874)	9,998 (843)	5.3 (0.4)	8.4	1.9 (1.3–2.7)
	2015	9 Apr–15 Nov	3.5–6.9 m/s (by temp)	9 (1,679)	13,893 (952)	8.3 (0.6)	6.9	2.1 (1.0–3.8)
New Creek	2017	NA	6.9 m/s[d]	NA	NA	NA	NA	2.6 (1.5–4.6)
	2017	NA	6.0–6.9 m/s (by season)[d]	NA	NA	NA	NA	2.2 (1.3–3.4)
	2017	19 May–14 Nov	5.5–6.9 m/s (by season)	5 (724)	9,281 (2,384)	12.8 (3.3)	25.7	4.0 (2.2–6.5)
	2017	19 May–14 Nov	4.5–6.9 m/s (by season)	2 (220)	2,394 (534)	10.9 (2.4)	22.3	1.9 (1.4–2.6)
	2018	9 May–16 Nov	control	4 (694)	4,981 (4,022)	7.2 (5.8)	80.7	38.2 (21.0–75.7)
	2018	16 May–16 Nov	4.0–6.9 m/s (by season)	5 (666)	6,936 (964)	10.4 (1.4)	13.9	3.7 (2.2–7.2)

[a] Bat fatality estimates for 2011/2012 combine results from the fall 2011 and spring/summer 2012 monitoring periods.
[b] The 3.5 m/s cut-in speed was discontinued after fall 2011.
[c] Carcass monitoring did not occur during the fall 2012 shutdown and no fatality estimate was available for this period.
[d] Acoustic data were unavailable from turbines in these operational treatments in 2017.

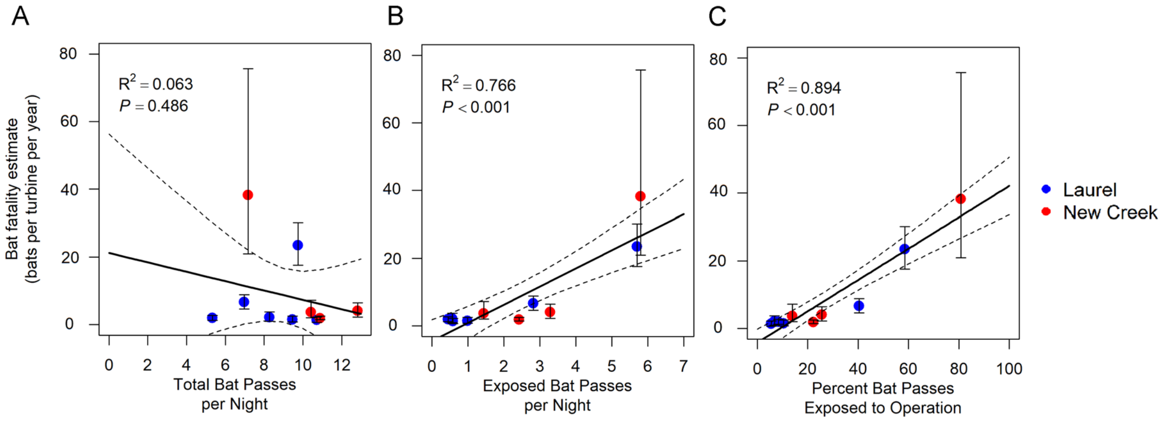

Figure 3. Estimated bat fatality rates as a function of total bat passes per night A), the subset of bat passes exposed to turbine operation B), and percent of bat passes exposed to turbine operation C) for curtailment treatments at Laurel Mountain and New Creek wind energy facilities, West Virginia, USA, 2011–2018. Dashed lines indicate 95% confidence intervals around the regression line. Error bars represent upper and lower 95% confidence intervals surrounding fatality estimates and were not included in the model structure.

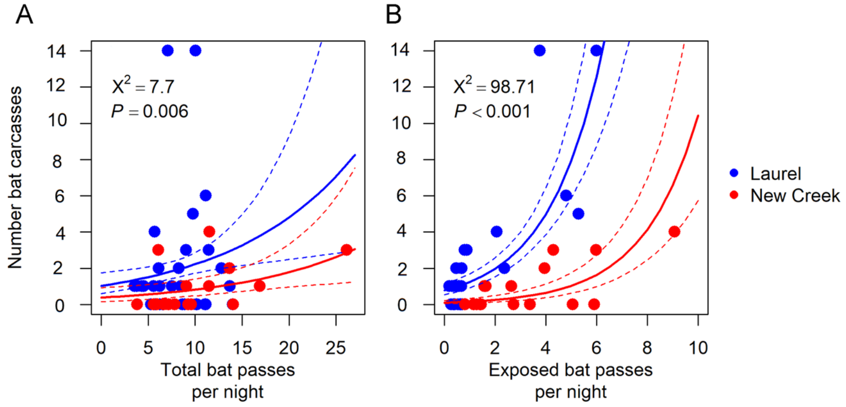

Figure 4. Total number of bat carcasses found per turbine as a function of total bat passes per night A) and the subset of bat passes per night exposed to turbine operation B) for Laurel Mountain and New Creek wind energy facilities, West Virginia, USA, 2011–2018. Dashed lines indicate 95% confidence intervals.

corresponding monitoring periods ($\chi^2_{(2)} = 98.71$, $P < 0.001$; Fig. 4). Total bat passes per night also explained variation in raw carcass counts per turbine ($\chi^2_{(2)} = 7.7$, $P = 0.006$), although this relationship was substantially weaker than when only exposed activity was modeled. Fewer carcasses were found at New Creek than Laurel Mountain due, in large part, to a longer search interval (fewer total carcass searches). Site was a significant factor in both models with raw carcass counts as the dependent variable.

Bat activity and carcass detection during individual turbine searches.—Acoustic and fatality data were available for 2,172 turbine search intervals at Laurel Mountain ($\bar{x}$ length = 3.05 days) and 322 intervals at New Creek ($\bar{x}$ length = 7.07 days). Carcasses were found following 55 intervals (2.5%) at Laurel Mountain and 10 intervals (3.1%) at New Creek. Probability of finding a bat carcass was greater following intervals with a higher rate of exposed bat activity, based on logistic regression ($\chi^2_{(1)} = 65.8$, $P < 0.001$; Fig. 5). Probability of carcass detection was also greater following intervals with higher rates of total bat activity ($\chi^2_{(1)} = 6.5$, $P = 0.01$), although this relationship was weaker as compared to the comparison with the subset of bat passes exposed to turbine operation. Site was not a significant factor for any models, based on likelihood ratio tests.

Simulating and Predicting Curtailment

Curtailment treatments implemented at Laurel Mountain and New Creek from 2011 to 2018 should have exposed 2.7–85.7% of recorded bat passes to turbine operation among turbines based on simulations using 10-min temperature and wind speed data. Corresponding amounts of acoustic bat activity exposure based on measured rotor speed ranged from 3.6 to 85.2% with turbines using a threshold of 1 rpm to determine exposure. Log-transformed (base 10) simulated and measured exposure were correlated, based on 62 operational datasets from individual turbines ($F_{(1,60)} = 748.7$, $R^2 = 0.93$, $P < 0.001$; Fig. 6A).

Predictions based on acoustic and weather data collected the previous year at the same turbine ($n = 33$ paired

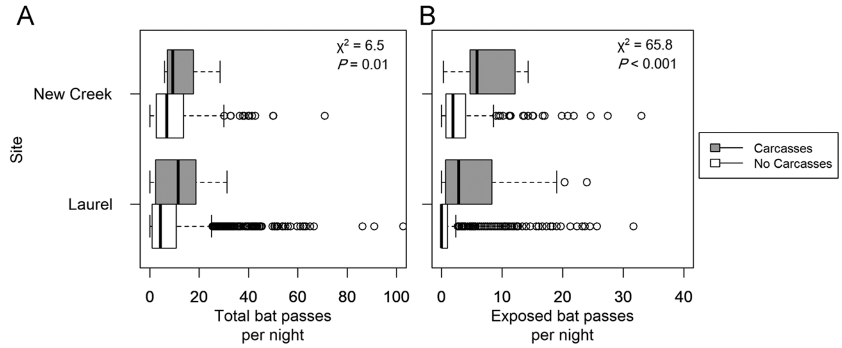

Figure 5. Distribution of bat activity in intervals preceding turbine searches with and without detection of bat carcasses as a function of total bat passes A) and the subset of exposed bat passes B) per night for Laurel Mountain and New Creek wind energy facilities, West Virginia, USA, 2011–2018. Boxes define the first quartile, median, and third quartile, whiskers represent 1.5 × the interquartile range, and circles identify points outside these limits.

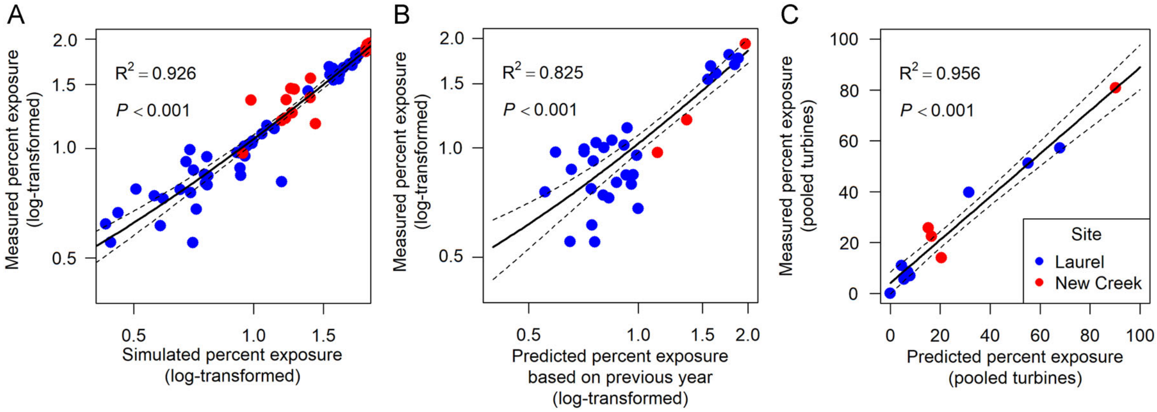

Figure 6. Measured versus simulated exposure (percent, log-transformed) of bat activity to turbine operation (A; $n = 62$) and predicted exposure based on the previous year's data (B; $n = 33$) for individual turbines (percent, log-transformed) and pooled turbines (percent) by operational treatment (C; $n = 12$) at Laurel Mountain and New Creek, West Virginia, USA, 2011–2018.

datapoints) were also closely related to measured exposure ($F_{(1,31)} = 146.6$, $R^2 = 0.83$, $P < 0.001$; Fig. 6B). Mean absolute value of differences between measured and predicted exposure, based on data from the previous year at the same turbine, was 4.3%. The 95% quantiles for residuals of the model comparing predicted and measured exposure ranged from −0.29 to 0.22, with a residual RMSE of 0.161. The relationship between predicted and measured exposure did not vary among sites.

Predicted exposure for 12 operational groups (including control) from which nacelle-height acoustic data were available ranged from 0 to 90.2% of recorded bat passes, based on data pooled among all turbines at each site, excluding those in the treatment in question (Table 5). Predictions were correlated with measured exposure ($F_{(1,10)} = 218$, $R^2 = 0.96$, $P < 0.001$), which ranged from 0 to 80.8% of bat passes per operational group (Table 5; Fig. 6C). The 95% quartiles for residuals of our model comparing predicted and measured exposure ranged from −6.7 to 8.8, with a residual RMSE of 5.0. Mean absolute value of differences between predicted and measured exposure based on pooled data was 5.3%. Relationships between predicted and measured exposure of bat activity did not differ among sites based on likelihood ratio tests and predicted exposure explained over 90% of variance in measured exposure among operational groups (Fig. 6).

DISCUSSION

Exposed bat activity, whether expressed as a nightly rate or percent of total passes, explained a significant amount of variation in bat fatality estimates for operational treatments ranging from unmodified operation to aggressive curtailment strategies designed to minimize risk to bats. Exposed bat activity also explained a significant amount of variation in raw carcass counts among turbines and probability of detecting bat carcasses during individual turbine searches. Total bat activity, which also included passes detected when turbine rotors were not spinning, had a weaker relationship with carcass detection during individual turbine searches and raw carcass counts and showed no relationship with fatality rates by treatment. The strongest and most compelling relationship between bat activity and fatalities was the positive correlation between pooled acoustic exposure and empirical fatality estimates by curtailment treatment. Fatality estimates provide the most accurate and complete representation of fatality risk because they account for varying survey methods and site-specific patterns in

Table 5. Predicted and measured exposure of bat activity to turbine operation by treatment (limited to treatments for which acoustic data were available) at Laurel Mountain and New Creek wind energy facilities, West Virginia, USA, 2011–2018.

Site	Period	Operational group	Predicted exposure %	Measured exposure %	Difference (%)
Laurel	2011–2012	control	67.9 ($n = 54{,}520$)	57.1 ($n = 4{,}824$)	−10.8
	2011	3.5 m/s	55.2 ($n = 59{,}084$)	51.2 ($n = 260$)	−4.1
	2011–2012	4.5 m/s	31.5 ($n = 55{,}013$	39.7 ($n = 4{,}331$)	8.2
	2012	shutdown	0.0 ($n = 55{,}836$)	0.0 ($n = 3{,}711$)	0.0
		3.5–8.0 (by temp)	4.6 ($n = 55{,}488$)	10.9 ($n = 3{,}636$)	6.4
	2013	3.5–8.0 (by temp)	5.5 ($n = 40{,}458$)	5.5 ($n = 18{,}666$)	0.0
	2014	3.5–6.9 (by temp)	7.1 ($n = 49{,}126$)	8.4 ($n = 9{,}998$)	1.3
	2015	3.5–6.9 (by temp)	7.9 ($n = 45{,}231$)	6.9 ($n = 13{,}893$)	−1.1
New Creek	2017	5.5–6.9 (by season)	15.3 ($n = 14{,}339$)	25.7 ($n = 9{,}281$)	10.4
		4.5–6.9 (by season)	16.5 ($n = 21{,}211$)	22.4 ($n = 2{,}410$)	5.9
	2018	control (2018)	90.2 ($n = 18{,}627$)	80.8 ($n = 4{,}993$)	−9.4
		curtailed (2018)	20.5 ($n = 16{,}684$)	13.9 ($n = 6{,}936$)	−6.6

carcass persistence, searcher efficiency, search areas, and spatial distribution of carcasses (Bernardino et al. 2013, Huso et al. 2016). Treatment-level results demonstrated that curtailment dramatically reduced fatality rates and that exposed bat activity provided a quantitative measure of reductions in estimated bat fatality rates.

Relationships between exposed bat activity and fatalities were similar at Laurel Mountain and New Creek; the only models in which site was a significant factor were those comparing raw carcass counts to acoustic activity. Raw carcass counts depend on search area, ground conditions, and number of searches per monitoring period, among other factors (Bernardino et al. 2013). Although such factors were similar among turbines at each site, they differed between sites, explaining the significance of site in models of carcass counts as a function of exposed bat activity. Most notably, search interval was shorter at Laurel Mountain, resulting in roughly twice as many carcass searches per turbine compared to New Creek.

Previous attempts to relate acoustic bat activity and fatality rates at wind energy facilities have yielded mixed results. Most recently, Solick et al. (2020) found no significant relationship between preconstruction bat activity levels and subsequent fatality estimates in an analysis of results from 49 paired studies. There was no relationship between the magnitude of preconstruction acoustic bat activity and fatality during operation across 12 wind facilities in Pennsylvania, although seasonal patterns in bat activity and fatalities were consistent (Taucher et al. 2012). By contrast, Baerwald and Barclay (2009, 2011) noted a significant association between preconstruction bat activity and fatalities among 5 sites in Alberta and reported significant relationships between bat activity and fatalities on a nightly basis. Johnson et al. (2011) also reported a correlation between regional trends in nightly acoustic bat activity and fatalities for certain species at a nearby wind energy facility near their study site for certain bat species.

Several factors could explain the lack of consistent relationships between acoustic bat activity and fatality patterns. Bats appear to be attracted to wind turbines (Cryan et al. 2014), and preconstruction surveys are poor predictors of bat activity near constructed turbines (Kunz et al. 2007*b*). Potentially complex behavioral processes affect temporal and seasonal variation in bat activity, and comparisons over coarse time scales may fail to detect relationships between activity and fatalities that occur in shorter intervals. Further, numbers of recorded bat passes do not reliably indicate the number of bats in an area (Hayes 2000) and bats do not echolocate at all times during flight (Corcoran and Weller 2018), thus, bat activity may not necessarily align well with fatality rates. Voigt et al. (2021) highlighted that acoustic detectors deployed on turbine nacelles can sample only a limited proportion of the rotor-swept zone of commercial-scale wind turbines. Perhaps most importantly, turbines pose a risk to bats only when operating and previous studies attempting to link acoustic bat activity and fatality rates have not differentiated acoustic activity that was exposed or not exposed to turbine operation.

Our detection of strong associations between exposed bat activity and fatality rates improves upon previous studies that documented weak or inconsistent relationships between acoustic activity and fatality rates. Our study was the first to differentiate exposed versus unexposed bat activity, and this distinction is critical. Turbine operation determines whether bats are at risk during a given interval, and bat presence when turbines are idle or curtailed should have no relationship with fatalities. By contrast, exposed activity measured at nacelle height represents bats flying in or near the rotor zone of an operating turbine and provides a direct indication of risk. Thermal imaging video footage of bats flying near operating turbines tends to document substantially more bat activity near turbine blades as opposed to collision events, suggesting that most bats that fly near turbine nacelles or pass through the rotor-swept zone of operating turbines do not collide with turbine blades (Horn et al. 2008, Cryan et al. 2014, Smallwood and Bell 2020). Nevertheless, bat activity in this zone indicates potential risk at any given moment. We suspect that future comparisons that analyze only the subset of activity exposed to turbine operation will likely detect relationships with fatality risk. Additional comparisons of exposed bat activity and fatality rates across a broader geographic range will provide better resolution surrounding this relationship, enabling more robust tests among different sites and landscapes.

Collecting acoustic data at nacelle height is relatively straightforward and substantially less costly than conducting carcass monitoring. Curtailment reduces bat carcass counts but does not affect ability to detect bat activity acoustically at nacelle height. As a result, acoustic monitoring provides direct evidence of how effectively curtailment strategies reduce exposure (and associated risk), whereas carcass monitoring provides information only on fatalities that were not protected by a curtailment strategy. Even though bat passes do not indicate numbers of individual bats and detectors sample only a small proportion of the rotor-swept zone, the rate of bat passes exposed to turbine operation is a sensitive and quantifiable metric that will likely be more effective than carcass counts or fatality estimates in detecting differences among curtailment treatments. Extracting additional information from acoustics (e.g., species composition) could further inform curtailment strategies that target listed or sensitive species. Exposed activity can also be analyzed with greater temporal precision than carcass searches, allowing for finer-scale characterization of fatality risk or evaluation of how successfully a curtailment strategy prevents turbine operation during times when bats are present. Quantitative feedback at a fine temporal scale will be essential for determining whether parameters of a curtailment strategy encompassed conditions when bats were active and whether bats responded consistently to changing weather conditions. Presently, bat fatalities are known to be higher following nights with low wind speed (Kunz et al. 2007*a*) but fatality studies based on carcass searches will not provide a basis to explore relationships between bat fatalities and wind speed, temperature, or other weather variables on a scale finer than nightly. Nightly analyses are insufficiently granular to detect changes in bat behavior and fatality risk associated with incremental shifts in wind speed or other environmental conditions that vary throughout the night. Exposed bat activity is therefore a suitable metric for evaluating and comparing how effectively alternative curtailment strategies reduce risk to bats.

When applied in the context of a curtailment study where bat fatality rates have been reduced, carcass searches typically yield small sample sizes, contributing to imprecise fatality estimates and complicating efforts to differentiate treatments. Fatality rates are calculated based on carcass totals aggregated among turbines, and curtailment strategies are evaluated based on comparing these treatment-level fatality rates (Arnett et al. 2013, Martin et al. 2017), although fatality estimates are often insufficiently precise or lack statistical power to distinguish treatments with subtly different parameters. A recent compilation of curtailment study results based on carcass monitoring illustrated considerable variation in measured effectiveness among curtailment studies, demonstrating difficulty in determining the relative benefit of discrete increases in cut-in speed (American Wind and Wildlife Institute 2018, Barnes et al. 2018). In our study, fatality estimates were between 1 and 3 bats/turbine/monitoring period for 7 of 12 operational groups at Laurel Mountain and New Creek. As a result, confidence intervals associated with most bat fatality estimates overlapped. By contrast, substantially larger sample sizes of acoustic datasets allowed for greater precision and clearer differentiation of bat activity exposure among strategies. Thus, we attribute some observed noise in relationships between activity and fatality rates to imprecision of fatality estimates themselves rather than noise in the more quantitative metric of acoustic bat activity or underlying relationships between bat activity and fatality risk.

We documented that bat activity exposed to turbine operation closely matched predictions, demonstrating that turbines in our study were curtailed as intended and suggesting, more notably, that simulations provide a realistic representation of exposure for novel curtailment strategies under consideration. Also, simulated exposure aligned closely with measured exposure during subsequent years. Together, our results demonstrated that bat acoustic exposure can be used to characterize site-specific patterns in fatality risk to bats, which in turn can be predicted for any conditions-based curtailment strategy under consideration. The ability to directly compare predicted effectiveness of curtailment alternatives based on site-specific data lays a foundation for designing activity-based, informed curtailment strategies that achieve a target exposure reduction threshold with minimal energy loss.

As the wind industry and regulatory agencies continue developing appropriate measures to reduce bat fatalities and population-level impacts or avoid risk to federally listed bat species, improved ability to measure how effectively curtailment strategies reduce risk and predict costs and benefits of curtailment alternatives will be critical. We suggest that exposed bat activity, as measured with nacelle-mounted bat detectors, can address both needs. This method also provides data necessary to characterize conditions associated with high fatality risk on a finer temporal and spatial scale, providing a framework to improve effectiveness of curtailment while reducing associated energy loss. Conducting similar studies across a broader range of habitats and geographic regions and facilities with more diverse curtailment treatments will help demonstrate flexibility and utility of nacelle-height acoustic data to evaluate effectiveness of different curtailment strategies at reducing bat exposure and fatality rates.

MANAGEMENT IMPLICATIONS

Curtailing turbine operation reliably reduces bat fatality rates at commercial wind energy facilities but remains an unfavorable minimization measure for the industry due to associated energy and revenue losses. Most curtailment strategies use wind speed alone to trigger turbine shutdown (Barnes et al. 2018), and information regarding bats' behavioral response to changing wind speed remains coarse. Requirements to curtail turbine operation also vary substantially among state, provincial, and federal regulatory agencies, resulting in inconsistent application of curtailment at wind energy facilities in different geographical regions. Poor temporal resolution of carcass monitoring inhibits understanding of relative effectiveness of alternative curtailment plans and provides insufficient feedback to fine tune or adaptively manage cut-in wind speeds and other parameters. High costs of carcass monitoring also preclude its use as a method to evaluate curtailment on a long-term basis. We suggest that nacelle-height acoustics, combined with turbine operational data to quantify exposed bat activity could address both shortcomings of carcass monitoring. Nacelle-height acoustic bat data aligned with turbine rotor speed provide quantitative and temporally precise feedback on when exposure occurs, thereby indicating how specific curtailment parameters could be adjusted to allow additional energy generation when risk to bats is low. Simulating bat acoustic exposure and energy loss and iteratively adjusting cut-in wind speeds on a finer temporal scale (e.g., month) or as a function of other variables (e.g., temperature or precipitation) could therefore result in an activity-based, informed curtailment alternative that is equally protective but less costly than blanket curtailment. Predicted reductions in bat acoustic exposure for either or both strategies could then be tested directly by collecting additional nacelle-height acoustic data and measuring exposure during implementation. Using nacelle-height acoustic exposure as opposed to carcass counts to evaluate effectiveness of curtailment at reducing risk to bats would in turn reduce cost of monitoring programs substantially. Further studies will be necessary to determine appropriate numbers of acoustic detectors and bat passes needed to design and evaluate curtailment strategies and to refine methods such as optimal detector placement.

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DATA AVAILABILITY STATEMENT

Research data are not shared.

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