Testing the effectiveness of an experimental acoustic bat deterrent at the Maple Ridge wind farm

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Executive Summary

As the wind industry continues to grow exponentially, an increasing number of studies are documenting bat fatalities due to collisions with operating wind turbines. One possible explanation for such high mortality rates is that bats are attracted to wind turbine sites and to the turbines themselves. Recent evidence confirms that some bats approach and alight on turbine towers and blades and also appear to forage aerially for insects within the airspace swept by the turbine rotor. We tested the first experimental ultrasonic bat deterrents designed for commercial-scale wind turbines at the Maple Ridge Wind Farm in Lowville, New York, USA where bat fatalities had been reported the previous year. This facility consists of 195 Vestas 1.65 MW turbines, widely dispersed across a landscape of open agricultural lands and scattered woodlots.

The deterrents emit randomized and continuous ultrasound designed to interfere with normal echolocation in insectivorous bats. We mounted deterrents on the towers of two treatment turbines and two control turbines with similar landscape characteristics and historic mortality rates and performed two experiments in succession. For each experiment, we simultaneously observed one treatment and one control turbine nightly for 10 consecutive nights using thermal infrared imaging cameras, which can capture images in complete darkness and do not disturb normal behaviors. We monitored an area within the rotor-swept zone adjacent to the mounted deterrents nightly for 3.6 hours beginning shortly after sunset.

Overall we observed 618 occurrences of bats (and an estimated 566 bat passes) during 288 hours of video observation, yielding a rate of 4–46 passes on a given night (1.9 bats / hour). While most bats observed were engaged in normal flight, 2% avoided collisions (n = 12), 3% investigated the turbines (n = 16), and <1% collided with the turbine blades (n = 2). Twenty eight percent of bats we observed flew within the rotor swept zone (n = 158). In the first 10-

night test, we observed a total of 131 bats ($\bar{x}$ = 13.1, SD = 5.5) at the deterrent-treated turbine versus 244 bats ($\bar{x}$ = 24.4, SD = 12.9) at the control turbine - a statistically significant difference (t = 2.54, p = 0.026). However, during the second test, there was no significant difference in bat activity between the treatment ($\bar{x}$ = 9.5 SD = 8.3) and control ($\bar{x}$ = 9.6, SD = 4.8) turbines (t = -0.003, p = 0.97). We also observed 24 separate instances (n = 56, 10%) of small groups of bats (2–5 individuals) flying together around turbines, which suggests that the timing of migration flights may be an important factor in bat fatalities at this and at similar wind facilities. Wind speed was positively related to bat passes observed (R^2 = 0.23, p = 0.01) whereas barometric pressure was a negative predictor (R^2 = 0.33, p = 0.002). Temperature, humidity, rotor speed, and cloud cover were all non-significant predictors of bat passes. A multivariate regression analysis showed a significant relationship between two wind measurements, barometric pressure, and the presence or absence of the deterrent (F = 3.87, R2 = 0.424, p = 0.02).

Our mixed results suggest that a variety of factors influence the effectiveness of an acoustic deterrent. The acoustic envelope of our deterrent system was probably not large enough to consistently deter the activity of bats within the large volume of the rotor-swept zone. For deterrents to be effective, they must operate at ranges that are large enough to encompass an entire turbine structure. Future studies must also examine the assumptions behind acoustic deterrence. Although bats are known to avoid ultrasound clutter, little is known about the behavioral responses of bats to artificial broadband ultrasound emissions. It must be demonstrated on a full-size scale that bats both can and will avoid large ultrasound fields before acoustic deterrent systems can be expected to function effectively at wind farms.

Introduction

As wind energy production has steadily increased worldwide, reports have surfaced on the effect that operating wind turbines have on bats. Bat injuries and fatalities have been reported at wind facilities throughout North America (Johnson 2005, Arnett et al. 2008) and Europe (Ahlen 2003, Bach and Rahmel 2004, Brinkman 2006) in a wide range of habitat conditions. Fatality rates observed at large commercial wind facilities on forested ridges in the eastern United States have ranged from 20.8–63.9 bats/turbine/year (Arnett et al. 2008). Assuming that reported mortality rates are representative and the projected megawatts of wind energy are developed, the projected number of annual bat fatalities in the mid-Atlantic Highlands alone could be 33,000–110,000 by the year 2020 (Kunz et al. 2007a). Given these mortality rates, the accelerating growth of the wind industry (AWEA 2008, EIA 2008), and the possible decline in populations in many bat species, it seems imperative to begin to develop and evaluate solutions that can reduce the number of future bat fatalities.

Migratory tree-roosting bats appear to be the most at risk of being killed by wind turbines Kunz et al. 2007a, Arnett et al. 2008). Several studies report a surge in numbers of bats found beneath turbines in the autumn, particularly in partly forested or forested areas in North America (Johnson 2005, Arnett et al. 2008). These studies have naturally raised questions of why and how these bats are killed, and why bats are most at risk during fall migration and several hypotheses have been proposed (Kunz et al. 2007a). Bats may be randomly colliding with turbine blades, and thus seasonal increases in bat mortality may reflect temporary increases in local populations, perhaps caused by migration patterns (Cryan and Brown 2007). Another factor may be weather patterns and environmental conditions that are optimal for migration flights. Kerns et al. (2005) noted that bat fatalities are associated with lower wind speeds and the timing of weather fronts. Bats may shift the flight altitudes of their nightly or migration flights based on weather conditions and cloud cover (Dürr and Bach 2004), which may result in greater numbers encountering operating wind turbines. Cryan and Brown (2007) observed that migrating hoary bats (*Lasiurus cinereus*) were more likely to visit a migration stopover point on darker nights during periods of low wind, high cloud cover, and lower barometric pressures.

Bats also may be attracted to landscape modification and edges created when wind facilities are constructed in forested areas (Arnett 2005). Bats may be indirectly attracted to turbines because insect densities are higher near turbines because of heat production, or rotor turbulence. Perhaps the most promising attraction hypothesis is that bats may be attracted to wind turbines in part, because some species that normally seek out large trees to roost in (Kunz and Lumsden 2003, Barclay et al. 2007) may view the large towers on cleared landscapes or fields as potential roosting habitat (Ahlen 2003, Arnett 2005, Kunz et al. 2007a). This hypothesis is supported by observations of bats investigating and alighting on turbine towers and even the blades themselves when they are stationary (Horn et al. 2008). In contrast to bats that may incidentally fly through the airspace occupied by an operating wind turbine while on a migratory flight or while foraging, bats that investigate turbines by repeatedly looping around and approaching the blades, tower, and nacelle are at higher risk of fatal collisions.

Several mitigation strategies to reduce bat fatalities at wind farms have been proposed. One strategy is to curtail operation of turbines during short periods when the risk is highest, in particular low wind periods favorable for increased insect activity and foraging by bats (Arnett 2005). Another strategy is to attempt to deter bats from flying through the rotor-swept zone of turbines. This approach has promise, especially if bats are attracted to turbines or turbine structures, whatever the causal mechanism. Reducing fatalities requires a mechanism that acts by deterring bat attraction to turbines or turbine sites. Perhaps the most easily constructed and deployed deterrent mechanism is an acoustic one. The bat species in question depend on echolocation for pursuing insect prey while in flight, and one hypothesis is that production of broadband ultrasound emissions in the same frequency range used by bats while echolocating could cause them to avoid the source of the emissions. Echolocation in bats (Griffin 1960) functions by comparison of delays and patterns in delays between pulses of ultrasonic sound produced by bats and the echoes that return to them (Simmons and Stein 1980). Species that have been found killed at wind turbines emit frequency modulated pulses and are known to avoid acoustic "clutter" over water (Mackey and Barclay 1989). Recent evidence suggests that if the bandwidth of the returning echoes is reduced, bats may lose some acuity in their ability to correctly detect objects in their environment (Simmons et al. 2004). A deterrent device that emits continuous broadband ultrasonic emissions with randomized pulses in various frequency ranges may have such an effect.

Spanjer (2006) tested the response of big brown bats (*Eptesicus fuscus*) to a prototype eight speaker deterrent emitting broadband white noise at frequencies from 12.5–112.5 kHz and found that during non-feeding trials, bats landed in the quadrant containing the device significantly less when it was broadcasting broadband noise. Spanjer (2006) also reported that during feeding trials, bats never successfully took a tethered mealworm when the device broadcast sound but captured mealworms near the device in about 1/3 of trials when it was silent. Szewczak and Arnett (2006) tested the same acoustic deterrent in the field and found that when placed by the edge of a small pond where nightly bat activity was consistent, activity dropped significantly on nights when the deterrent was activated. In this study, we tested the effectiveness of a larger, more powerful version of this deterrent device to reduce nightly bat activity. Our objective was to mount the deterring device to operating wind turbines at a facility where recent bat fatalities had been documented and observe bat activity at treated and untreated turbines simultaneously.

Study Area

We evaluated the behavioral responses of bats to a prototype broadband ultrasonic bat deterrent at the Maple Ridge Wind Farm in Lewis County, New York in August 2007. This facility is located on the Tug Hill plateau west of the Adirondack State Park and adjacent to the town of Lowville. The landscape is primarily agricultural, with crop fields, grassland, and pastures separated by small wooded areas and riparian corridors, and elevation ranges from 460–540 m. The facility consists of 195 Vestas 1.65 MW turbines, and four meteorological towers (met towers) widely dispersed across the eastern, downwind edge of the plateau. Each turbine tower is 79 m high and blades of the rotor are 39.6 m long. The rotor-swept area is 4,962 m^2 and reaches from 38–120 m above ground. The rotor can yaw through 360 degrees and the blades sweep through a volume that is 260,120 m^3 (the rotor-swept zone). The speed of the rotor varies with wind conditions, but the maximum speed is 14.3 revolutions per minute.

Methods

Deterrent Device

Fundamental Theory and Supporting Evidence. The choice of ultrasonic masking technique for this study, and those performed by Spanjer (2006) and Szewczak and Arnett (2006), is based on the observation that many species of bats, especially insectivorous bats, use chirped echolocation calls. We hypothesized that bats use these chirped calls, or chirped waveforms, for similar reasons that chirped waveforms are often used in high performance radar systems. First, because chirped waveforms occupy a broad frequency range, they can be exploited to gain higher spatial resolution. Second, because chirped waveforms are not limited by trade-offs between standard pulse duration and resolution, the call durations can be longer which effectively increases the total power of each call and allowing bats to detect targets with smaller cross sections. Third, chirped waveforms are inherently resistant to jamming, which is obviously an advantage for bats and a disadvantage for many acoustic bat deterrence devices that have been developed to date. While our hypothesis has not been directly proven, research performed by Simmons et al. (2004) clearly demonstrates that bats have at least some capability to perform the complex time/frequency processing required to exploit chirped waveforms. Therefore, the real challenge in deterring bats acoustically is to generate an ultrasonic masking or jamming waveform that is effective against a highly evolved echolocation system inherently resistant to jamming. Griffin et al. (1963) demonstrated that broadband random ultrasonic noise could mask bat echolocation somewhat, but not completely.

Devices tested by Spanjer (2006) and Szweczak and Arnett (2006) and the device used in this study employ the classic radar counter measure of broadband jamming. The masking generator creates a continuous broadband waveform that is built out of a random sequence of pulses with randomly fluctuating frequencies. This technique is effective against chirped radar system systems because it rapidly generates waveforms that are miss-interpreted by time/frequency processors to generate rapid and random sequences of false detections which obscure any detection of the surrounding environment. In essence, the ultrasonic masking technique attempts to use the bats amazing time/frequency processing capability against it. In theory, broadband masking will introduce a rapid and random sequence of false echolocation returns that will interfere with the bats ability to navigate or may at least reduce the “acoustic” visibility of its surrounding environment.

Device Specifications, Placement, and Effective Range. We used ultrasonic deterrent devices custom built by Binary Acoustic Technology (http://binaryacoustictech.com/). Each device deployed at a turbine consisted of a power and amplifier unit measuring 20 cm x 20 cm x 15 cm, connected by protected cables to three separate emitter arrays measuring 120 cm long (Figure 1). Each emitter array contained four downward-firing ultrasonic transducers within protected housings. The deterrents produced broadband ultrasound containing randomized pulses in various frequency ranges ranging from 20–80 kHz. Previous testing of an earlier prototype (Szewczak and Arnett 2006) demonstrated that masking signal strength of 98 dB SPL at 1 m will produce an 8 m "keep out zone," or area avoided by bats. For this experiment, the transmit power of the combined devices was increased to approximately 119 dB SPL at 1 m, extending the keep out zone to about 20 m, at which point the field strength is again reduced to about 62 dB SPL.

The three emitters from each device were placed equidistant from each other around the circumference of the turbine tower (~120 degrees from one another; Figure 1), creating an omni-directional effect, and we placed two complete devices spaced ~12 m apart on each tower (one at 36.5 m and the other at 48.7 m above ground). These heights were determined based on previous findings of higher bat activity in the lower portion of the rotor-swept zone (Horn et al. 2008) and by the limitations of the crane used to access mounting locations on the tower. Placement of the devices produced two horizontal, doughnut-shaped keep out zones around the tower.

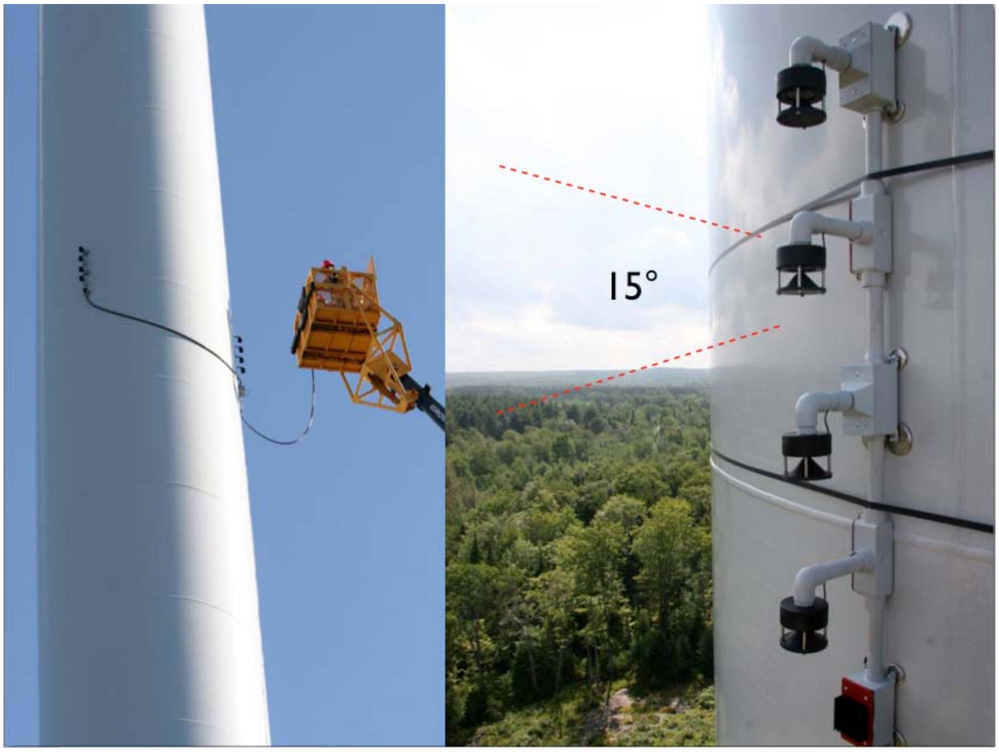

Figure 1. The ultrasonic bat deterrent during the mounting procedure (left) and installed (right). Each device contains three arrays of four transducers each (right), and treated turbines received two devices installed at two heights along the towers. (photos, Jason W. Horn and Scott Appleby)

Sampling Design

To test the effect of the deterrents' emissions on bat behavior and activity near the turbines, we conducted two 10-night experiments wherein we compared bat activity at turbines treated with ultrasonic emissions with activity at control turbines with no emissions. We selected treatment turbines using two criteria. First, we favored turbine sites with both surrounding forest edges and adjacent open fields and sites where higher numbers of bat carcasses had previously been reported (Jain et al. 2007). We selected control turbines that were sited in areas that were as similar in vegetation structure, wind exposure, and physical landscape features to the treatment sites as possible. Deterrents were turned on at the beginning of each 10-night test, and left running continuously.

Thermal Imaging and Analysis

We monitored the airspace adjacent to the towers for bat activity at both treatment and control turbines using thermal infrared imaging (Kunz et al. 2007b, Horn et al. 2008). Thermal infrared cameras provide digital video images by detecting heat emitted by all objects within the field of view without the need for accessory illumination. We used four FLIR Inc. ThermaCAM P640 cameras. Each camera has a 24° field of view and produces video images where each frame measures 640 x 480 pixels. We positioned two cameras at the base of each of the treatment and control turbines, at a distance of 50 m from the base. The fields of view were positioned one above the other to create a single large viewable area to the right of the tower (Figure 2). This view encompassed the right half of the lower portion of the rotor swept zone (including both the upper and lower deterrents, when present), and an area below the rotor swept zone. The radiometric thermal infrared video from the cameras was captured directly to hard disk using FLIR Researcher software on portable ruggedized computers containing 1TB hard drives. Observation stations including the camera, computers and operator were protected from weather with portable tents.

We simultaneously monitored nightly bat activity at one treatment (turbine 275) and one control (turbine 212) turbine for 10 consecutive nights beginning August 8. We began our recordings 20 minutes after sunset on each night and continued for 3.6 hours. We focused on the first hours after sunset as bats are often most prevalent around wind turbines during this time (Horn et al. 2008). At the end of the first 10-night experiment, we moved our cameras and observation stations to a second treatment (turbine 296) and control turbine (turbine 240) pair and again recorded for 10 consecutive nights beginning August 19.

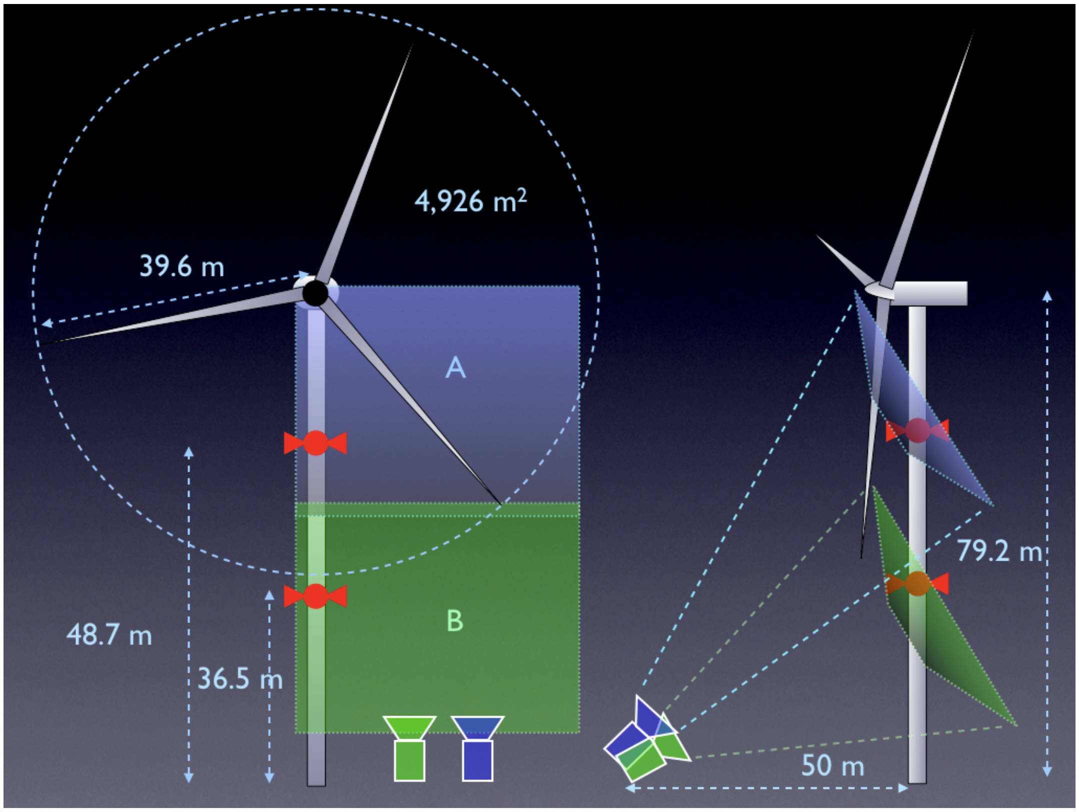

Figure 2. The position of the thermal infrared cameras relative to the turbine being monitored. Two cameras were used in a top (A) over bottom (B) configuration to yield a larger effective viewing area. Each cameras' field of view contained the deterrent (on treatment turbines, red symbols) and approximately one half of the lower portion of the rotor swept zone.

We analyzed thermal video sequences by way of playback and human observation, and recorded timing, behavior types, and flight characteristics when bats appeared in the field of view. Events were scored as one of four types. Normal flight behavior was recorded if the bat flew through the field of view and exited without incident. This included straight-line flight as well as various looping, chasing and diving maneuvers that bats use in pursuit of insects. Avoidance behavior was noted when bats engaged in evasive flight maneuvers in response to encountering rotating turbine blades, or another part of the turbine structure. Contact was noted in the case when bats collided with any part of the turbine structure. Finally, investigation behavior was noted when bats flew up to, hovered near, or alighted on any part of the turbine.

We categorized flight altitude as either low (below the rotor-swept zone), medium (within the rotor-swept zone) and high (above the rotor-swept zone). Similarly, we categorized range from the camera position as close (between the camera and turbine rotor swept zone), medium (within the rotor swept zone) and distant (beyond the rotor swept zone).

We were conservative when identifying images as containing bats. In addition to bats, thermal infrared sequences may contain birds, aircraft, and insects at great distance from the camera. In cases where the identity of an object was not clearly a bat, we used quantitative and qualitative criteria for identifying bats and bat flight behaviors. First, only objects with wing beat frequencies between 10 and 15 beats/second were counted. Second, we qualitatively judged the inertia of the object that was evident during sharp flight maneuvers and only counted objects that were in the range of expected bat masses. Thirdly, we used surface temperature values, and rejected objects that were not consistent with the production of metabolic heat. In general, bats were distinguishable from insects by their motion and temperature profiles, and distinguishable from birds by their wing beat frequencies, wing and body shapes, and flight maneuvers. In cases where we did not have confidence in our identifications, we simply discarded the observation. To prevent double counting of bats that exited the field of view, and then re-appeared in the same camera's field of view, or in another camera's field of view, we carefully noted the heading of bats when entering and exiting the frame for each observation. We then used these heading values, whenever possible, to identify multiple bat passes in separate camera views as one pass made by a single individual. All data were compiled and analyzed using a relational database. We used a multivariate regression (ANOVA) to analyze relationships between covariates and the number of bats observed. We summed the number of bats present in 10-minute intervals on all nights of observation and used this aggregate as the dependent variable in a series of regression tests. We tested the relationship between wind heading and the number of bats flying near turbines using circular statistical models (von Mises distribution). All statistical tests were performed with the statistical software package R (http://www.r-project.org/).

Results

In the 288 hours of video recordings we captured over the course of 20 nights, we observed 618 instances of bats in the field of view and 566 individual bat passes. The number of passes observed ranged from 4–46 on a given night ($\bar{x}$ = 26.8, SD = 14.1). 95% of these observations were simple fly-by events (n = 536), 2% were collision avoidance (n = 12), 3% were investigation events (n = 16), and <1% were collision events (n = 2, Table 1). We found that most bats that we observed flew at a low height and close range (n = 223, 39%), at low height, medium range (n = 110, 19%) and at medium height, medium range (n = 158, 28%, Table 1). While the thermal imaging cameras were capable of detecting bats both beyond the range of the turbine and high above it, we did not observe many bats flying above the rotor. Twenty eight percent of the bats we viewed were within the volume of space swept by the rotor blades, and 59% were flying below the reach of the blades.

The average occurrence rate of bats was 0.93 bats/turbine/hour. However, bats were generally more abundant during the earlier part of the recording session and activity gradually decreased over time (Figure 3). This observation coincides with our expectation that bats would be more abundant in first hours after sunset. In the first 10-night test, we observed 131 bat passes ($\bar{x}$ = 13.1/night, SD = 5.5) at the deterrent-treated turbine versus 244 ($\bar{x}$ = 24.4, SD = 12.9) at the control turbine, a significant difference (t = 2.54, p = 0.03, Table 2, Figure 4). However, during our second 10-night test there was no significant difference in bat activity

Table 1. Summary of the observations of bats flying near operating wind turbines during both experiments. Bats were categorized by height above ground (low, medium, high), range from the cameras (close, medium, distant), and by the type of event (normal flight, investigation, avoidance, or collision with the turbine).

		Flight Behaviors				Height / Range relative to Turbine Rotor Swept Zone							
day	Experi- ment	fly	investi- gate	avoid	collide	low / close	low / medium	low / distant	medium / close	medium / medium	medium / distant	high / medium	high / distant
1	1	13	0	0	0	2	6	1	1	2	0	0	1
2	1	34	1	1	0	12	8	0	2	11	1	0	2
3	1	29	2	1	0	8	3	0	1	15	4	0	0
4	1	10	0	1	0	3	4	0	0	3	1	0	0
5	1	50	6	0	0	23	4	0	2	19	3	0	5
6	1	17	0	0	0	5	4	0	0	5	2	0	0
7	1	40	1	0	0	18	2	0	0	11	5	0	4
8	1	15	0	2	0	5	3	0	0	6	1	0	1
9	1	46	1	2	1	21	7	0	0	12	0	0	9
10	1	18	0	0	0	7	6	0	0	5	0	0	0
1	2	33	0	0	0	20	2	0	0	6	2	1	2
2	2	4	0	0	0	4	0	0	0	0	0	0	0
3	2	46	0	1	0	18	8	0	1	14	3	0	3
4	2	5	0	0	0	2	3	0	0	0	0	0	0
5	2	38	0	2	0	15	11	0	0	12	1	0	1
6	2	30	2	0	0	7	9	0	0	15	1	0	0
7	2	34	0	1	0	15	7	4	0	7	1	0	0
8	2	13	1	1	1	4	5	0	0	6	0	1	0
9	2	27	1	0	0	14	10	0	0	2	2	0	0
10	2	34	1	0	0	20	8	0	0	7	0	0	0
	TOTAL	**536**	**16**	**12**	**2**	**223**	**110**	**5**	**7**	**158**	**27**	**2**	**28**
	mean	**26.8**	**0.8**	**0.6**	**0.1**	**11.15**	**5.5**	**0.25**	**0.35**	**7.9**	**1.35**	**0.1**	**1.4**
	sd	14.1	1.4	0.8	0.3	7.2	3	0.9	0.7	5.4	1.5	0.3	2.3

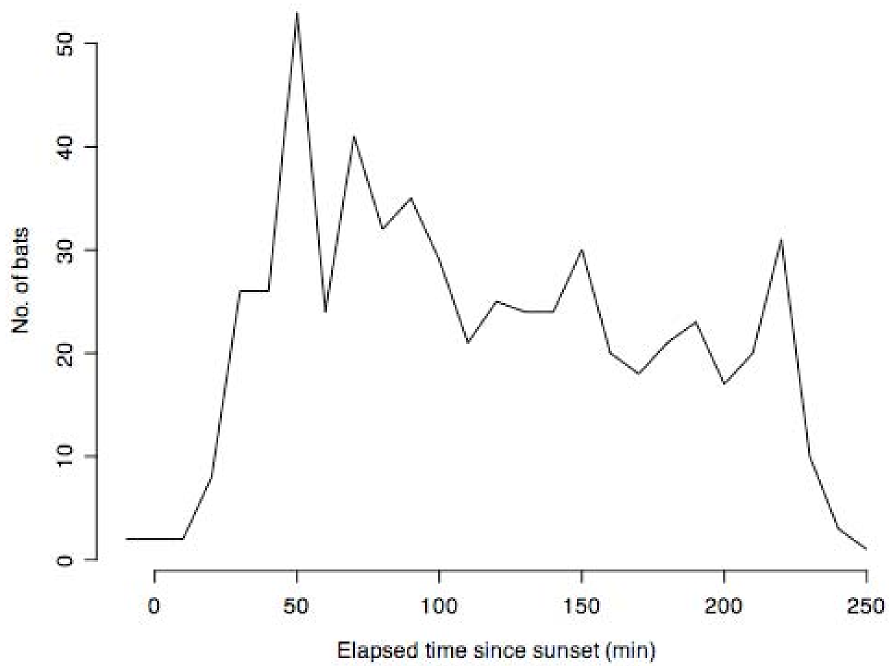

Figure 3. The abundance of bats over the course of our nightly recordings, summed at 10-minute intervals. Bat abundance, on average, decreased steadily after an initial surge following sunset.

Table 2. Summary of the numbers of bats observed during both 10-night experiments of deterrent-treated versus control turbines. Numbers of bat varied greatly from night to night and we observed greater numbers during the first experiment.

Experiment Day	Total Bats		deterrent turbine		Control Turbine	
Experiment #	**1**	**2**	**1**	**2**	**1**	**2**
1	32	11	19	2	13	9
2	56	17	11	8	45	9
3	41	17	16	8	25	9
4	50	18	8	13	42	5
5	33	4	21	0	12	4
6	47	5	16	1	31	4
7	40	32	10	17	30	15
8	35	16	9	4	26	12
9	28	35	17	25	11	10
10	13	36	4	17	9	19
TOTAL	**375**	**193**	**131**	**95**	**244**	**96**
mean	37.5	19.1	13.1	9.5	24.4	9.6
SD	12.3	11.63	5.47	8.29	12.96	4.81

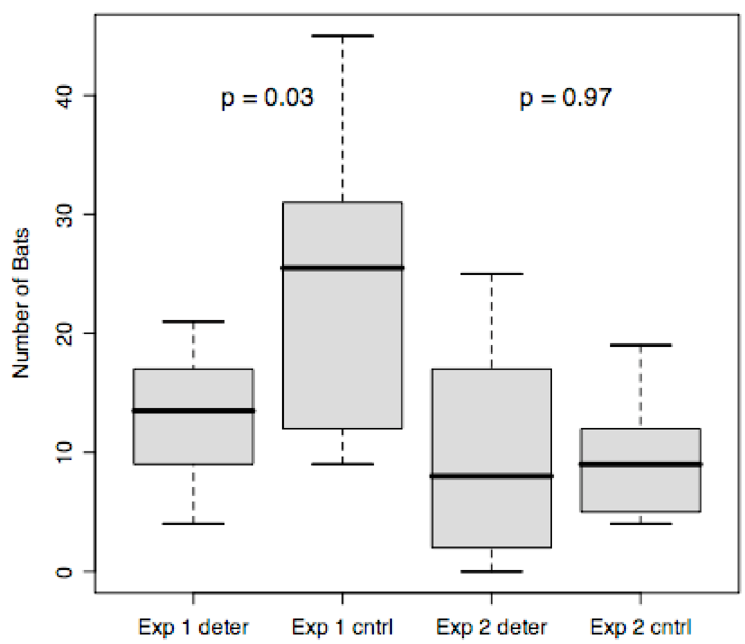

Figure 4. A box and whisker plot showing numbers of bats observed during 2 10-day observations of deterrent-treated and control turbine pairs. From left to right, the first two bars represent experiment 1 deterrent and control, the second two, experiment 2 treatment and control. P-values for T tests for differences in means are given above each group.

between the treatment ($\bar{x}$ = 9.5, SD = 8.3) and control ($\bar{x}$ = 9.6, SD = 4.8) turbines (t = -0.003, p = 0.97, Table 2, Figure 4).

Bat flights were generally one of two types; straight-line flights, and looping, foraging flights. Although we did not quantify the number and type of maneuvers in each individual flight, we observed that many of the individuals that occurred in the rotor-swept zone appeared to be actively foraging. Although we could not directly identify the individual insects that bats were pursuing, we inferred that many of the sharp turns, quick climbs, dives and erratic maneuvers that we observed were executed in the course of normal foraging behavior. When bats investigated the turbines, they often approached the tower and, executing touch-and-go type behavior, hovered or briefly alighted on it, then flew away. Such investigation events often involved repeated touch-and-gos on the tower, or the nacelle. We did not observe any direct investigation or approach to the blades, although a small number of bats reacted to rapidly approaching blades. The two instances of contact behavior that we witnessed appeared to be glancing blows by blades on the downswing portion of rotation. It was not clear whether the blows were fatal, and the bats appeared to fall to the ground (although the ground was not in the field of view of either camera).

We also observed 24 separate instances of small groups of bats (2–5) flying together in small flock-like groups; this totaled 56 bats, 10% of the total observed. We identified these groups by noting that individuals flew on similar trajectories as they passed through the field of view, often with trailing bats appearing to be following and matching the flight maneuvers of leading bats. These incidents were not clumped in time, but rather occurred on 13 of the 20 nights that we observed. Bats in these groups were separated by approximately 10–20 m. In the case of 2-bat groups, one individual often appeared to be chasing the second. Occasionally, two bats in such groups would briefly make contact during flight after having executed pursuit-like maneuvers normally observed during foraging.

We also investigated whether variables such as wind speed, wind heading, humidity and turbine rotor speed were associated with increased bat activity (Figure 5). Mean rotor speed of all nacelles had no predictive effect on bat abundance, nor did relative humidity measured at the met tower. Mean wind speed at the nacelle ($R^2 = 0.14$, $p = 0.06$) and at the met tower ($R^2 = 0.23$, $p = 0.01$) both showed a slight positive relationship with number of bats observed. Barometric pressure recorded at met towers was slightly negatively associated with bat abundance ($R^2 = 0.33$, $p = 0.002$). Presence of the deterrent (coded as 1 = treatment and 0 = control) showed no significant association with bat abundance. A multivariate regression (ANOVA) showed a significant relationship between these same four variables and the number of bats observed ($F = 3.87$, $R^2 = 0.424$, $p = 0.02$)

We examined the relationship between numbers of bats observed nightly (between sunset + 20 minutes and sunset + 3.6 hours) and the following mean nightly variables: temperature at the ground, wind speed at the ground, humidity, barometric pressure, estimates of percentage cloud cover, and again deterrent coded at 1 or 0. In individual regression tests, only barometric pressure ($R^2 = 0.12$. $p = 0.04$) and deterrent ($R^2 = 0.08$, $p = 0.09$) were significant predictors of bat activity, while all other variables were non-significant. We also performed a multivariate regression analysis of these variables which was significant (ANOVA, $F = 3.32$, $R^2 = 0.44$, $p = 0.01$), with wind speed, pressure, and deterrent having significant regression coefficients. Nightly wind headings had a strong westerly and north-westerly component (winds out of the west and northwest, Figure 6). Mean nightly wind heading was 299.2° +/- SD = 40.03°. Because wind headings are circular in nature, they cannot be used in regression analysis.

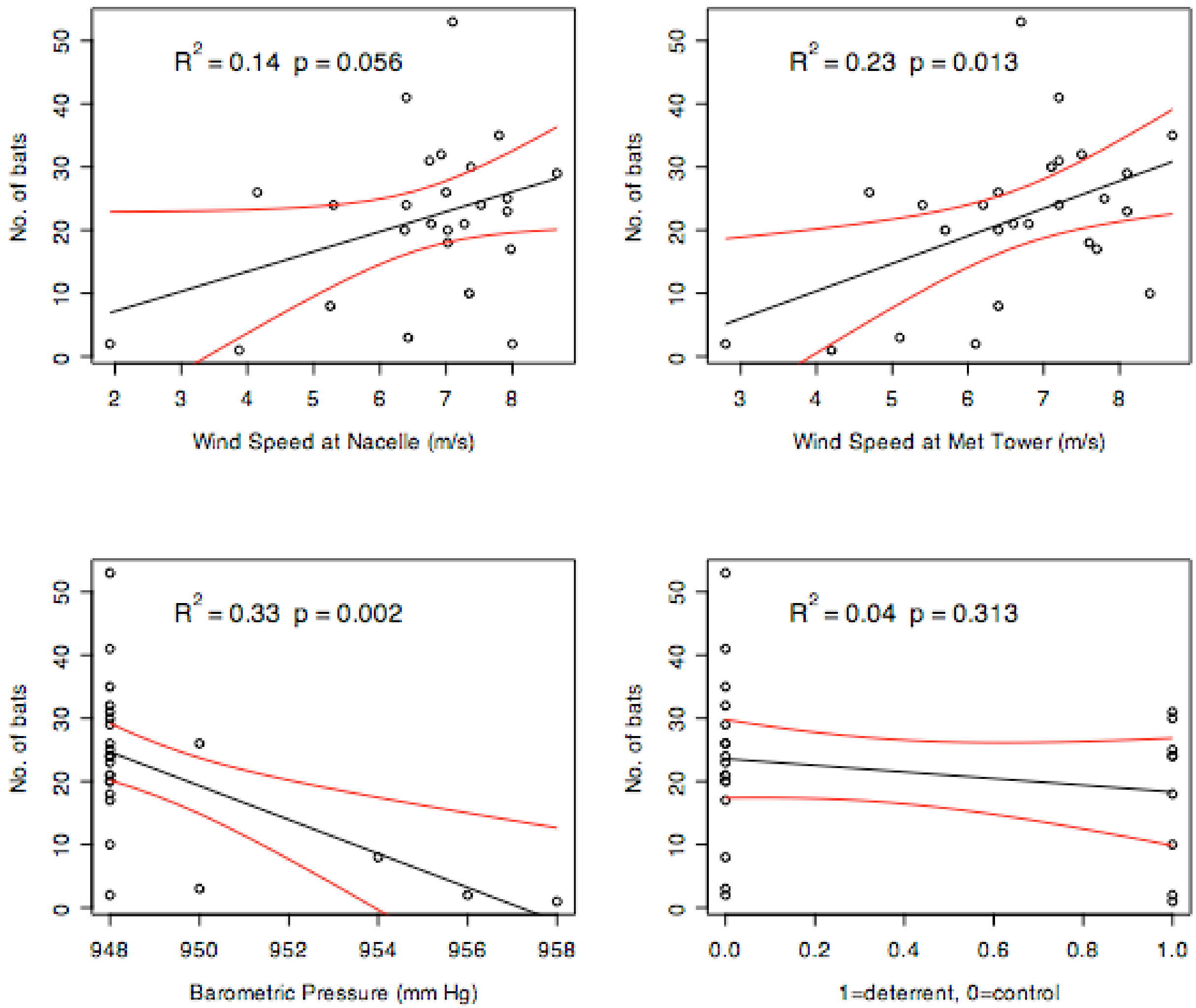

Figure 5. Individual regression analyses showing 3 variables that were significant in predicting the number of bats observed. Deterrent, coded as a 1=deterrent, 0=control was not significant when combining the results of both 10-day experiments.

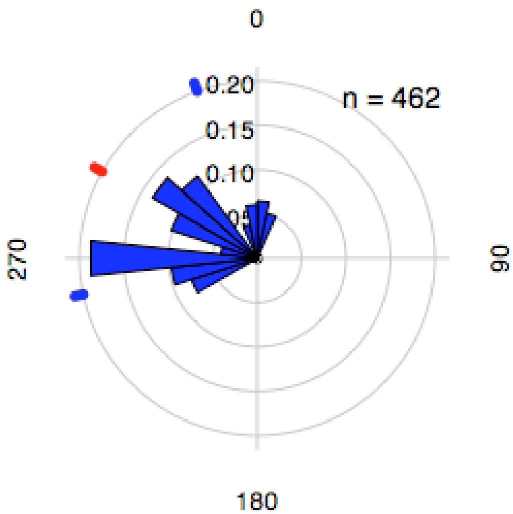

Figure 6. Wind headings recorded during nightly observation periods. Headings in compass degrees represent the direction from which the wind originates. The grey tick on the outer range ring represents the mean wind heading, and the black ticks to either site of it represent the standard deviation.

We therefore used a separate circular-linear regression (the dependent variable has a von Mises distribution) to test the effect of the number of bats observed on the mean nightly wind heading during our recording period. We found no relationship between the number of bats observed and wind heading in 10-degree increments. The regression coefficient for numbers of bats on wind heading was not significant ($t = 1.23$, $p = 0.11$).

Discussion

This project represents the first documented test of a full-sized, experimental, in-situ acoustic deterrent for mitigating bat mortality at operating wind turbines. Our first 10-night experiment yielded a significantly lower number of bats passes at the deterrent site. This suggests that the deterrent device may act to lower the incidence of bat flights. However, there are several factors that may have contributed to this result. Such a difference in bat activity levels may have been pre-existing between these two sites due to habitat differences (although we did our best to minimize habitat differences through careful site selection), proximity to nearby roosts, some other underlying pattern such as a preference for an area due to recent foraging success, or sampling bias. We considered these factors carefully when designing our experiments. Due to logistical constraints, we could not perform experiments to control for both environmental conditions (current study design) and site differences (examining the same turbine site with deterrents alternately switched on or off). Because nightly bat activity at wind turbine sites, as with normal nightly bat activity, is highly variable with temperature and weather events (Arnett 2005, Horn et al. 2008), we chose to control for these variables. This may explain why we did not detect a difference during our second 10-night experiment. Either the effect that we observed during the first experiment or the lack thereof in the second experiment may be due to pre-existing site differences that we attempted to control for by selecting sites that had similar levels of bat mortality in previous years (Jain et al. 2007).

We attempted to explain the effect that environmental factors such as temperature and wind speed may have on the incidence of bat flight we observed at Maple Ridge. Previous studies have suggested that increased mortality events at wind facilities may occur just prior to or following frontal weather systems, and that mortality may also occur more frequently when prevailing wind speeds are low (Arnett 2005, Arnett et al. 2008). We found a slightly positive, significant relationship between wind speed and bat activity. However, we found that as barometric pressure increases, there is a slight decrease in bat activity. Cryan and Brown (2007) similarly found that low barometric pressure is associated with migration timing in hoary bats. Our finding that ambient temperature did not correlate with bat activity was surprising, since bat foraging activity is often positively related to insect activity, which in turn is positively related to ambient temperature (Hayes 1997). These results indicate that such relationships may be site specific. The absence of a relationship with temperature may also indicate that the bats we observed may be not only individuals from local populations foraging, but also migrating bats en route, or making stopovers. The number of bats that are observed near turbines at this time of year may be predicted more by conditions optimal for migration rather than for foraging.

The incidence of bat fatality at wind turbines increases during the fall migration period at several facilities (Ahlen 2003, Jain et al. 2007, Arnett, et al. 2008). We observed flight behavior that suggests that some of the bats we observed around wind turbines may have been actively migrating. Migratory tree-roosting bats have been observed flying in small groups or flocks during late summer and autumn (Cryan and Veilleux 2007). At the Mountaineer facility (West Virginia, USA), bats were occasionally observed flying in pairs or small groups (Horn et al., 2008). In the current study, 10% of the total number of bats we observed were in groups which suggesting the possibility that these bats may have been migrants.

The underlying assumption of our bat deterrence device is that individuals will avoid airspace containing ultrasonic emissions because they find it disruptive to normal echolocation, and therefore their ability to navigate and to locate prey. We assume that as bats encounter a gradient of increasingly stronger emissions as they approach turbines, they will respond by flying opposite to that gradient to escape the effect of the emissions. However, at present we do not know enough about the general responses that various species have upon entering a large field of ultrasound emissions. It is therefore important to consider our assumptions when interpreting out results.

Bats may be able to escape a small ultrasound field by simply continuing on their current (or similar) trajectory. Flying in a straight line may serve to effectively clear the field equally well as well as any turning maneuver. This may help to explain why, in small-scale tests, acoustic deterrents lead to reduced bat activity (Szewczak and Arnett 2006). Bats flying into a large acoustic field may be disoriented by the emissions, and may not be able to quickly find a flight path that allows them to move away from their source. If so, bats attempting to escape the effects of the deterrent may end up venturing further into areas we wish to deter them from. Our observations included several instances of bats avoiding contact with moving blades by deviating their flight path. If bats that are within the acoustic envelope are disoriented by ultrasound emissions, we may actually increase the risk of collisions by hampering their ability to detect approaching turbine blades. This effect may also help to explain why, in our second treatment and control test, we did not observe lower bat activity at the deterrent site. Bats that approach a deterrent area may not be able to immediately avoid it, and hence the incidence of bats, given the camera's field of view, may not decrease.

Another important consideration for measuring the effectiveness of ultrasonic deterrents is that bats may learn from their experience with the deterrent, and modify their behavior over time. We do not necessarily expect such a system to repel first-time visitors to turbine areas equipped with deterrents, because they may not yet have had the opportunity to learn from such an experience. Such individuals might be first-year bats that have left natal roosts, migrant bats making stopovers along migration routes, or individuals in local populations that have not yet foraged or explored these areas. Bats' learning to avoid deterrents is particularly important when the effective envelope of deterrent emissions only just encapsulates the entire turbine structure, or part of the turbine. In this case, bats will have to fly in the area of increased strike risk around the turbine to experience the ultrasound emissions. In our study, the acoustic envelope of the deterrents was far smaller than the total volume of air occupied by the turbine. Our mixed results may be due to our relatively small coverage area. We attempted to match the camera's field of view with our estimate of the ultrasound field (both much smaller than the total turbine rotor-swept volume). However, if bats only experience ultrasound upon entering the field of view, we would most certainly count then no matter what their subsequent response. Bat deterrence, as measured by number of individuals observed, would not necessarily go down if most of the bats were experiencing the field for the first time. If the coverage area had been larger than our field of view, perhaps we would have demonstrated a stronger effect of the device.

To increase the effectiveness of deterrents, the coverage area must be made larger. However, more powerful deterrents are technically more difficult to build and mount to the turbine tower or nacelle. One possible solution would be the use of more powerful deterrents that operate only in short bursts. Spanjer (2006) suggested that bats may more readily avoid different sound types, such as erratic pulses of loud, high-frequency or broadband sound, rather than continuous white noise. She further suggested that such sound spikes would need to occur at unpredictable intervals, otherwise bats may be able to time their echolocation calls around the sound spikes.

Over time, bats may learn to avoid all turbines from their experience with those equipped with deterrents. Conversely, bats may habituate to the presence of ultrasound emissions, and acoustic deterrents may actually lose their effectiveness over time, although recent experiments indicate bats did not habitat ate to a device similar to the one we tested (Szewczak and Arnett 2007). Incorporating behavior modification into future deterrent designs may help to increase their short- and long-term effectiveness. Not only might this help to reduce bat fatalities on a larger scale, but it may reduce initial cost, facilitate installation, and reduce maintenance over time.

Future Work

Future studies of acoustic deterrents should be extended to longer, more comprehensive monitoring periods. Different sounds and pulse rates also should be tested (Spanjer 2006). To properly answer the question of what happens when an acoustic deterrent is introduced, monitoring should be conducted at test sites before, during, and after deterrent testing. In addition, areas of similar habitat without turbines should be monitored to develop a baseline understanding of local activity levels and flight behaviors before turbines or deterrents are introduced. If acoustic deterrents are to be successful, the effect of equipping a wind facility as a whole must be examined. If facilities are equipped with, for example, deterrent on half its turbines, will activity levels decrease at those turbines only? Will activity rates and mortality rates subsequently increase at non-deterrent turbines because the same number of curious bats will be visiting fewer turbines? Would activity and mortality rates drop because, as suggested above, bats learn over time to avoid turbines in general? Finally, and most importantly, if deterrents are effective in reducing bat activity levels we must address the question of whether this translates into lower mortality rates by conducting ground searches following nightly monitoring.

Although thermal infrared video is necessary for studies of behavioral interactions of bats at wind turbines, this approach is time consuming and expensive, requiring large amounts of digital storage per hour and a minimum of 2 hours to analyze each hour of video. These constraints make extending research efforts using this valuable technique logistically and financially difficult, if not impossible. Automation solutions for identifying bat flight behavior in video sequences must be developed. One such solution that has been used to great effect when examining bat flight is the use of computer vision techniques to identify and enumerate bats from thermal infrared video (Hristov 2005, Betke 2007, 2008, Kunz et al. 2008). This technique can be easily adapted to the problem of identifying bat flight around wind turbines, drastically reducing analysis time and project costs, and enabling longer and more comprehensive studies.

Our results suggest that while there is potential for ultrasonic emissions to repel bat activity around turbine towers, nacelles, and blades, further development and testing such devices under a variety of conditions is essential for developing a working, functional system.

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