EVIDENCE THAT BATS PERCEIVE WIND TURBINE SURFACES TO BE WATER

By

AARON MCALEXANDER

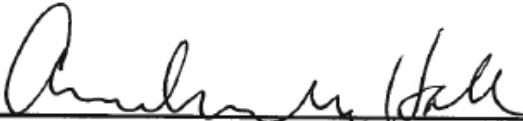Bachelor of Science, 2008
Purdue University
West Lafayette, Indiana

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Aaron Michael McAlexander

Dissertation approved:

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Major Professor

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INTRODUCTION

Wind power has become one of the fastest growing sources of renewable energy worldwide and despite its recognized environmental benefits, concerns persist over the potential threats to bird and bat populations. In particular, migratory tree bats are dying in large numbers at wind energy facilities across North America. There are three species that have been consistently reported in the majority of bat fatalities at wind resource facilities in North America; the hoary bat (*Lasiurus cinereus*), the eastern red bat (*Lasiurus borealis*) and the silver-haired bat (*Lasionycteris noctivagans*; Arnett et al. 2008, Baerwald and Barclay 2011). The peak fatality periods at wind turbines for these species coincides with their fall migration period from July through October. Considerable progress has been made toward understanding patterns of bat fatalities (e.g., Kunz et al. 2007, Arnett et al. 2008), estimating bat fatality rates (e.g., Huso 2011), and understanding the proximate causes of fatalities (e.g., Baerwald et al. 2008, Horn et al. 2008, Grodsky et al. 2011, Rollins et al. 2012).

Nevertheless, we still do not understand the ultimate causes that explain why bats come close to wind turbines. Two broad hypotheses have been proposed to explain why bats are in the vicinity of wind turbines: 1) fatalities are random or coincidental events and simply reflect bat activity, abundance, or behavior in the area; and 2) bats are attracted to wind turbines. The attraction hypotheses that have been proposed to date are varied and suggest that bats may be attracted to blade motion, lights, the sounds of the moving blades and generators, and insect aggregations; alternatively, bats may perceive the turbines as suitable roosts or mating and gathering sites (Cryan and Barclay 2009, Cryan et al. 2012). These broad hypotheses are not mutually exclusive and may differ among species.

To our knowledge, only one attraction hypothesis has been tested thus far. The hypothesis that bats are attracted to aviation warning lights mounted on turbines has not been supported by the available data (Arnett et al. 2008, Baerwald et al. 2008). To date, several solutions to reduce bat

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fatalities have been proposed, including acoustic deterrents (Horn et al. 2008, Arnett et al. 2013) and electromagnetic radiation (Nicholls and Racey 2009). The only solution that has been successfully implemented at an operational wind facility has been curtailing wind turbine operations when wind speeds are low, which corresponds to conditions when bats are most active. This strategy successfully reduces bat fatalities by more than 40%; however, curtailment comes at an economic cost by reducing the amount of energy that is produced (Baerwald et al. 2009, Arnett et al. 2011). Identifying and testing the hypothesized causes of bat fatalities at wind turbines is a critical step toward developing practical solutions that will simultaneously maximize energy production while minimizing the impacts of wind turbines on bats (Cryan and Barclay 2009).

While we currently have not identified which aspect of their ecology is bringing bats into contact with wind turbines, we know that the bats that are commonly found dead at wind resource facilities rely on echolocation for navigation and foraging (Altringham 2011). Echolocation plays an integral role in all aspects of their ecology and this system undoubtedly influences how bats interact with wind turbines. Bats use returning echoes from ultrasonic vocalizations (>20 kHz) to generate a three-dimensional image of their immediate surroundings (Altringham 2011). Bats are able to discern differences between the spectral and temporal characteristics of source calls (i.e., short vocalizations emitted by bats) compared to returning echoes to gather detailed information about their environment (Ratcliffe et al. 2013). This system is so sophisticated that bats can determine the size, shape, texture, trajectory, and relative distance of moving objects (Falk et al. 2011). Accordingly, bats rely on echolocation to navigate and locate resources such as prey items, water sources, and roost sites in the dark (von Helversen and von Helversen 2003, Greif and Siemers 2010, Altringham 2011). Nevertheless, this system may have its flaws. For example, recent studies have demonstrated that bats perceive any smooth, flat surface to be water, even in the presence of conflicting information from other senses including vision, olfaction, and touch (Greif and Siemers

2010, Russo et al. 2012). Bats attempted to drink from smooth, manufactured surfaces such as wood, metal, and plastic, suggesting that the spectral characteristics and temporal characteristics of returning echoes from water and these smooth, manufactured surfaces were indistinguishable to bats. Because wind turbine surfaces are flat and smooth, this recent discovery could help explain why bats are coming into contact with turbines at wind energy facilities worldwide.

We propose a novel attraction hypothesis suggesting that bats are attracted to wind turbines because they perceive the smooth turbine surfaces to be water. Previous research using thermal infrared cameras has shown bats approaching both rotating and non-rotating blades and investigating various parts of wind turbines with repeated fly-bys (Horn et al. 2008, Horn and Kunz 2008). This behavior is consistent with the water investigation hypothesis, as these bats may have been attempting to drink from the smooth wind turbine surfaces. We used a combination of approaches to determine if water attraction could be contributing to bat-wind turbine interactions. First, we conducted an ultrasound playback experiment to determine if smooth wind turbine tower surfaces produced echoes that are indistinguishable from water. Second, we conducted night vision surveys to determine if bats behave at wind turbine tower surfaces as they do at water. And third, we conducted acoustic monitoring surveys to determine whether the bat species active around water and wind turbine surfaces were similar.

METHODS

Study area

Our study area was Wolf Ridge Wind, LLC in north-central Texas (N 33° 44' 01.19", W 97° 24' 57.26"; Fig. 1). This 112.5 megawatt (MW) facility consists of 75 GE wind turbines (turbine specifications: total height- 122.8 m, height-to-hub- 78 m, blade length- 40.3 m) arranged in an east-to-west orientation approximately 6.5 km south of the Red River (Fig. 1). Private owner land use was

primarily agriculture to the south, consisting of cattle grazing and, to the north, an encroaching

scrub-woodland habitat extending from the riverine valleys of the Red River escarpment.

Additionally, several oil and gas wells existed on the cleared pasture lands. Wolf Ridge began

operations in October 2008; fatality searches began the following spring and acoustic surveys began

one and a half years later in the summer of 2010.
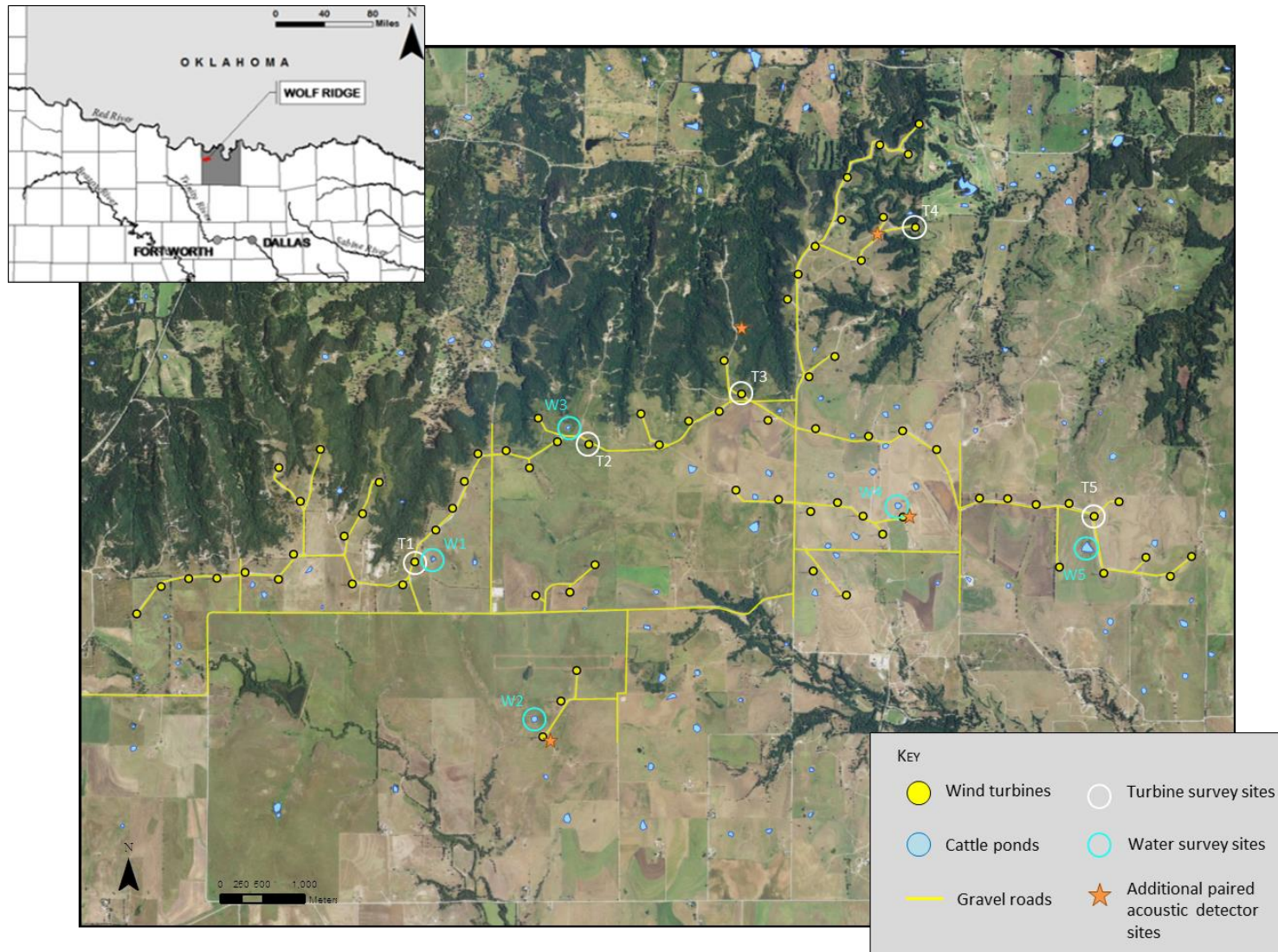
Figure 1. Site map of Wolf Ridge Wind, LLC in north-central Texas, including locations of night vision and acoustic detector survey sites at wind turbines and water sources (cattle ponds).

Wolf Ridge and the surrounding area contain resources for both resident and migratory bats. The forested area within the wind resource area provides roosting habitat for tree bats and the nearby Red River corridor may be an important migratory pathway, foraging area, and water source for migrating and residential bats (Schmidly 1999, Kurta 2005, Furmankiewicz and Kucharska 2009). One-hundred seventy eight cattle ponds, ranging from 410 to 13,436 m^2 (mean ± SD = 2,057 ± 1,598 m^2), are found throughout the wind facility. These ponds represent a stable and yet dynamic source of fresh water as some ponds dry up and others are excavated from one year to the next. Additionally, several old barns and sheds are scattered throughout the property which may provide additional roosting habitats (Schmidly 1999). Through both acoustic surveys and fatality searches, the following six species have been recorded at Wolf Ridge during at least some part of the year: eastern red bat *(Lasiurus borealis),* hoary bat *(Lasiurus cinereus)*, evening bat *(Nycticeius humeralis)*, Mexican free-tailed bat *(Tadarida brasiliensis),* silver-haired bat *(Lasionycteris noctivagans)*, and tri-colored bat *(Perimyotis subflavus)*.

We conducted night vision and passive acoustic surveys at five cattle ponds (sites W1 to W5; see Fig. 1) and five wind turbines (sites T1 to T5; see Fig. 1) at Wolf Ridge from May 15 to October 1, 2012. The selected cattle ponds were broadly spaced across the wind resource area, were within 500 m of a wind turbine, and varied in size and proximity to forest edge (Table 1). Like the ponds, the selected wind turbines were also broadly spaced across the wind resource area. Four of these ponds (W1-W4) and two wind turbines (T2 and T5) were also used in the playback experiment. In addition, as wind turbine sites T1, T2, and T5 were in close proximity to water sites W1, W3, and W5, respectively, we conducted paired acoustic surveys at these sites (detailed below; see Fig. 1). An additional two wind turbines, near W2 and W4, were used in paired acoustic surveys and the playback experiment.

Table 1. Characteristics of five cattle ponds that were used in night vision and passive acoustic surveys at Wolf Ridge in 2012.

Pond ID	Nearest Turbine ID	Turbine Distance to Forest Edge (m)	Pond Surface Area (m^2)
W1	16	150	2,184
W2	75	560	1,653
W3	25	220	1,480
W4	56	1,250	1,956
W5	63	970	5,846

Playback experiment

We conducted an ultrasound playback experiment to compare spectral and temporal characteristics of returning echoes from various surface types and to assess if wind turbine surfaces had an echo acoustic signature similar to water. In this experiment, frequency-modulated, synthetic bat calls were projected at four different surface types: (1) water sources, (2) wind turbine towers, (3) gravel at the base of turbine towers, and (4) dirt on the banks of the water sources (Fig. 2). The former two surfaces represented smooth surfaces, whereas the latter two represented rough textured surfaces. The frequency-modulated, synthetic calls were generated using the graphical sound synthesis software in Avisoft SasLab Pro (Avisoft Bioacoustics, Berlin, DE). We generated five synthetic calls, each with a 10 kHz frequency modulated sweep (1.5 msec duration), beginning at 20 kHz and ending at 70 kHz. Each call was digitized with a 250 kHz sample rate and 16 bit resolution. The amplitude rise- and fall-time was 0.75 msec, in a smooth inverted U-shaped profile. The frequency range of the synthetic calls was selected to represent the range of frequencies used by echolocating bats in the study area (i.e., 18 to 81 kHz, representing the lowest and highest frequencies emitted by hoary and eastern red bats, respectively (Szewczak 2011). We did not use natural calls collected from acoustic monitoring in the experiment because these calls would contain relatively high levels of background noise that would produce only low-quality echoes. The short

duration sound pulse of the synthetic calls also ensured that we could effectively differentiate the

source call from the echo in each of our recordings.
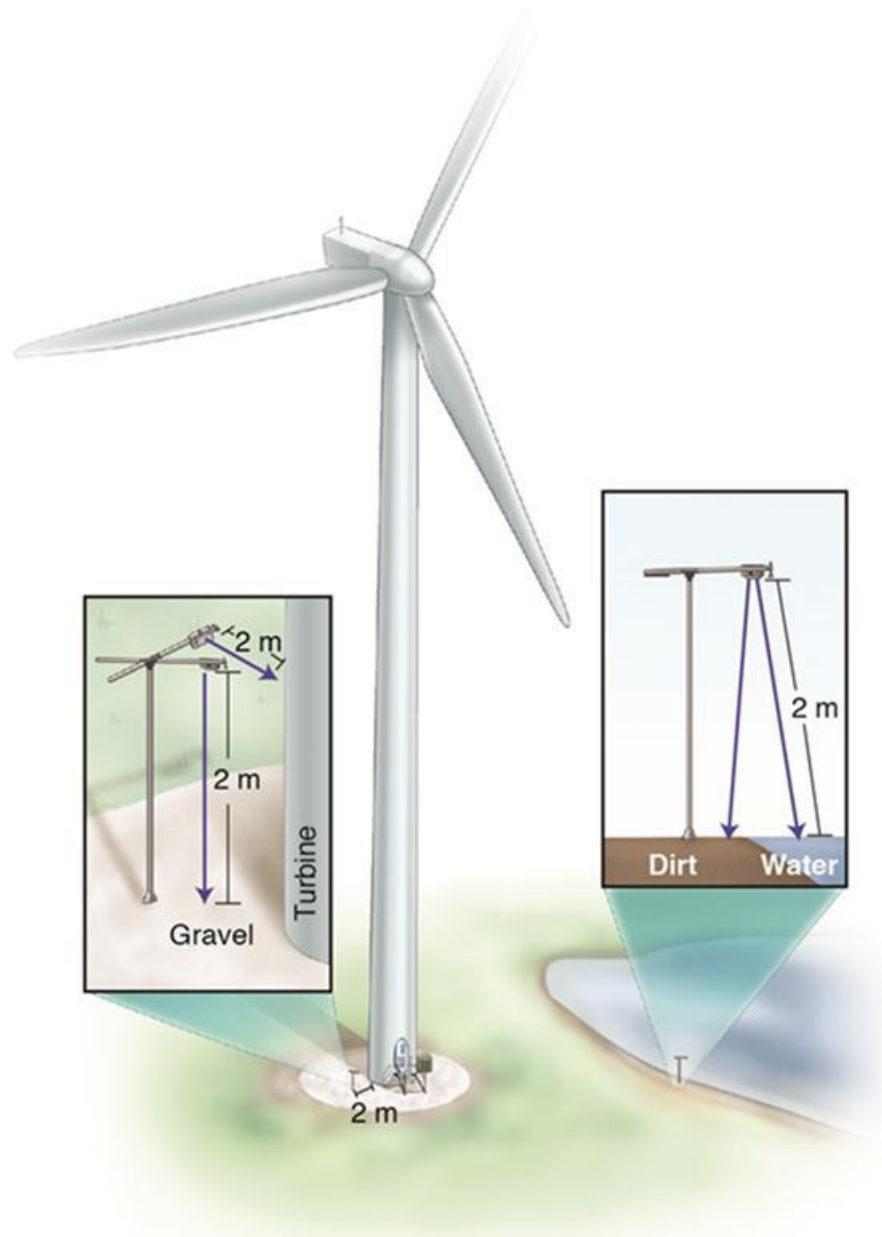
Figure 2. Representative placement of the playback equipment, including the ultrasonic speaker and external microphone, at the four surface types, (water, turbine tower, gravel, and dirt) included in the playback experiment.

As outlined above, we used four cattle ponds (sites W1-W4) and four wind turbines (sites T2 and T5, as well as turbines near W2 and W4, see Fig. 1) in the playback experiment. Thus, we surveyed a total of 16 surfaces (4 cattle ponds, 4 wind turbine towers, 4 gravel pads, and 4 dirt banks) at Wolf Ridge during June to September 2012 and February 2013. At each surface location, we set-up a playback outfit which included an Avisoft Bioacoustics UltraSoundGate Player 116, ultrasonic electrostatic speaker ESS16, UltraSoundGate 116H recorder, and external CM16/CMPA ultrasound microphone. The data were acquired with a 250 kHz sample rate and 16 bit resolution on a HP Elitebook 6930p lap-top computer. The equipment was positioned so that the speaker and external microphone were 10 cm apart and 2 m from the target surface (water, turbine, gravel, or dirt; see Fig. 2) using a K&M microphone stand. A synthetic call (source call) was then played at each surface and the returning echo recorded. As a power supply, we used an AGM SLA1156 12 volt/35 amp hours battery connected to a 400 watt inverter.

Prior to the playback experiment, we conducted a speaker-to-microphone test. We positioned the speaker and microphone at a distance of 4 m from each other to obtain baseline recordings of each source call. We played each source call six times to account for variation in the recording environment (e.g., different ambient background noise levels due to insects and wind) and hardware settings (e.g., differences in amplitude or gain settings on the microphone input prior to digitization) that can influence sound propagation and adversely impact entropy or amplitude measurements. These unreflected source recordings provided a baseline amplitude for each source call without sound attenuation induced by absorption and scattering of the reflected sound pressure waveform. We then used these baseline amplitude values to calculate relative changes in amplitude between unreflected source calls and returning echoes across the different recording sessions. Furthermore, recording the unreflected source calls enabled us to control for any differential frequency-response characteristics of the microphone and speaker.   As the external microphone

was directionally sensitive (i.e., the source call was not recorded by the external microphone), we custom built a Y-Jack that would allow us to simultaneously record the source call and the returning echo. A time delay of ~11.6 msec at 20 °C between the source call and returning echo confirmed that the returning echo had travelled the 4 m round trip from the speaker to the microphone. Because the microphone input was overloaded during the presentation of the source call, a delay time of ~11.6 msec ensured that the returning sound was not affected by this signal distortion that occurred at the onset of the call playback. Four meters provided sufficient delay time to optimize the recording of different frequency ranges and to eliminate the signal distortion.

We played each of the five synthetic bat calls five to six times at each of the 16 surfaces. The microphone and speaker were placed 2 m from each surface type so that the total distance travelled would be equivalent to the 4 m baseline recordings. All sound files were directly recorded onto an HP Elitebook 6930p lap-top and saved to an external hard drive for analysis. As weather could impact echo quality by altering sound speed and producing background noise, we recorded temperature (°C), wind speed (km/hr), and humidity (%) using a Kestrel 4500 pocket weather meter.

Playback analysis

We filtered and analyzed echoes from each of the 16 surfaces using Avisoft-SasLab Pro acoustic analysis software. First, the data were digitally filtered with a high-pass infinite impulse response filter (15 kHz cutoff) to attenuate low frequency background noise. Second, we applied a notch filter to reduce background electrical noise generated by our equipment and the wind turbines, which occurred at a frequency of 56.9 kHz. To quantify spectral characteristics of the returning echoes, we measured $\int_{maxE}$, which is the frequency of sound with the highest acoustic energy, and entropy, which has arbitrary units with 0 corresponding to a perfectly sinusoidal waveform and 1.0 to a random waveform. To quantify sound intensity, we measured the relative echo amplitude as a percentage change in echo amplitude compared to the unreflected source call. For each of these variables, we calculated the average value from the 5-6 replicates for each synthetic call played at each surface, and then used these averages as response variables in a series of statistical analyses. All analyses were computed from spectrograms created in SasLab Pro using the settings in Table 2.

Table 2. Spectrogram settings used for analysis in Avisoft-UltraSoundGatePlayer 116 software.

Controls	Settings
Window size	50 ms
FFT length	1024 points
Frame Size	100%
Window type	flat top
Bandwidth	918 hertz

Five to six repetitions of each waveform were aligned to the maximum values for each peak in the waveform, and an average echo for each frequency range and testing condition was calculated. We calculated the sum of the squared deviations between the mean amplitude waveform obtained from water compared to turbine towers, gravel, and dirt for each source call to

assess waveform variation in the returning echoes. We used general linear models (GLM) to

determine if the intensity and the spectral and temporal characteristics of returning echoes varied

with source call frequency and with the surface on which they were projected. Data were

transformed as necessary to meet the assumptions of GLM. We checked for interactions between

factors and retained all interactions that were significant in the models ($\alpha = 0.05$). We then used

Tukey Simultaneous Tests (95% family-level confidence) to conduct all pairwise post-hoc

comparisons among levels when a factor was deemed significant in the overall model ($\alpha = 0.05$).

Means ± SE were presented unless otherwise noted. All statistical analyses were conducted using

Minitab version 16 (State College, PA).

Night vision surveys

We conducted night vision surveys at Wolf Ridge to determine if bats behaved similarly at water

sources and wind turbines. From May 22 to October 1, 2012 we used ATN models MO4-3 and

NVM14-3 generation-three night vision monoculars and IR-450 infrared illuminators (ATN

Corporation, San Francisco) to visualize bats. Night vision technology has been used to conduct

behavioral studies and population-level assessments of nocturnally active birds and bats (McCracken

and Gustin 1991, Delaney et al. 1998, Cryan et al. 2011). The benefit of using night vision equipment

with an infrared light source is that we can observe bat behavior in darkness, without using visible

light. Under low light conditions, night vision units work by gathering ambient light from the

environment using a unique front lens and photocathode tube to generate electrons into an image.

If there is too much light, an image cannot be produced. Several levels (i.e., generations) of night

vision technology are commercially available, ranging from 1st to 4th generation, with the quality of

the image produced by the photocathode tube and the cost of the equipment increasing from one

generation to the next.

Each night vision unit and infrared illuminator was coupled to a Sony Handycam DCR-SX45 camcorder and mounted on a tripod. In addition, we attached a Pettersson D240x ultrasound bat detector to the coupled unit to record bat echolocation calls during the survey periods (discussed below). Echolocation calls picked up by this detector (set at a frequency of 40 kHz and volume high) from bats flying near the night vision unit were audibly recorded on the night vision videos (.mpg format).

In our night vision surveys, we recorded bat activity in two fields of view at five water sources (Water Zones 1 and 2; Figs. 1 and 3) and three fields of view at five wind turbines (Turbine Zones 1, 2, and 3; Figs. 1 and 4). Surveys were conducted during the two 3-hour primary foraging periods for bats during each survey night (Hayes 1997, Baerwald and Barclay 2011). The first period began approximately 1 hour after sunset and the second period began 3 hours before sunrise to ensure the best night vision imaging. Each zone was surveyed for 30 minute sessions and we rotated the order in which the zones were surveyed each night. To ensure a balanced survey effort, we alternated between pond and wind turbine sites and visited each site within a two-week interval. Surveys were only delayed or canceled if lightning was within 50 miles of Wolf Ridge, wind speeds were above 20 mph, or if it was raining. High wind speeds and precipitation not only reduced bat activity (Erickson and West 2002, Burles et al. 2009), but could potentially damage survey equipment.

At the beginning of each 30-minute survey zone we recorded the following data: turbine status (on or off), nacelle position, night vision unit location relative to the turbine tower base, temperature (^{o}C), wind speed (km/hr) and direction, barometric pressure (in), dew point (^{o}C), humidity (%), moon phase, and amount of cloud cover. With the exception of moon phase and cloud cover, we recorded all other weather attributes using a Kestrel 4500 pocket weather meter.
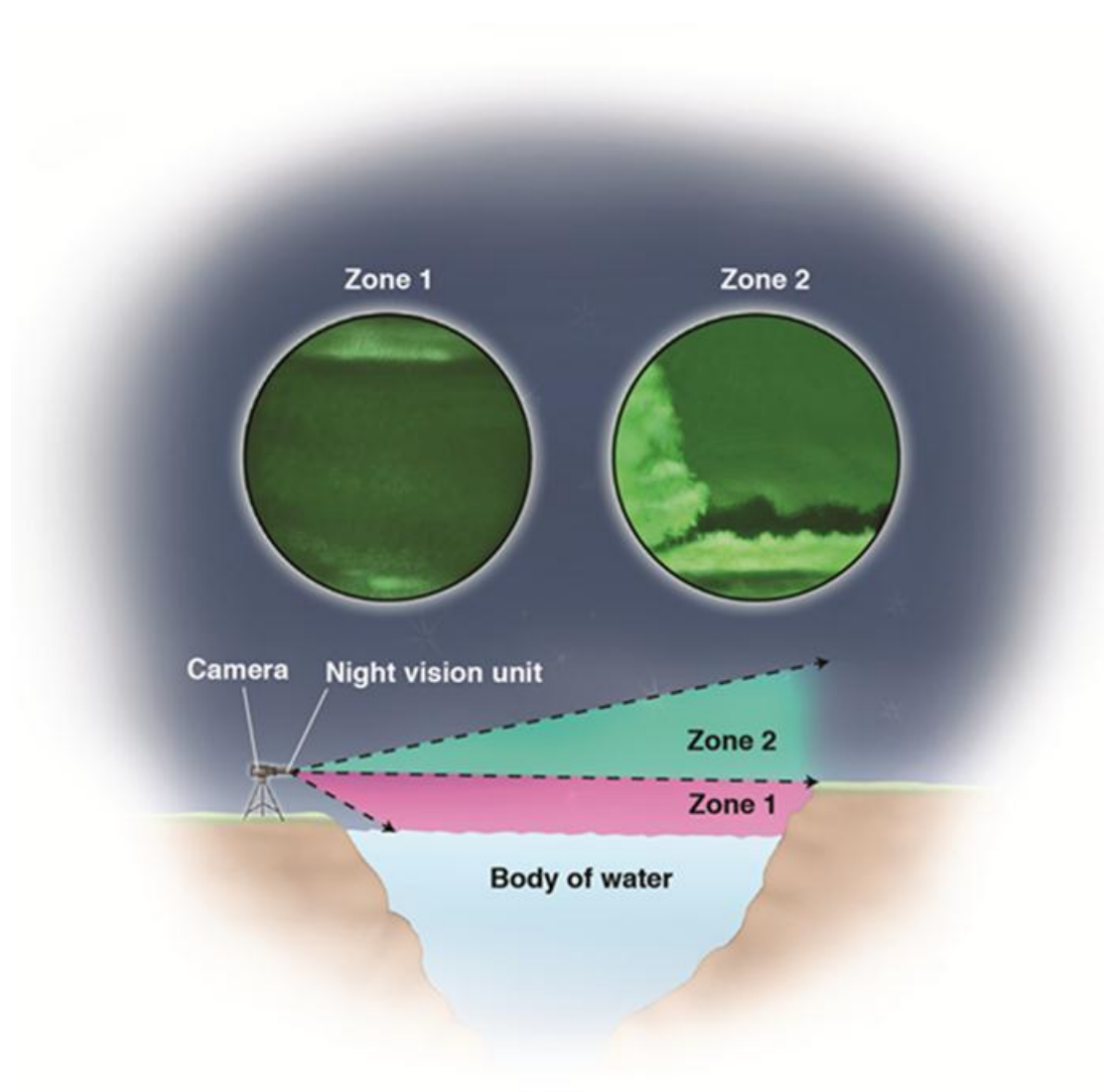
Figure 3. Diagram illustrating Water Zones 1 and 2 during night vision surveys at cattle ponds, including a view of each Zone as seen using night vision technology at Wolf Ridge.
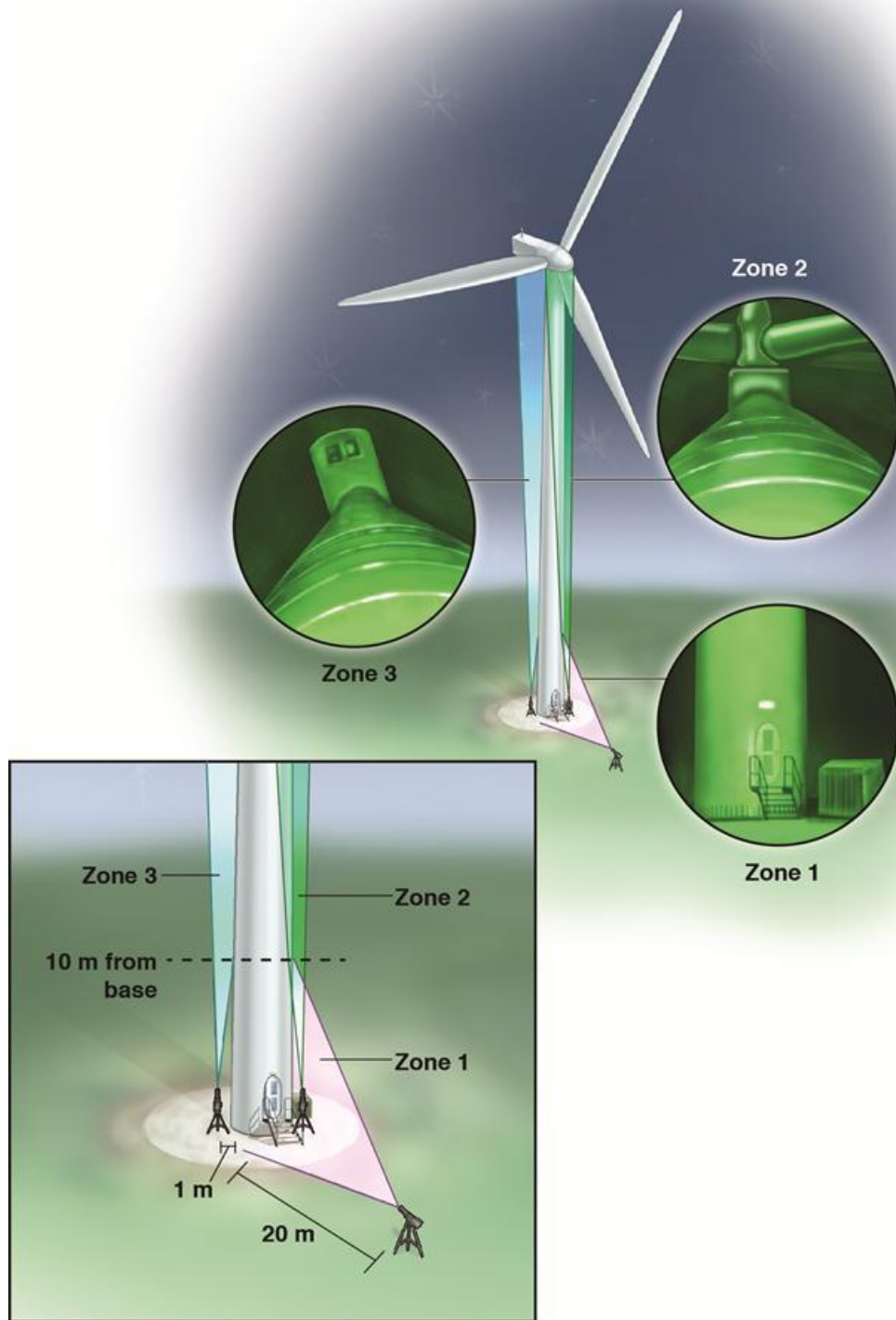
Figure 4. Diagram illustrating Turbine Zones 1, 2, and 3 during night vision surveys at wind turbines, including a view of each Zone as seen using night vision technology at Wolf Ridge.

Of the two different 3rd generation night vision units that we used in our study, the MO4-3

unit had an 11° field of view and a 5x zoom lens, whereas the NVM14-3 had a 40° field of view and a

1x lens (Fig. 5). With the MO4-3 unit, Water Zone 1 focused only the surface of the water source

immediately in front of the camera, whereas Water Zone 2 focused on the distant shoreline (Fig. 3).

With the NVM14-3 unit, both Water Zones 1 and 2 were visible with the initial position, so no

camera adjustment was necessary between the 30-minute sessions. We positioned night vision

units at water sources to maximize the surface area viewed but to also avoid emerging aquatic

vegetation, which could make drinking behavior more difficult to detect (Jackrel and Matlack 2010).

Furthermore, we kept night vision unit locations at water sources consistent throughout the survey

period. The NVM 14-3 night vision unit was placed approximately 10 m from the edge of the pond,

whereas the MO4-3 unit was positioned approximately 30 m from the pond edge (Fig. 5). We

provide estimates of the amount of area in each field of view in Table 3.

Figure 5. Representative coverage of one cattle pond by the NVM14-3 (yellow cross-hatch) and MO4-3 (green diagonal lines) night vision units. Blue stars indicate each night vision unit placements relative to the pond.

Table 3. Comparison of the field of view obtained from each night vision unit at each water source surveyed at Wolf Ridge.

Site	Nearest Turbine	Pond Area (m^2)	NVM14-3 Area (m^2)	MO4-3 Area (m^2)
W1	16	2,184	511	338
W2	75	1,653	565	286
W3	25	1,480	425	243
W4	56	1,956	733	545
W5	63	5,846	1,585	1,005

For the night vision surveys at wind turbine sites, we defined Turbine Zone 1 as the field of view encompassing the tower door, transformer, and base section of the turbine tower up to 10 m above ground (Fig. 4). Turbine Zone 2 included the middle and upper tower surfaces under the front of the nacelle from 10 m above ground up to the bottom of the nacelle (~80 m above ground). Turbine Zone 3 included the middle and upper tower surfaces under the back of the nacelle from 10 m above ground up to the bottom of the nacelle. We placed the NVM14-3 night vision unit 20 m from the turbine tower base to view Zone 1 and 1 m from the tower base in a vertical orientation to view Zones 2 and 3. The MO4-3 unit was placed 40 m from the turbine tower base to achieve a similar field of view as with the NVM14-3 for Zone 1. For Zones 2 and 3, the MO4-3 unit was also placed 1 m from the tower base in a vertical orientation.

Night vision analysis

Two observers analyzed night vision videos using Sony Picture Motion Browser video software (version 5.5, Sony, Tokyo) with HPL1950 LCD monitors. When a flying object was observed on the screen, the video was paused and reviewed multiple times in order to ascertain the overall size, shape, and flight pattern of the object. Based on these characteristics, we assigned the object to one of three categories: (1) bat, (2) bat-like, or (3) non-bat. We categorized an object as a bat when it met two or more of the following criteria: the object was the size and shape of a bat; we observed defined wings and separate body; the flight pattern was representative of bat foraging behavior, e.g., random zigzagging flight with continuous wing beats; or a bat acoustic call was recorded simultaneously from the accompanying Pettersson bat detector (Pettersson, Sweden). An object was classified as bat-like when it was the size and shape of a bat and exhibited continuous wing beats. Finally, we classified all other objects as non-bats. The non-bat category included objects that 1) were the size and shape of a bat, but had a slow flight pattern with intermittent wing beats indicative of a moth; 2) had visible wings but the body was small or indistinguishable, again suggesting a moth; and 3) had a visible tail indicating that the object was a bird.

We recorded the time and activity associated with each bat observation. Bat activities included passing, foraging, drinking (water sources only), drinking attempts (turbine sources), roosting, and avoidance (turbine). We categorized the activity as passing when a bat exhibited a straight flight pattern without obvious turns or maneuvers. We categorized the activity as foraging when a bat exhibited zigzagging flight with multiple turning angles. Drinking (water sources only) occurred when a bat swooped down to the surface of a water source and made head-first contact with the water one or more times. A drinking attempt (turbine towers only) occurred when a bat swooped toward the surface of the turbine tower with its ventral surface parallel to the turbine and made head-first contact with the turbine tower one or more times. Roosting behavior occurred

when a bat landed or flew out of a turbine structure such as the nacelle, transformer, door, or light structures. Avoidance behavior was recorded when a bat exhibited evasive maneuvers to escape impact with moving turbine blades. From these observations, we calculated a total bat activity rate as the number of bats seen per hour during each video session.

To test for repeatability between video observers, a subset of the videos analyzed by observer 1 were also viewed by observer 2. These sixteen videos were selected using a stratified random sample to balance video distribution between AM/PM shifts and water sources/wind turbine sites. We calculated a percent similarity score for each video using the equation 2S/(2S+A+B) where S is the number of bats identified by both observer 1 and observer 2, A is the number of bats identified by only observer 1, and B is the number of bats identified by only observer 2. The mean percent similarity score was used to provide an estimate of the difference in bat identification between the two observers. We also used a paired t-test to determine if the total number of bats seen per video differed between observers (i.e., was there a bias?). In order to address potential observer discrepancies, we also randomly selected 48 bat passes from these videos and measured the amount of time the bat was within the field of view. As we found no evidence of bias between the observers (see Results), we pooled the data across both observers in subsequent analyses.

Since two different night vision units (MO4-3 and NVM14-3) with different field of views were used throughout the surveys, we compared bat activity rates using Mann-Whitney U-tests between the two units for wind turbine zones and water zones separately. As we found no consistent difference between the units (see Results), we pooled the data across both units in all subsequent analyses.

We used nonparametric tests (Mann-Whitney U-tests or Kruskal-Wallis tests depending on the number of categories) to compare bat activity rates among survey zones at turbine towers and

water sources and between turbine towers and water sources overall. Because the bat activity rate data for the ~30-minute sessions was right skewed with many zero values, it could not be successfully transformed to meet the assumptions of parametric tests. We then pooled the data by zones within turbines and water sites to calculate mean bat activity per PM and AM survey period, and analyzed these data using nonparametric tests. We pooled by PM and AM survey periods to calculate a mean bat activity rate per survey night (n = 43 turbine nights and n = 48 water nights). After transforming the data, we used a general linear model to test for differences in bat activity at wind turbines and water sources across the study season.

We also investigated whether bat activity during the survey period was impacted by percent moon illumination. For each session, we obtained moon illumination data (see www.die.net/moon/) and recorded percent cloud cover (no cloud cover, partly cloudy, mostly cloudy). From these data, we calculated a single composite variable that incorporated both moon illumination and cloud cover. For sessions with clear skies, moon illumination percentages were unchanged. During partly cloudy sessions, moon illumination percentages were reduced by half, and mostly cloudy sessions were assigned a 0% illumination value. Pooling bat activity data across turbines and water sources, we used a Kruskal-Wallis test to determine if there was a relationship between percent moon illumination (<33%, 33-66%, and >66%) and bat activity rates.

We used Fisher's exact tests to determine if there were differences in the proportions of activity types (e.g. passing, foraging, drinking attempt, etc.) exhibited by bats in the PM and AM sessions at wind turbines and water sources.

Acoustic monitoring

We conducted acoustic monitoring surveys at wind turbines and water sources to (1) compare the rates of acoustic activity recorded (bat passes/hour) with rates of activity in night vision surveys

(bats seen/hour) at water sources and wind turbines, (2) determine which bat species were in close proximity to water and wind turbine tower surfaces, and (3) explore whether the types and proportions of activities recorded acoustically were equivalent to the types and proportion of activities observed at water sources and wind turbines. From 22 May to 1 October 2012, we conducted acoustic monitoring surveys using Binary Acoustic Technology (BAT, Tucson, AZ) AR125-EXT ultrasonic receivers mounted to tripods that were coupled with BAT FR125 recorders and externally powered by 12V 35 amp hour batteries. The BAT FR125 recorders were programed to trigger at frequencies between 5 KHz and 90 KHz with a 0 second delay between recordings, and at a threshold >18.0 dB to encompass the range of echolocation frequencies and call intensities known for local bat species. Each sound file was recorded for 4 sec onto a 32 GB SD card as a standard wav file (.wav) at a 98000 bit resolution. We placed one acoustic receiver at each of our night vision survey sites (see night vision methodology above) and these were set up to begin recording at dusk and continue until dawn on night vision survey nights. Where night vision surveys were not coupled with a respective water source or wind turbine, we placed a second acoustic receiver at a nearby water source or wind turbine, when possible. Thus during night vision surveys, sites T1 and W1, T2 and W3, and T5 and W5 were acoustically surveyed simultaneously, and sites W2 and W4 were paired with nearby turbines (see Fig. 1).

At water sites, we set up the acoustic detector assembly at the pond's edge with the AR125 receiver angled 135° toward the water surface in order to capture bat echolocation in close proximity to that surface. At wind turbines, we positioned the acoustic detector assembly on the gravel pad approximately 2 m from the turbine base with the AR125 receiver pointing 45° toward the tower surface. Again, we did this to record bat activity within close proximity of the wind turbine tower surface.

Acoustic analysis

We used SonoBat Batch Scrubber software (version 4) to remove all files containing sounds that were not characteristic of bat echolocation calls (i.e., noise such as rain, wind, katydids, crickets, and grasshoppers). The scrubber software was set at a high call quality filter setting to remove as many non-bat sound files as possible, leaving only the highest quality calls (i.e., those calls that could be effectively analyzed). Following this exercise, we used SonoBat bat call analysis software (version 3.04) to visually and audibly confirm that the remaining scrubbed data files contained bat calls. Each file containing a bat call was counted as one bat pass (Miller 2001). Using full-spectrum spectrograms generated in Sonobat and classifiers for the northeast U.S. and the Ozarks, we manually determined (1) whether each call was a low (20-30 KHz) or high (30-40 KHz) frequency call, (2) species (if possible), and (3) activity. For the latter, we identified the following four distinct activities: *commuting* – consecutive calls (i.e., individual chirps) were synchronized with wing beats (Altringham 2011) and were either constant, steadily decreasing, or steadily increasing in call strength, in addition any sound file with <2 calls was also categorized as commuting (e.g., bats that were moving through the area from one foraging site to another); *searching* – consecutive calls were synchronized with wing beats, but varied in strength due to the bat turning its head from side to side while echolocating (Altringham 2011); *foraging* – call interval varied with multiple calls occurring in succession within a single wing beat, and call strength was constant, steadily decreasing, or steadily increasing (Altringham 2011); and *feeding buzz* – interval between successive calls decreased rapidly and the frequency of these calls was higher or lower (depending on species) than calls representing the other three activities (Altringham 2011).

After the calls were processed, we analyzed the acoustic data for discernible patterns in bat activity. First, we calculated mean number of bat passes per detector per hour across the entire survey period. We then compared bat activity (mean number of bat passes per detector per hour)

between water sources and wind turbine sites using a Mann Whitney U-test. In addition, we used

Spearman rank correlations to determine if there was a relationship between bat activity recorded

in acoustic monitoring and bat activity seen in night vision surveys for PM and AM sessions at

separate wind turbine and water sources.

To determine if acoustic bat activity at water sources and wind turbine sites varied during

the night, we calculated the number of bat passes per hour from dusk until dawn, as well as for each

survey session (AM/PM). To compare sessions, we used a Mann Whitney U-test. We also used

Spearman Rank correlation to assess whether there was a relationship between bat activity

recorded in acoustic monitoring and activity recorded in night vision surveys at water sources and

wind turbines sites for both AM and PM sessions. In addition, to ascertain whether seasonal

changes in bat activity varied between water sources and wind turbine sites, we compared mean

number of bat passes recorded per hour at weekly intervals. Again, we compared the patterns of

acoustic bat activity with the equivalent activity rates observed in night vision surveys.

We then explored species-specific patterns of acoustic activity. From the echolocation calls

identified to species using Sonobat, we determined which of the species were present at water

sources and which were present at wind turbine sites. We investigated whether species-specific

acoustic activity varied between water sources and wind turbine sites (i.e., do different species visit

water sources and wind turbines at different rates?). For this analysis, we used Spearman rank

correlations to see if the number of bat passes recorded at water sources correlated with the

number of bat passes recorded at wind turbine sites for each species identified. We also

investigated species-specific differences in nightly and seasonal activity (i.e., are different species

active at different times across the season?).

We then examined the various types of behavior exhibited by bats in the acoustic

monitoring (i.e., commuting, searching, foraging and feeding buzz; see above). We determined the

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rates at which these behaviors were exhibited and explored whether their rates varied between water sources and wind turbine sites. Additionally, we compared the types and proportion of behavior recorded acoustically and the types and proportion of behavior that were observed in night vision surveys.

Finally, at sites where night vision and acoustic monitoring surveys were undertaken concurrently, we matched (where possible) the calls recorded in acoustic monitoring by time with bat activity observed in night vision surveys. Where calls were successfully matched up, we were able to identify the species of the observed bat. This measurement provided another variable used in the night vision analysis (see above).

GIS analysis

We used ArcGIS version 10.0 to create a site map of Wolf Ridge and to plot night vision and passive acoustic survey sites. We calculated the area of each water source surface and the area of coverage for each night vision unit and created individual shape files to illustrate the 11° and 40° field of view for the MO4-3 and NVM14-3 units, respectively. The surface area of each pond that was within the night vision field of view was calculated for each unit by intersecting each night vision unit's shape file with the pond area shape file.

RESULTS

Playback experiment

Among the four temporal and spectral characteristics compared that we measured from the returning echoes, we found no discernible difference in f_{maxE} among surface types for the five frequency-modulated source calls (Fig. 6A and Table 4). However, there was a significant difference in the percent change in amplitude among the surfaces on which the source calls were played (Fig.

6B and Table 5). Returning echoes from water and wind turbine towers where much louder and

showed a smaller reduction in amplitude compared to returning echoes from dirt and gravel

surfaces. Additionally, echoes returning from water and wind turbine surfaces were not significantly

different from each other. Overall, we found no effect of source call frequency on the percent

change in amplitude of the returning echoes.

Entropy of returning echoes also varied significantly with the surface on which the source

calls were played (Fig. 6C and Table 6). The entropy of echoes from water and turbine towers were

again similar and were significantly lower (i.e., less disordered) than the entropy of echoes from the

textured surfaces. Furthermore, the echo entropy was greatest in higher frequency source calls

compared to lower frequency source calls.
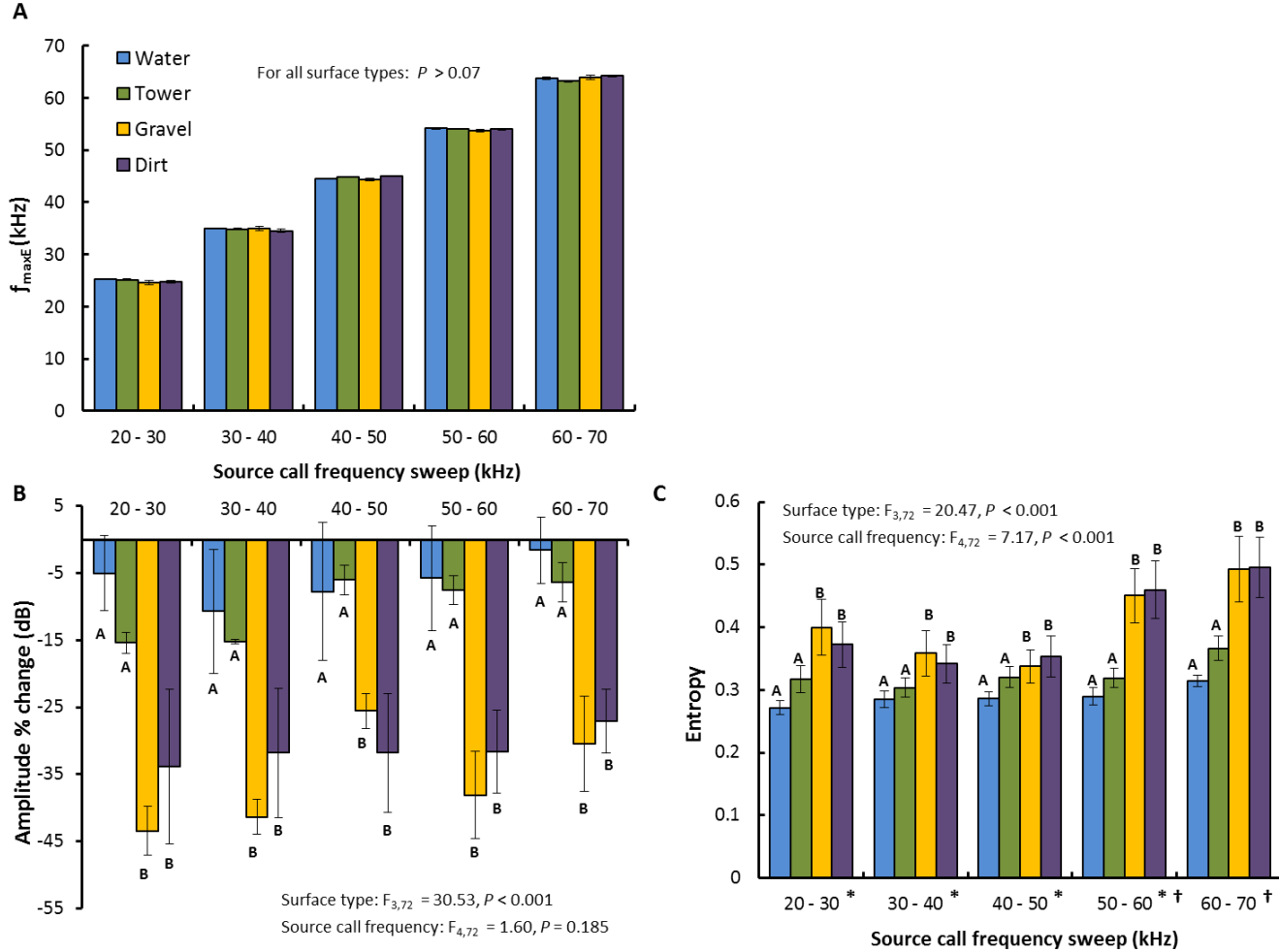
Figure 6. Comparison of spectral characteristics of returning echoes from a range of frequency-modulated synthetic source calls played at water, wind turbine tower, gravel, and dirt surfaces. Surface types that do not share a letter in common and source calls that do not share a symbol in common were significantly different (GLM followed by Tukey Simultaneous Tests [95% confidence]). (A) Mean ± SE f_{maxE} (kHz). (B) Mean ± SE % change in amplitude (dB). (C) Mean ± SE entropy (arbitrary units, with 0 corresponding to a perfectly sinusoidal waveform and 1.0 to a random waveform).

Table 4. General linear models (GLM) showing no significant difference in f_{maxE} (kHz) for returning echoes from water, turbine towers, gravel, and dirt for five different frequency-modulated synthetic bat calls. No transformation was needed prior to analysis.

20-30 kHz Calls

Source of variation	df	Seq SS	Adj MS	F	P
Surface type	3	1.220	0.407	1.73	0.214
Error	12	2.820	0.235		
Total	15	4.040			

30-40 kHz Calls

Source of variation	df	Seq SS	Adj MS	F	P
Surface type	3	0.590	0.197	0.64	0.606
Error	12	3.717	0.310		
Total	15	4.307			

40-50 kHz Calls

Source of variation	df	Seq SS	Adj MS	F	P
Surface type	3	0.712	0.237	3.09	0.068
Error	12	0.921	0.077		
Total	15	1.633			

50-60 kHz Calls

Source of variation	df	Seq SS	Adj MS	F	P
Surface type	3	0.443	0.148	1.80	0.201
Error	12	0.985	0.082		
Total	15	1.428			

60-70 kHz Calls

Source of variation	df	Seq SS	Adj MS	F	P
Surface type	3	2.094	0.698	2.47	0.112
Error	12	3.393	0.283		
Total	15	5.487			

Table 5. General linear model (GLM) showing that the percent change in sound amplitude (dB) varied significantly among surfaces, but not with frequency of the synthetic bat calls. No transformation was needed prior to analysis.

Source of variation	df	Seq SS	Adj MS	F	P
Surface type	3	13252.1	4417.4	30.53	<0.001
Source call frequency	4	923.6	230.9	1.60	0.185
Error	72	10417.1	144.7		
Total	79	24592.8			
S = 12.03		R^2 = 57.64%			

Table 6. General linear model (GLM) showing that entropy varied significantly among surfaces and with frequency of the synthetic bat calls. Entropy was log-transformed prior to analysis.

Source of variation	df	Seq SS	Adj MS	F	P
Surface type	3	0.281	0.094	20.47	<0.001
Source call frequency	4	0.131	0.033	7.17	<0.001
Error	72	0.330	0.004		
Total	79	0.742			
S = 0.068		R^2 = 55.57%			

Temporal analysis of the echo waveforms across the range of source call frequencies revealed significantly greater differences between echoes reflected from gravel and dirt compared to water than the differences between echoes reflected from wind turbine towers compared to water (Fig. 7, Fig. 8, and Table 7). The echo waveforms from wind turbine towers and water surfaces had a unimodal distribution of amplitude across time and were similar between the two sources. In contrast, the echo waveforms from gravel and dirt surfaces showed multiple peaks in amplitude peaks across a longer time period, and were thus dissimilar to the echo waveforms obtained from both wind turbine tower and water surfaces.
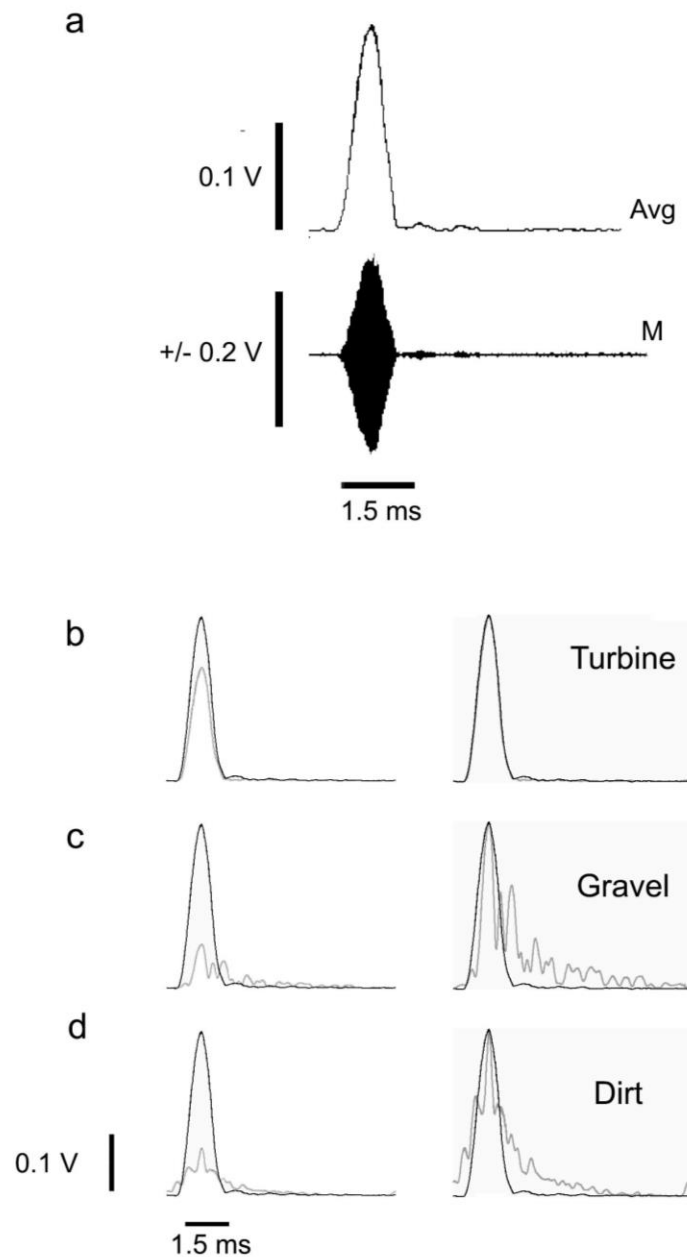
Figure 7. Illustration of waveform averaging and temporal variance analysis procedure (A) A 7 msec period of the microphone recording was segmented, rectified, and smoothed (0.1 msec sliding window). Five to six replicates were averaged to calculate the mean echo amplitude profile for each source call from each surface type. The echo waveform from water is shown here. (B) The mean water echo (dark trace) was then compared to the mean turbine echo (light gray trace) by aligning the waveforms (left) and then normalizing the peak amplitude to scale between 0 and 1.0 (right). This procedure was repeated with the waveforms from (C) gravel and (D) dirt. The sum of the squared differences between the water waveform and each of the other waveforms was then calculated.
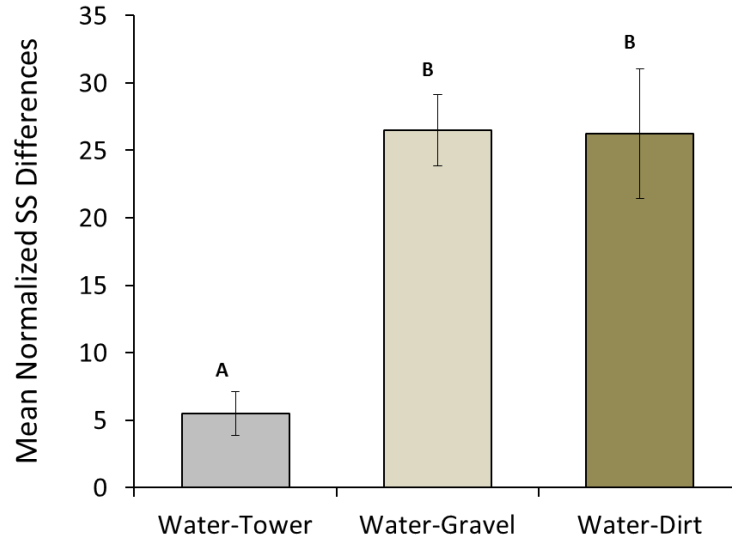
Figure 8. Mean ± SE normalized sum of squared deviations in amplitude (arbitrary units) between echoes reflected from water compared to echoes reflected from gravel, dirt, and wind turbine towers. The data presented are pooled across all source call frequency sweeps as we found no difference in the deviations among source call types (see Table 7). The differences in waveform between water and gravel and water and dirt did not differ from each other (GLM followed by Tukey Simultaneous Tests [95% confidence], P = 0.85), but were significantly greater than the differences in waveform between water and wind turbine towers (GLM followed by Tukey Simultaneous Tests [95% confidence], P < 0.0001 in both cases). Means that do not share a letter are significantly different.

Table 7. General linear model (GLM) showing that the normalized sum of the squared deviations between the mean amplitude values obtained from water and wind turbine towers, water and gravel, and water and dirt varied significantly with surface type, but not with frequency of the synthetic bat calls. The response variable was log-transformed prior to analysis.

Source of variation	df	Seq SS	Adj MS	F	P
Surface type comparison	2	64.63	32.32	35.77	<0.001
Source call frequency	4	5.75	1.44	1.59	0.190
Error	53	47.89	0.90		
Total	59	118.27			

S = 0.950 R^2 = 59.51%

By comparing the overall acoustic composition of the source calls and their associated echoes at all four surface types, it was evident that changes in amplitude and entropy significantly altered the acoustic signatures of echoes between smooth and textured surfaces (Fig. 9). Echoes recorded from towers and water had higher intensities (seen as a greater proportion of red in the echo signature) compared to echoes returning from gravel and dirt. The echoes produced from gravel and dirt also tended to have longer acoustic tails, which were likely due to dispersion of the sound wave as a function of being reflected from a rough surface. Moreover, there was no discernible difference between the acoustic signatures of echoes from water and wind turbine tower surfaces.
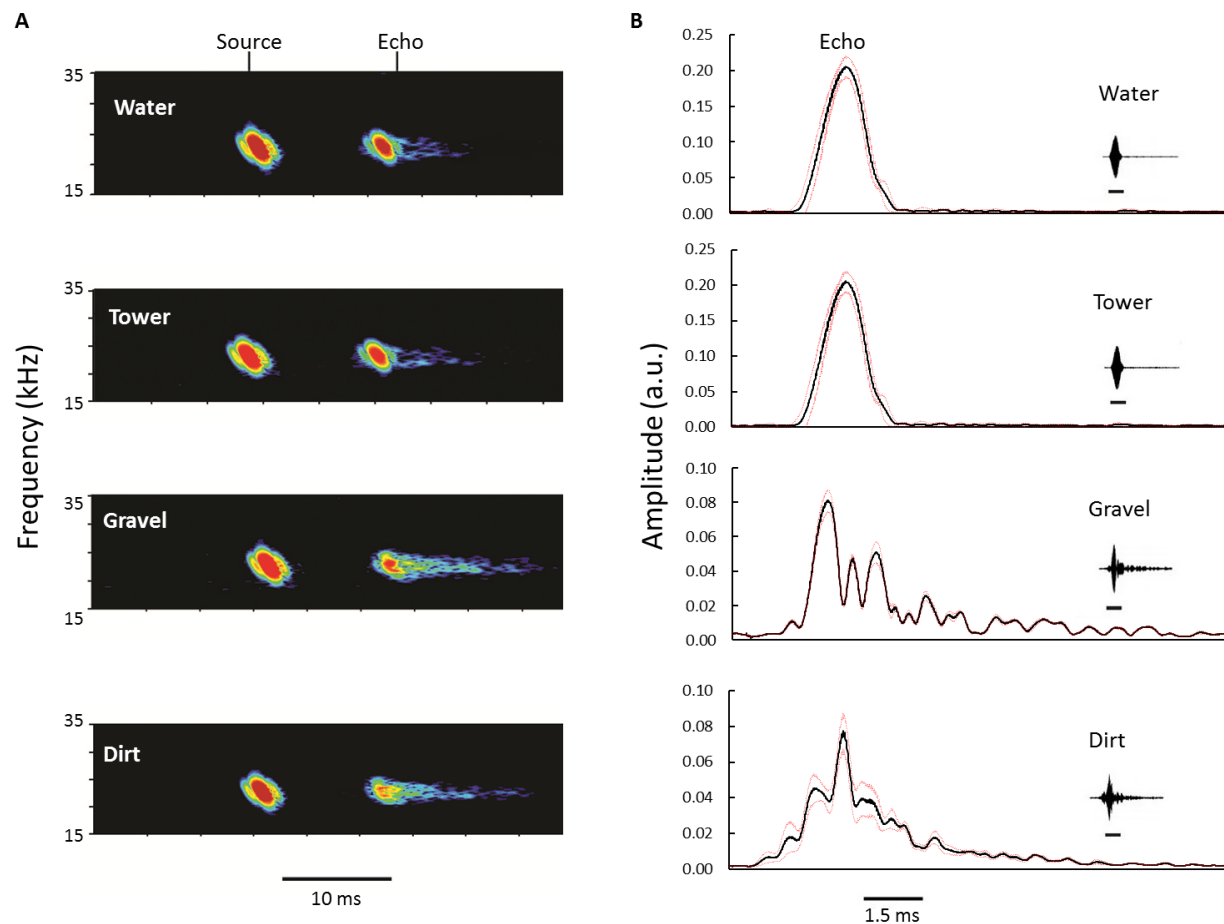
Figure 9. Spectral and temporal characteristics of ultrasound echoes vary as a function of the reflective surface features. (A) Spectrograms of a 20-30 kHz frequency-modulated synthetic call and echo recorded from water, turbine tower, gravel, and dirt. Echoes from smooth surfaces returned with a greater sound amplitude (red indicates higher intensity sound, darker colors lower intensity) than those from rough surfaces. Additionally, there was greater acoustic energy in the tail of the echo recorded from rough surfaces compared to smooth. (B) Mean (± SE) echo amplitude (arbitrary units, rectified and smoothed with a 0.1 msec sliding window) for each of the aforementioned surfaces. The inserts display individual microphone traces (scale bar = 1.5 msec) from which the average was derived based on 5 to 6 replicates. The recorded acoustic waveform showed greater temporal modulation when reflected from rough compared to smooth surfaces..

Night vision surveys

We recorded 109 hours of video from water sources and 113 hours of video from wind turbines, totaling

222 hours of night vision videos for analysis. We analyzed 224 water sessions (mean ± SD video length =

29.28 ± 4.36 min, n = 5 cattle ponds) and 227 wind turbine sessions (mean ± SD video length = 29.85 ±

3.27 min, n = 5 turbines) with an even distribution of time across each site's zones (W1 = 114 videos,

and W2 = 110 videos, T1 = 76 videos, T2 = 74 videos, T3 = 77 videos). For analysis, we used only objects

categorized as bats (see night vision analysis) and excluded bat-like classifications.

Video observer comparisons

Mean (± SE) percent similarity for the two observers was 72.6% ± 0.345 (n = 16 videos). This

means that any one observer is likely missing 27% of bats that are present in the videos. This downward

bias is to be expected because the mean (± SD) time a bat was present in the field of view to be seen by

an observer was 0.67 ± 0.41 seconds (n = 48 bat passes). Between the two observers, we found no

significant difference in the number of bats seen per video (paired t-test: t = 0.52, df = 15, P = 0.61).

Collectively, these results indicate that the bat activity data presented below will likely underestimate

the true levels of bat activity at the site, but that we don't need to consider which observer scored the

data in the analyses.

Night vision unit comparisons

We found no difference in bat activity rates between the night vision units at wind turbine

sources (Mann-Whitney test, data pooled across zones: W = 10530, n_{MO4} = 95, n_{NVM} = 132, P = 0.51; Fig.

10). We also found no difference in bat activity rates between units in Water Zone 1 (Mann-Whitney

test Zone 1: W = 4505.5, n_{MO4} = 73, n_{NVM} = 41, P = 0.063; Fig. 10); however, bat activity in Water Zone 2

was significantly higher with the MO4-3 than with the NVW14-3 unit (Mann-Whitney test Zone 2: W =

4468, n_{MO4} = 68, n_{NVM} = 42, P < 0.001; Fig. 10). Because we found no systematic difference between the night vision units, we did not include night vision unit as a factor in subsequent analyses.
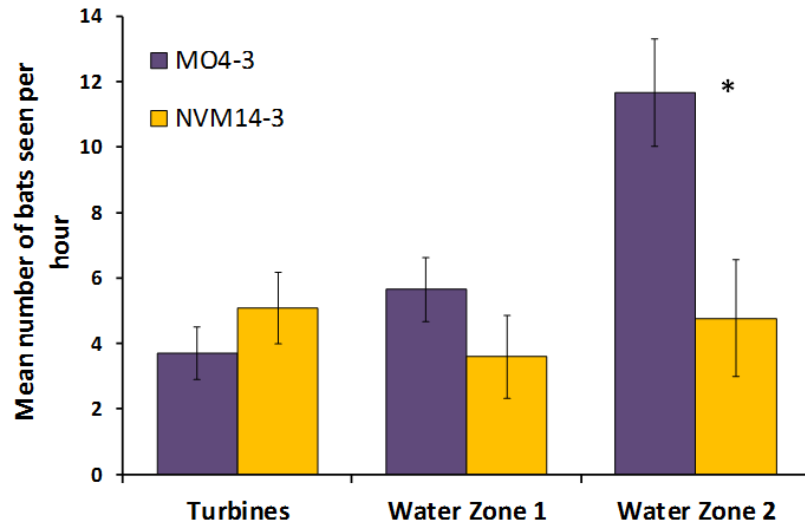
Figure 10. Mean ± SE number of bats seen per hour using two different night vision units at wind turbines (pooled across zones) and at water sources (Zones 1 and 2 presented separately) at Wolf Ridge from 12 June to 1 October 2012. See methods for a description of the zones. * indicates a significant difference between night vision units at a survey location.

Bat activity

Of the 1,232 objects classified as bats, 764 were seen at water sources and 468 were seen at wind turbines. Bat activity at water sources was significantly higher (mean ± SE = 6.6 ± 1.1 bats per hour, n = 46 survey nights) than at wind turbines (mean ± SE = 4.1 ± 0.9 bats per hour, n = 46 survey nights), although the magnitude of this difference was not large (Mann-Whitney test: W = 1913.5, P = 0.04).

Mean hourly rates of bat activity at turbine towers ranged from 3.25 to 5.80 bats per hour, but there was no significant difference among the three zones (Kruskal-Wallis test: H = 0.11, df = 2, P = 0.947; Fig. 11). Mean hourly rates of bat activity at water sources ranged from 4.91 to 9.04 bats per hour, with significantly higher activity in Zone 2 (Mann-Whitney test: W = 11485.5, n_1 = 114, n_2 = 110, P = 0.005; Fig. 11).
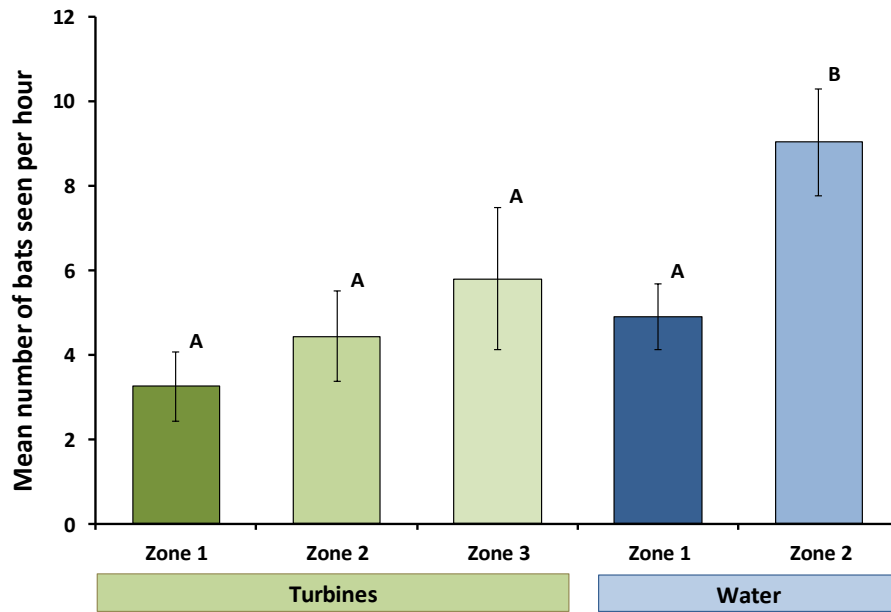
Figure 11. Mean ± SE number of bats seen per hour using night vision technology in three fields of view at wind turbines and two fields of view at water sources at Wolf Ridge from 12 June to 1 October 2012. See methods for a description of the zones. Means that do not share the same letter were significantly different from each other (Kruskal-Wallis test followed by post-hoc Mann-Whitney tests with α = 0.0056).

Pooling across PM and AM sessions and survey location (wind turbines and water sources), we also found a significant difference in bat activity with percent moon illumination (Kruskal-Wallace test: *P = 0.007*; Fig. 12), with a greater amount of bat activity present when moon illumination was <33%.
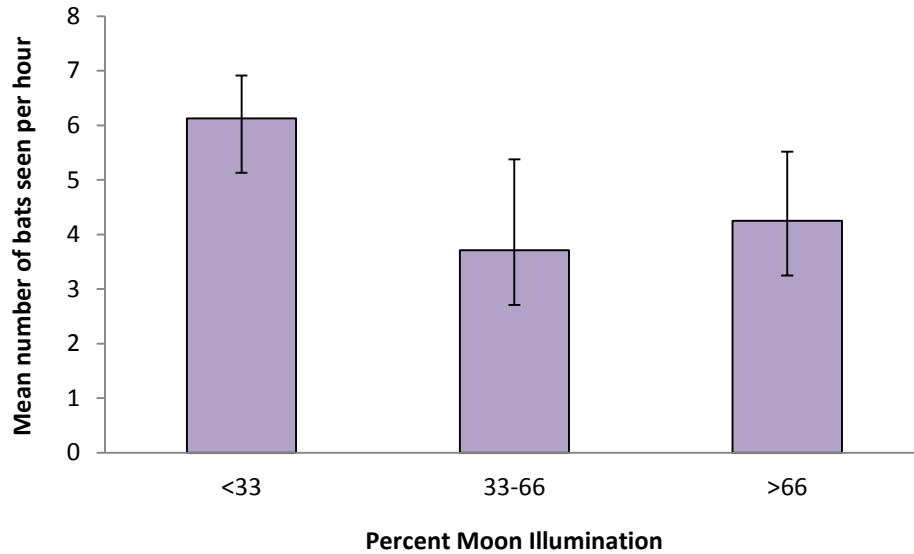
Figure 12. Mean number of bats seen per hour at wind turbines and water sources based on percent illumination of the moon at Wolf Ridge.

Bat behavior

Night vision observations confirmed that bats were drinking from water sources in a manner that was consistent with previous research (Tuttle et al. 2006, Razgour et al. 2010). We observed two distinct types of drinking behavior at water sources, one in which bats made contact with the surface in one quick motion and immediately flew away (Fig. 13A), and another in which bats were seen coming down and skimming along the water surface (Fig. 13B). We observed what appeared to be drinking by bats at wind turbine surfaces as well. Bats were recorded coming into contact with the surface of the turbine towers head-first. These bats swooped in making contact with the surface of the turbine in one quick motion (Fig. 13C), or they skimmed the surface of the turbine tower in a relatively straight line (Fig. 13D), before flying away.
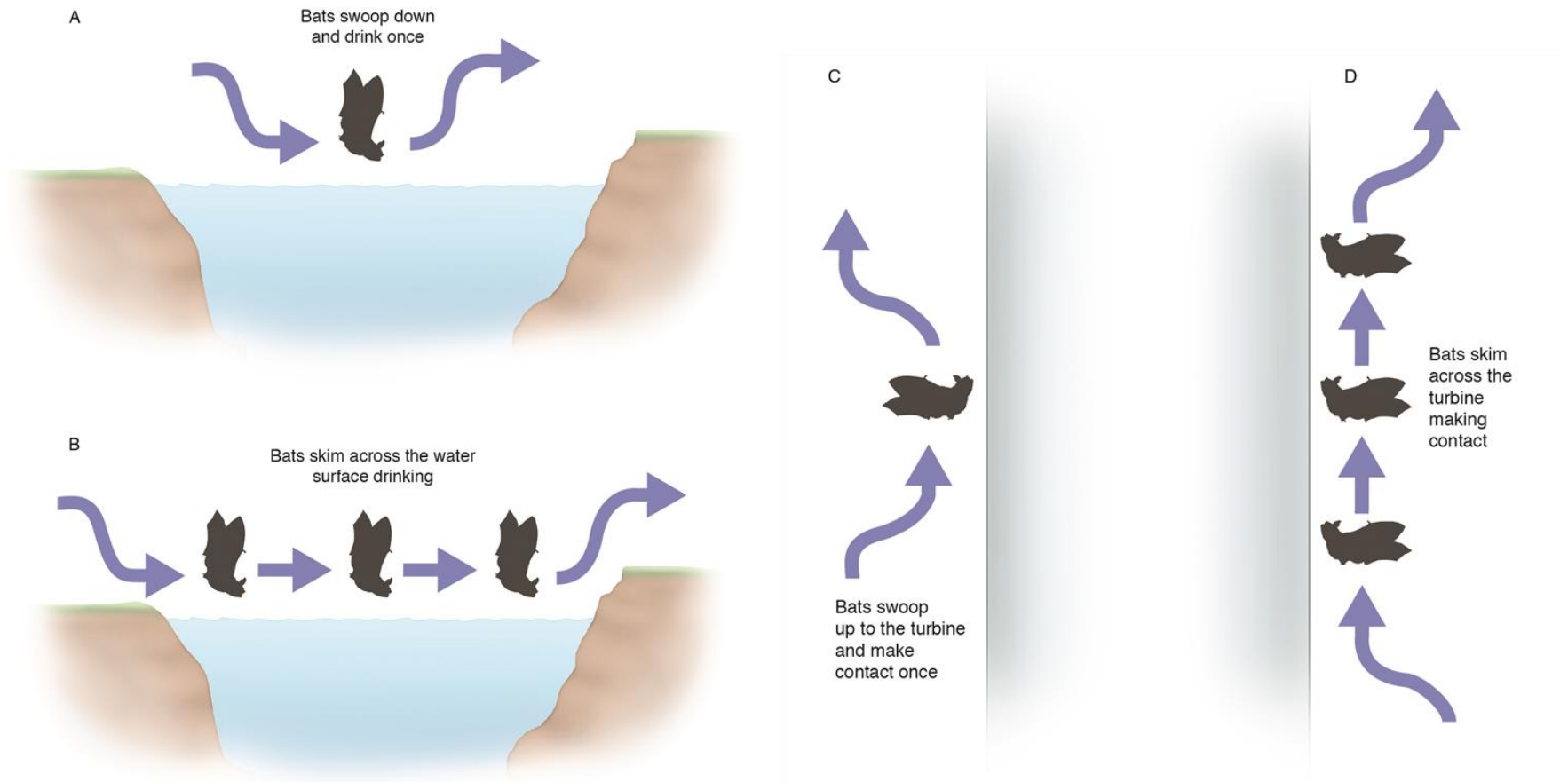
Figure 13. Illustration of drinking behavior at water sources and drinking attempts at wind turbines by bats. (A) Drinking behavior in which the bat makes contact one time with the surface of the water. (B) Drinking behavior in which the bat skims the surface of the water. (C) Drinking attempt in which the bat makes contact one time with the surface of the turbine. (D) Drinking attempt in which the bat skims the surface of a turbine.

Drinking at water sources and drinking attempts at turbines towers occurred at a much
lower frequency than passing and foraging for either water sources or wind turbine (Table 8 and Fig.
14). Among all zones at wind turbines, 17 of 479 (3.6%) bat observations were drinking attempts
while 10 of 276 (3.6%) bat observations at water zone 1 were drinking (zone 2 by default cannot
have drinking). However, the frequency of drinking attempts at wind turbines did not differ from
the frequency of drinking at water (Fisher's exact test, P = 1.00). Although, drinking behavior only
represented 3.6% of the activity seen by bats near the surface of wind turbine and water sources,
this contact rate is comparable to other studies (Jackrel and Matlack 2010). Additionally, we found
no significant difference in the proportion of drinking attempts between PM and AM session at
water sources (PM – 8 drinking events of 158 bat observations; AM – 2 drinking events in 118 bat
observations; Fisher's exact test, P = 0.20) or turbines (PM – 9 drinking events in 305 bat
observations; AM – 8 drinking events in 163 bat observations; Fisher's exact test, P = 0.30).

Table 8. Total number of bats seen in each zone at wind turbines and water sources at Wolf Ridge.

	Zone	Passing	Foraging	Drinking	Potential Drinking	Avoidance	Roosting
Turbines	**1**	78	47	.	1	.	4
	2	79	75	.	9	7	1
	3	24	144	.	7	3	0
	Total	181	266	.	17	10	5
Water	**1**	164	102	10	.	.	.
	2	261	231	.	.	.	.
	Total	425	333	10	.	.	.
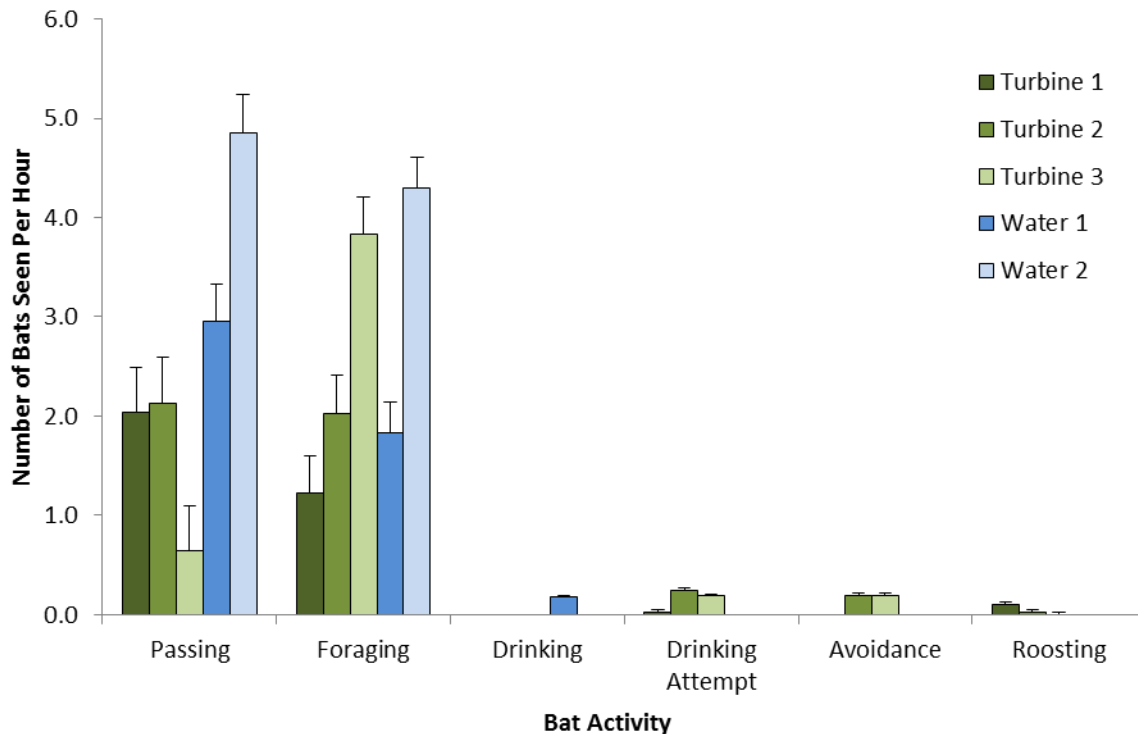
Figure 14. Hourly rates of bat passes, foraging activity, drinking attempts, and drinking seen using night vision technology at three turbine zones and two water zones at Wolf Ridge Wind, LLC. Observations of drinking attempts, avoidance, and roosting were restricted to turbines, whereas observations of drinking were restricted to water sources. See methods for descriptions of zones.

Passing activities accounted for a majority of the activity observed for both zones at water sources (425 of 768) with foraging activities being second most common (333 of 768). Among all zones at wind turbines, we observed more foraging activities (266 of 479) than passing activities (181 of 479). The proportion of foraging at wind turbines differed from the proportion of foraging at water (water- 333 foraging events of 758 bat observations (43.9%); turbine- 266 foraging events of 447 bat observations (59.5%); Fisher's exact test, P = 0.0002). In addition, the proportion of passing at wind turbines differed from the proportion of passing at water (water- 425 passing events of 758 bat observations (56.1%); turbine- 181 passing events of 447 bat observations (40.5%); Fisher's exact test, P = 0.0002). We found no significant difference in the proportion of passing activity between PM and AM session at water sources (PM – 281 passing events of 507 bat observations; AM – 144 passing events in 251 bat observations; Fisher's exact test, P = 0.73). At wind turbines, we

found a significant difference in passing activity between PM and AM sessions (PM – 131 passing

events in 292 bat observations; AM – 50 passing events in 155 bat observations; Fisher's exact test,

P = 0.046). However, this difference was marginal. Additionally, we found no significant difference

in the proportion of foraging activities between PM and AM session at water sources (PM – 226

foraging events of 507 bat observations; AM – 107 foraging events in 251 bat observations; Fisher's

exact test, P = 0.70) or wind turbines (PM – 161 foraging events in 292 bat observations; AM – 105

foraging events in 155 bat observations; Fisher's exact test, P = 0.10).

We observed avoidance maneuvers and roosting behavior at wind turbines, but the

frequency of occurrence was low and comprised <3% of total observed bat activity at wind turbines

(Table 8 and Fig. 14). Avoidance maneuvers were primarily seen in zone 2 (7 of 10 avoidance

observations) at the front of the nacelle but some bats (3 of 10 avoidance observations) were still

seen avoiding the blades from the rear of the nacelle in zone 3. We observed roosting behavior

primarily in zone 1 with bats either landing on or flying out from the lights, door, or transformer. In

one instance, we observed a bat appearing from the rotor hub; presumably it had been roosting on

the nacelle.

Acoustic monitoring

A total of 3,444 bat passes were recorded across the entire survey period. This equated to an

average of 3.5 bat passes per hour per detector for a total of 983 hours across 84 survey nights. Of

the bat passes recorded, 2,564 were recorded at the same time as night vision surveys were

conducted. Comparing water sources and wind turbine sites, we found significantly more bat passes

at water sources (mean ± SE = 5.8 ± 1.1 bat passes/hour/detector, n = 52 survey nights) than wind

turbine sites (mean ± SE = 0.8 ± 0.2 bat passes/hour/detector, n = 52 survey nights; Mann-Whitney

test: W = 1933.5, P < 0.0001). While the variation in acoustic activity at water sources and wind

turbine sites was comparable to the variation in observed activity recorded in night vision surveys, we found that the correlation between bats heard and bats seen was weak at best (Fig. 15).

Using Spearman rank correlations, we compared observed bats per hour in night vision surveys against bat passes per hour recorded in concurrent acoustic monitoring sessions at water sources and wind turbine sites. We found only a weak positive correlation in activity at water sources in the PM session and wind turbine sites in the AM, a very weak positive relationship at water sources in the AM, and a very weak negative relationship at wind turbine sites in the PM session (Fig. 15).
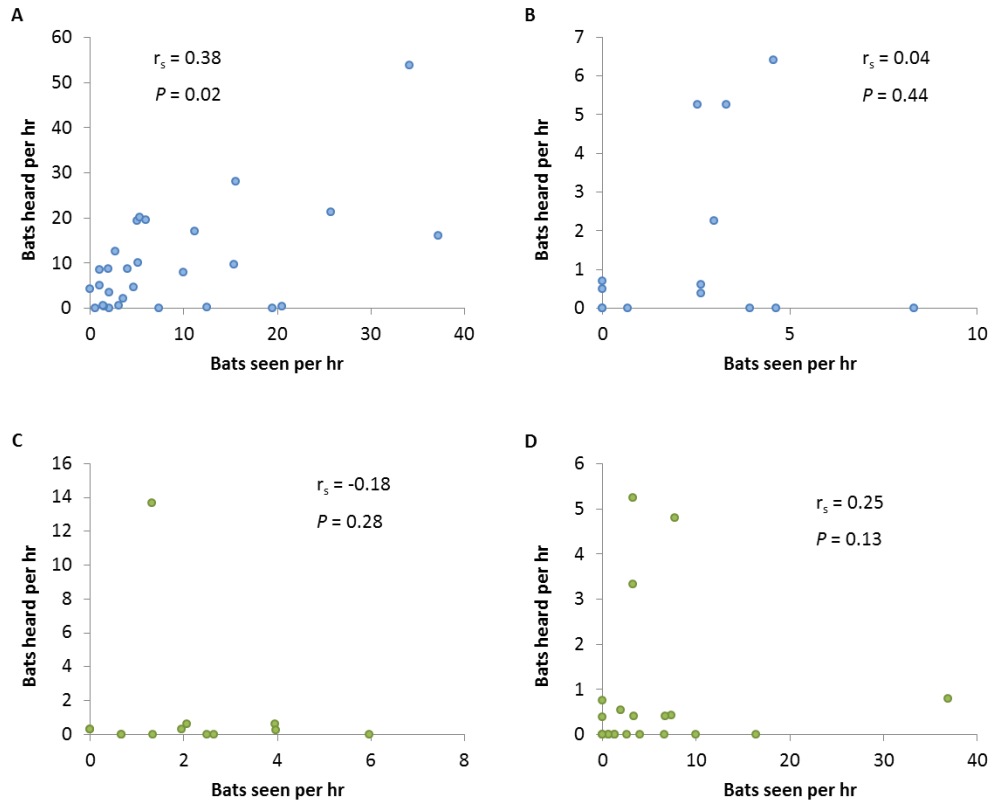
Figure 15. Scatterplots illustrating the relationship between number of bats heard per hour in acoustic monitoring to the number of bats seen per hour in concurrent night vision surveys at A) water sources in the PM session, B) water sources in the AM session, C) wind turbines sites in the PM session, and D) wind turbine sites in the AM session.

Temporally, we found that across a survey night (dusk until dawn), the rates of bat activity varied among all our sites. Across the survey sites, acoustic activity peaked at an average of 2 bat passes/hour/detector from 20:00 just after dusk to 21:00 (Fig. 16). However, apart from this initial peak in bat activity at water sources, there were no other distinct peaks in activity at either water sources or wind turbine sites. We also found that bats were more active at water sources than wind turbine towers in both PM and AM sessions (Mann-Whitney test for PM: W =2098, $n_{water} = n_{turbine} =$ 40 survey nights, P < 0.0001; Mann-Whitney test for AM: W = 1879.5, $n_{water} = n_{turbine} = 46$ survey nights, P = 0.028), although the magnitude of this difference was smaller in the AM sessions (Fig. 16). In addition, bats were more active at water in the PM session compared to the AM session (Mann-Whitney test: W = 2111.5, n_{PM} = 40 survey nights, n_{AM} = 46 survey nights, P = 0.001). This pattern was not evident at wind turbines (Mann-Whitney test: W = 1799.5, n_{PM} = 40 survey nights, n_{AM}= 46 survey nights, P = 0.57).
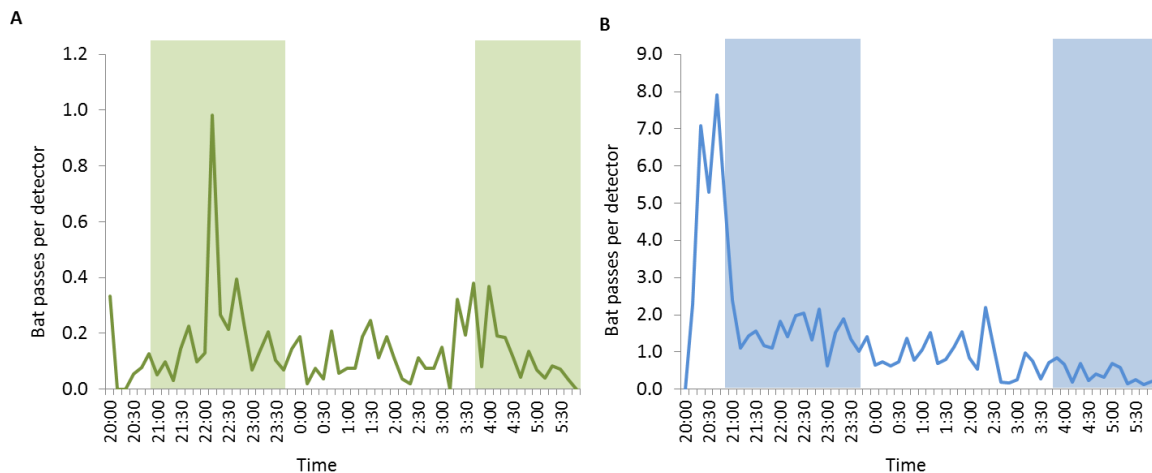
Figure 16. Acoustic activity levels (measured as bat passes/hour/detector) at A) wind turbine sites, and B) water sites from 22 May to 1 October 2012 at Wolf Ridge Wind, LLC. Colored bands indicate when night vision sessions were conducted.

When we compared weekly bat activity rates over the entire survey period (May to October), we found that at water sources there was a main peak in activity at the week starting 20 August 2012 during the fall migratory period and an equivalent peak at wind turbine sites (Fig. 17). However, the seasonal acoustic bat activity did not correspond to the seasonal activity rates observed in night vision surveys (i.e., peaks in activity were not equivalent; Fig. 17).
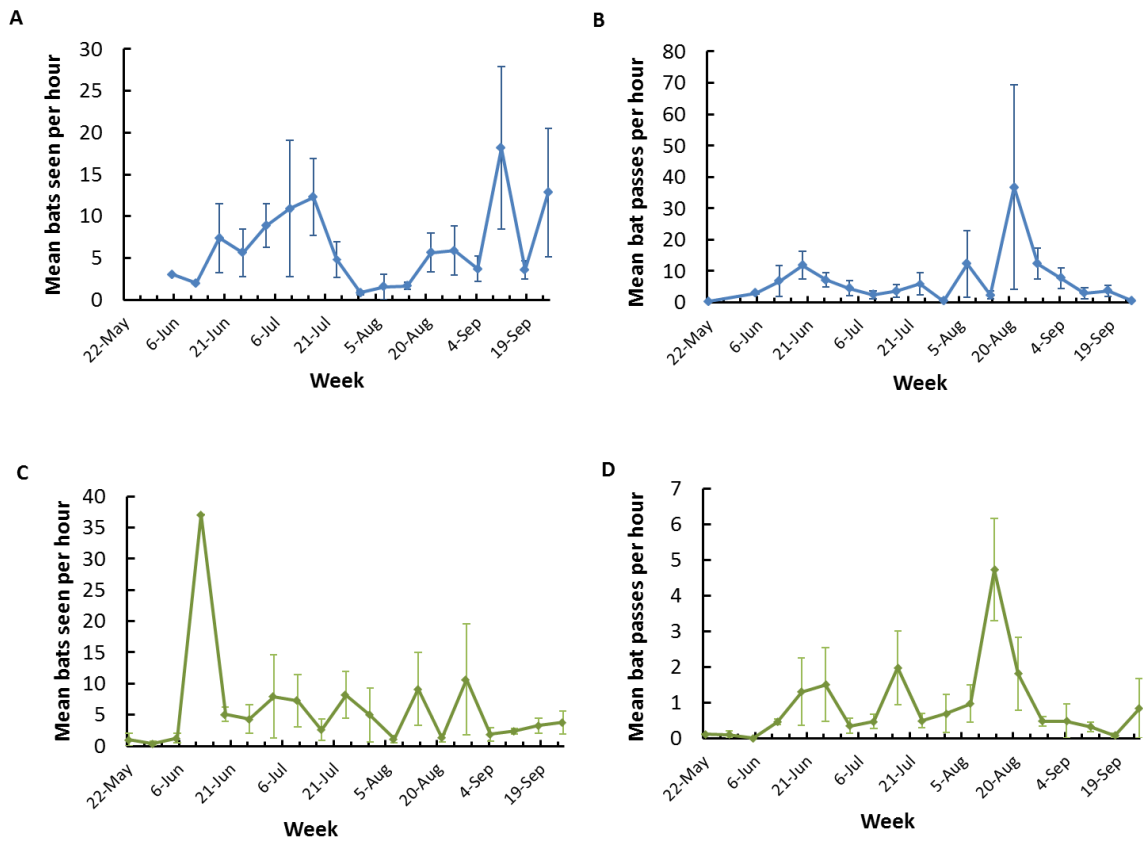
Figure 17. Changes in mean bat activity at water sources and wind turbines throughout the study season. (A) Mean (± SE) number of bats seen per hour in night vision surveys at water sources. (B) Mean (± SE) number of bats heard per hour in acoustic monitoring at water sources. (C) Mean (± SE) number of bats seen per hour in night vision surveys at wind turbines. (D) Mean (± SE) number of bats heard per hour in acoustic monitoring at wind turbines.

Across our survey period, we recorded bat passes for the six species known to be present within the wind resource area at both wind turbines and water sites (Table 9). The highest number of bat passes recorded across the entire survey period came from *Lasiurus borealis* with an average

of 1.6 bat passes/hour/detector, followed by *Nycticeius humeralis* with an average of 1.1 bat

passes/hour/detector. While activity was higher at water sites compared to the wind turbine sites

for the majority of species, species-specific activity at water sources predicted species-specific

activity at wind turbines (Fig. 18).

Table 9. Acoustic activity rates (mean number of bat passes per hour per detector) at water sources and wind turbines for each of the six species present at Wolf Ridge. The last two columns show the percentage of total bat activity at each location by species.

Species	Mean ± SE number of bat passes/hour/detector		Total % bat activity	
	Water	Turbine	Water	Turbine
Eastern red bat (*Lasiurus borealis*)	3.54 ± 0.91	0.34 ± 0.09	51.9	43.6
Hoary bat (*Lasiurus cinereus*)	0.03 ± 0.04	0.03 ± 0.05	0.4	4.5
Silver-haired bat (*Lasionycteris noctivagans*)	0.10 ± 0.05	0.02 ± 0.01	1.5	2.4
Tri-colored bat (*Perimyotis subflavus*)	0.54 ± 0.19	0.02 ± 0.06	7.9	3.0
Evening bat (*Nycticeius humeralis*)	2.49 ± 1.3	0.31 ± 0.10	36.6	39.8
Mexican free-tailed bat (*Tadarida brasiliensis*)	0.11 ± 0.09	0.05 ± 0.04	1.6	6.6
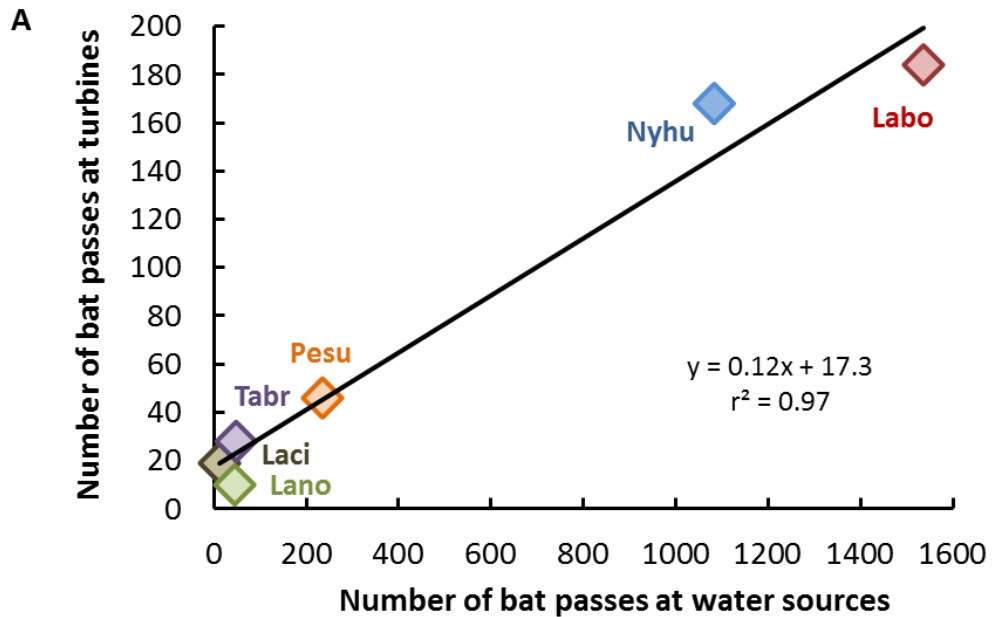
Figure 18. Relationship between acoustic activity at water sources and acoustic activity at wind turbines at Wolf Ridge in six species of insectivorous bats (Labo – *Lasiurus borealis*, Laci – *Lasiurus cinereus*, Lano – *Lasionycteris noctivagans*, Pesu – *Perimyotis subflavus*, Nyhu – *Nycticeius humeralis*, Tabr – *Tadarida brasiliensis*).

For individual species, acoustic activity was consistently higher at water sources compared to wind turbine sites throughout the night for every species (Fig. 19). As a result of this higher activity at water sources, it was possible to discern species-specific patterns in activity. While a synchronized peak in activity was observed between 20:00 and 21:20 comprising *Lasiurus borealis*, *Lasionycteris noctivagans*, *Perimyotis subflavus*, and *Nycticeius humeralis*, any other species-specific peaks in activity were asynchronous (i.e., different species were active at the sites at different times; Fig. 19).

Furthermore, when we specifically looked at species-specific activity rates across the survey period, we found that the two peaks of activity on the 18 June and 20 August were driven by *Lasiurus borealis* (Fig. 20). While each of the six species exhibited peaks in activity levels within our study period, the timing of these peaks varied by species.

A. *High frequency bats at water sources*

Legend:
- *Lasiurus borealis*
- *Nycticeius humeralis*
- *Perimyotis subflavus*

Y-axis: Bat passes per 10 min increment

X-axis: Time

B. *High frequency bats at wind turbines*

Legend:
- *Lasiurus borealis*
- *Nycticeius humeralis*
- *Perimyotis subflavus*

Y-axis: Bat passes per 10 min increment

X-axis: Time
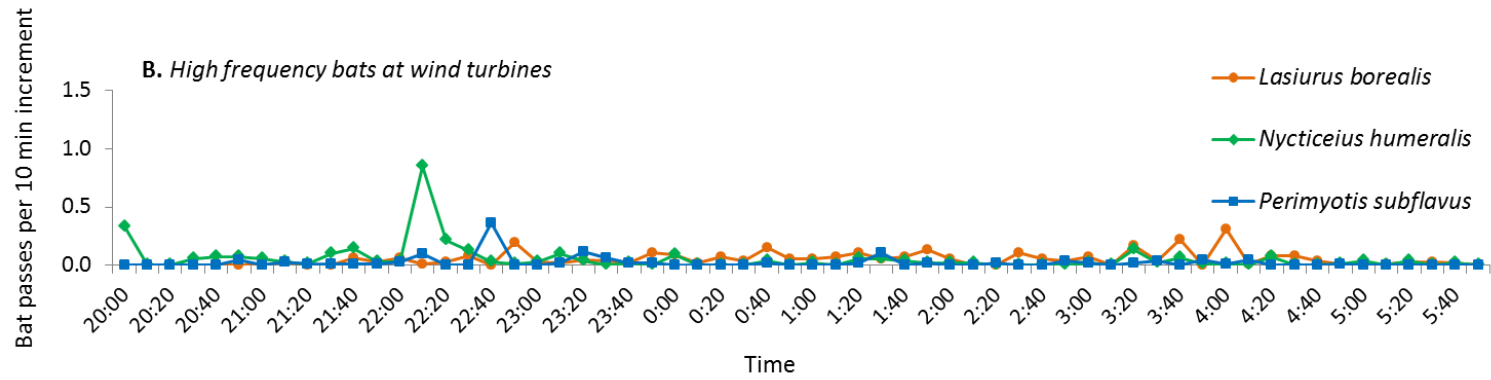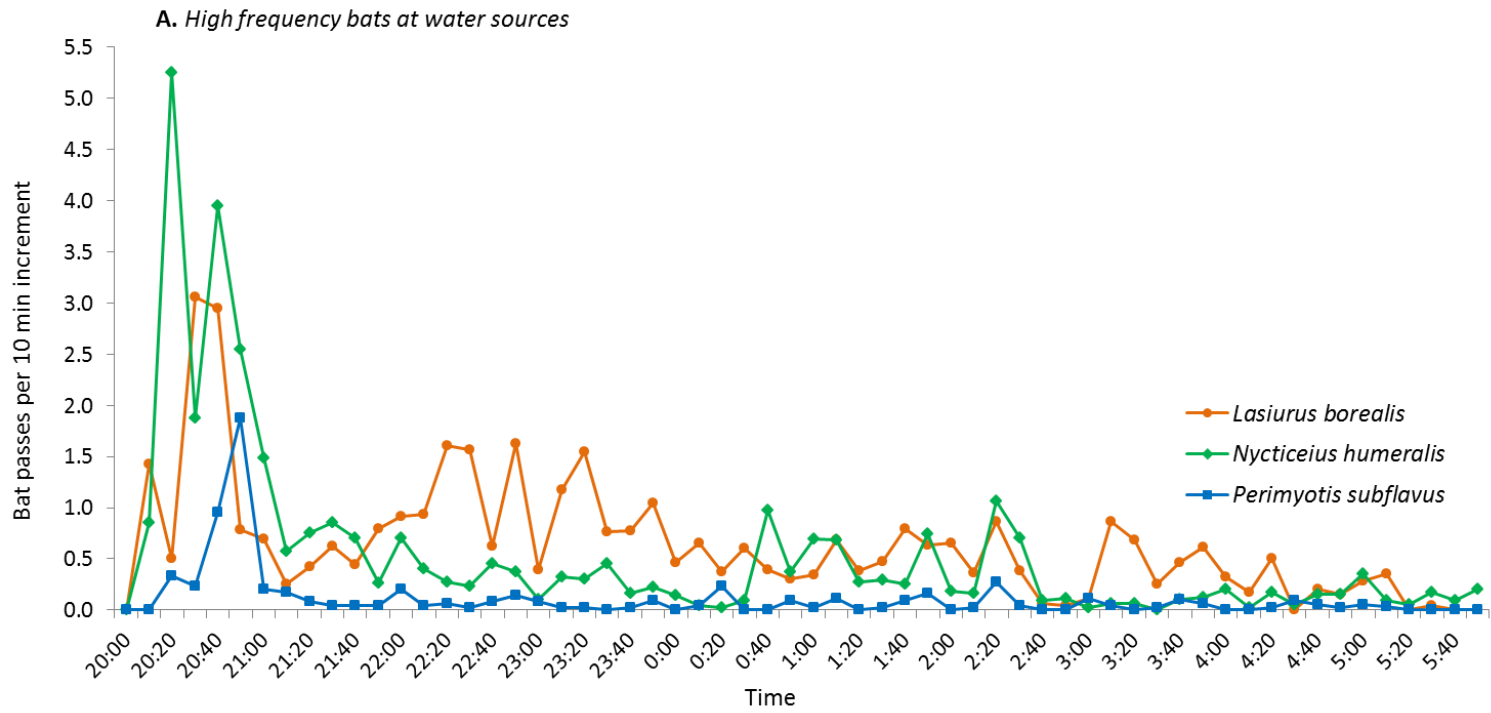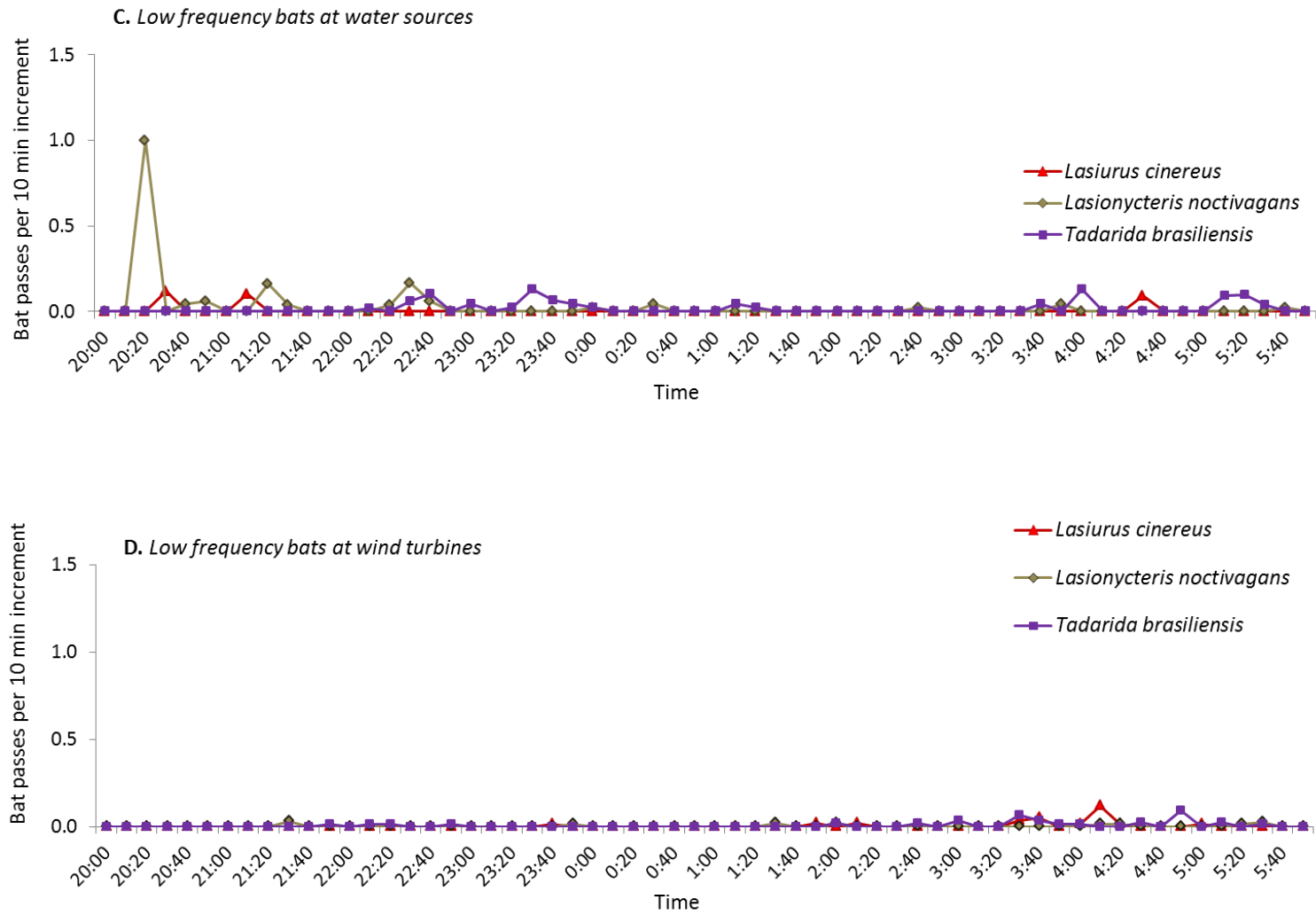
Figure 19. Mean number of bat passes per 10 min increment observed from dusk to dawn in acoustic monitoring for A) high frequency bats at water sources, B) high frequency bats at wind turbine sites, C) low frequency bats at water sources, and D) low frequency bats at wind turbine sites.
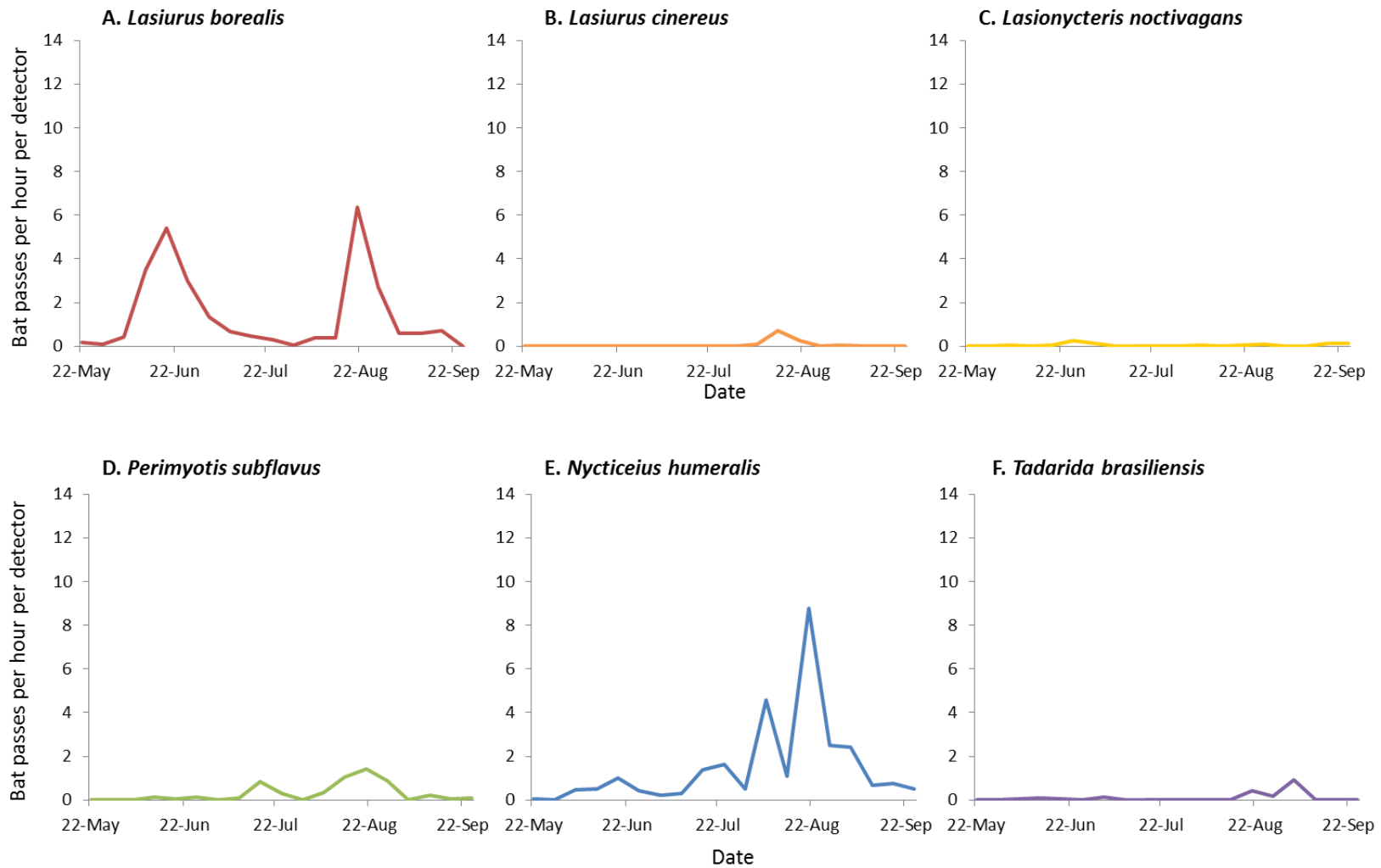
Figure 20. Acoustic activity measured as the total number of bat passes per hour per detector pooled across all survey sites for each of the six bat species present at Wolf Ridge over the survey period (12 May to 1 October 2012).

We recorded four acoustically distinct activities (commuting, searching, foraging, and feeding buzzes) at both water and wind turbine sites. Our analysis revealed that the frequency of most activities was significantly higher at water sources, but again each activity appeared to be exhibited at a proportionally similar rate at both water sources and wind turbine sites (Table 10).

Table 10. Mean rates of four acoustically distinct activities by bats at water sources and wind turbines at Wolf Ridge. The last two columns show the total percentage of acoustic activity by activity type and water and wind turbines survey sites.

Activity	Mean ± SE number of bat passes per hour per detector		Total % bat activity	
	Water	Turbine	Water	Turbine
Commuting	0.64 ± 0.18	0.06 ± 0.03	9.4	6.8
Searching	4.60 ± 1.76	0.41 ± 0.12	67.5	46.2
Foraging	1.31 ± 0.28	0.34 ± 0.06	19.2	38.8
Feeding buzz	0.26 ± 0.08	0.07 ± 0.03	3.8	8.2

For the call matching exercise, 708 bats were heard on video during night vision surveys (506 bats at water sources and 202 bats at wind turbines). We successfully matched 143 of these bats with bat echolocation calls recorded and identified to species in acoustic monitoring (125 bats at water sources and 18 bats at wind turbines). We confirmed that *Lasiurus borealis, Lasionycteris noctivagans, Perimyotis subflavus, Nycticeius humeralis, and Tadarida brasiliensis* were present in close proximity to both water sources and wind turbine tower surfaces when night vision surveys were being conducted.

Playback experiment

The results of the playback experiment suggest that water sources and wind turbine tower surfaces are acoustically indistinguishable from each other across the range of frequencies used by local bats. Among the four temporal and spectral characteristics that we analyzed, we found that f_{maxE} did not differ among the four tested surface types. This is not unexpected because f_{maxE} is determined by the frequency range of the source calls, and should therefore not have varied with surface type. In contrast, we found that both echo amplitude and echo entropy varied significantly with surface type.

Our playback experiment revealed that the hard smooth surfaces of the wind turbine towers produce echoes with reductions in amplitude comparable to water. Sound waves typically decrease in amplitude over time due to spherical spreading, but loss of acoustic energy can also be due to reflection scattering and absorption when a sound pressure wave reflects off of a surface (Ingard 1953, Stilz and Schnitzler 2012). The amount of energy lost therefore strongly depends on the structure and composition of the surface. For example, when echolocation calls strike a rough or irregular surface, more of the acoustic energy will be deflected rather than reflected back to the echolocating bat. As water is approximately 800 times denser than air, it provides a smooth homogenous surface for call reflection (Dodson 2005). Similarly, dense steel alloys also provide a smooth homogenous surface (Borsutzki et al. 2000), which explains the similar characteristics we observed between echoes from steel and water surfaces. In contrast to these smooth surfaces, both dirt and gravel surfaces produced quieter returning echoes. Irregularities in gravel and dirt surfaces lead to spherical spreading, and surface effects such as these influence sound propagation and enable echolocating bats to distinguish between textures (Siemers et al. 2005). Amplitude therefore plays a critical role in how bats are able to discriminate among different surfaces.

Our playback experiment also showed that the entropy of returning echoes did not vary between water and wind turbine surfaces and that rough surfaces have greater entropy and longer acoustic tails than smooth surfaces. Furthermore, the echo entropy was greatest in higher frequency source calls compared to lower frequency source calls. This finding is expected as high frequency calls are typically used by bats adapted to cluttered environments as the returning echoes from these calls provide high resolution information regarding the immediate surroundings (Schmieder et al. 2012, Geipel et al. 2013). Indeed, entropy is an important spectral characteristic that enables echolocating bats to distinguish texture and thus identify resources such as prey items.

Overall, we found very few differences in the spectral and temporal characteristics of returning echoes from water sources and those from wind turbine towers. While there may be other characteristics that bats use to discern differences among surfaces, water is the only naturally occurring surface that is perfectly smooth. Furthermore, Greif and Siemers (2010) demonstrated that bats have innate recognition of water that depends on its acoustically smooth surface and suggested that bats would attempt to drink from other smooth, man-made structures (such as vehicles), although it is unlikely that bats making this mistake will suffer fitness consequences or be killed in the process.

One potential limitation of our study is that we used synthetic calls as opposed to natural calls, in order to minimize noise and keep returning echo quality consistent. Alternatively, using natural calls would allow us to explore species-specific call characteristics that help bats detect and distinguish between surfaces in their immediate surroundings. To avoid or reduce inter-specific competition, different bat species have evolved to exist in discreet niches (Altringham 2011). One aspect of this niche partitioning is that bats have evolved species-specific call characteristics (for example, see Fig. 21). Among the bat species present at Wolf Ridge, some echolocation calls are frequency-modulated sweeps, whereas others are constant frequency calls or a combination of the

two call types. Furthermore, within an individual species or even an individual bat, the structure of

echolocation calls can vary based on function (e.g., social calls vs. foraging calls, foraging in more

cluttered or less cluttered environments, etc.; Altringham 2011). Furthermore, even among bat

species with similar shaped calls, spectral and temporal characteristics, such as f_{maxE}, and intensity

(i.e., creating harmonics), can vary. An area of further research, therefore, would be to repeat the

playback experiment in a sound-proof room using natural calls from local bats that had been

recorded in a noise-free environment (i.e., a sound-proof room).
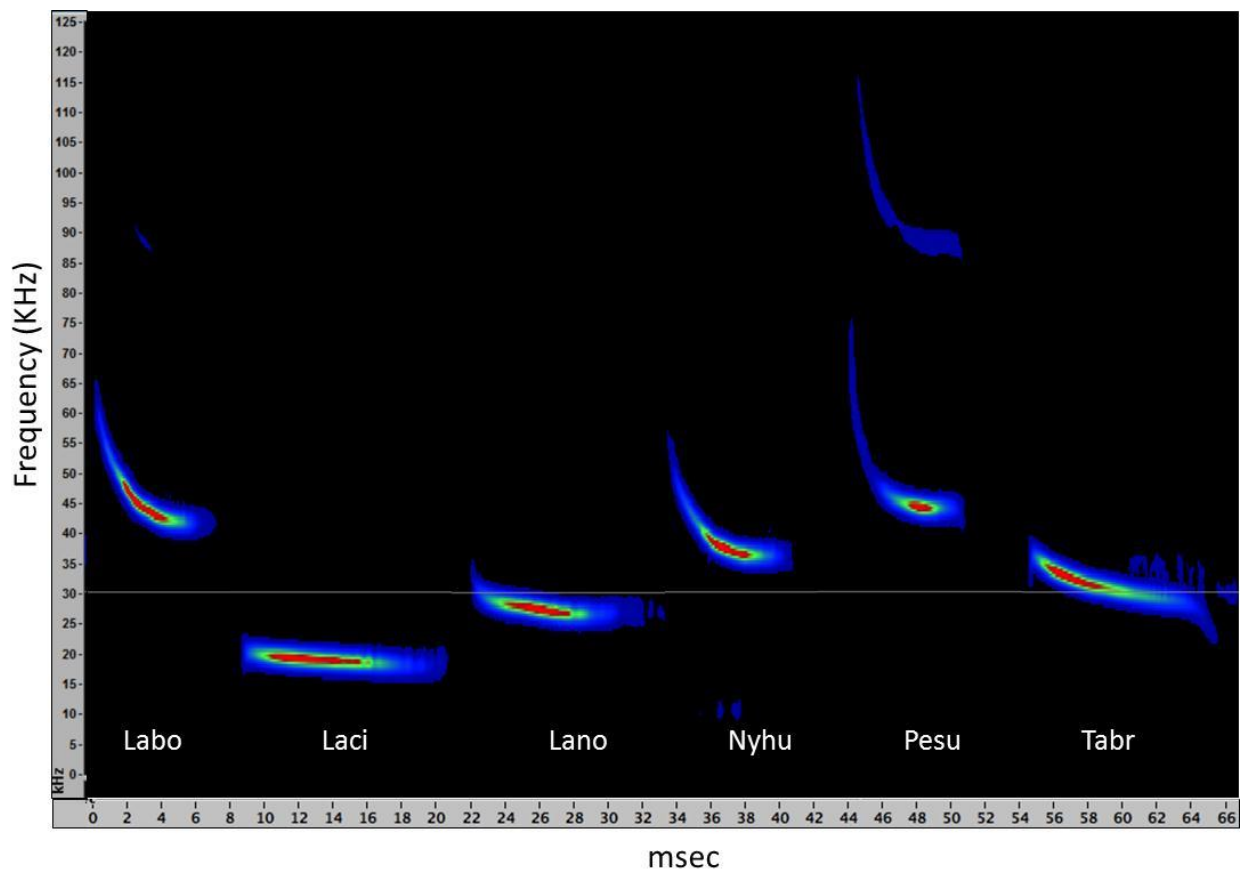

Figure 21. Spectrograms of representative echolocation calls recorded from the six bat species present at Wolf Ridge (Labo - *Lasiurus borealis*, Laci - *Lasiurus cinereus*, Lano - *Lasionycteris noctivagans*, Pesu - *Perimyotis subflavus*, Nyhu - *Nycticeius humeralis*, and Tabr - *Tadarida brasiliensis*. The spectrograms were produced using Sonabat software.

Night vision surveys

Drinking behavior at water resources and drinking attempts at wind turbine towers accounted for 3.6% of the bat activity recorded at each location. Although these drinking and attempted drinking rates are a small fraction of the bat activity we observed, they are comparable to the drinking rates recorded in other studies (Tuttle et al. 2006, Jackrel and Matlack 2010) and suggest that wind turbines are providing a similar resource or perceived resource as the cattle ponds at Wolf Ridge. Our findings are further supported by a study by Razgour et al. (2010) in which an individual echolocating bat was observed taking multiple passes over water before engaging in drinking behavior. This high level of passing activity coupled with foraging activity above the surface of the water would undoubtedly lead to the relatively low rates of drinking that we observed. Furthermore, the similarity in foraging rates between water sources and wind turbine towers suggest that both surfaces provide similar foraging opportunities. A study by Siemers et al. (2001) found that insectivorous bats can more readily catch prey items flying above the surface of a water body than prey items flying in a cluttered environment (i.e., in a woodland). They suggested that the smooth reflective surface of the water acts as an acoustic mirror enabling bats to better distinguish prey targets from the background environment (Siemers et al. 2001). As all the species known to be present at our study site are aerial hawkers (i.e., a foraging strategy that involves bats catching prey items on the wing (Ammerman et al. 2012)), bats may be foraging at water sources to take advantage of the acoustic mirror effects. Therefore, if wind turbine towers have similar acoustic properties it is possible that bats are foraging in proximity to wind turbine towers for the same reason.

At wind turbines, in instances where bats were observed making contact with the turbine tower, this behavior could be perceived as gleaning, a foraging strategy employed by some insectivorous bats in which prey items are captured from surfaces in the environment (Geipel et al.

2013). Nevertheless, this type of foraging strategy is typically associated with morphological and

acoustic adaptations not seen in the bats at our study site, and is commonly observed in species that

forage in very cluttered environments (e.g., northern long-eared bat (*Myotis septentrionalis*; (Faure

et al. 1993, Faure and Barclay 1994, Andreas et al. 2012). Although it is possible that individual bats

could switch between foraging strategies (i.e., gleaning to aerial hawking; Todd and Waters 2007),

none of the local bat species relies on gleaning as a primary foraging strategy. Furthermore,

gleaning bats typically hover or exhibit zigzagging flight with multiple turning angles just prior to

making contact with a surface on which they capture prey. These bats do not swoop in head first or

skim the surface of objects in their environment (Entwistle et al. 1996, Geipel et al. 2013).

Additionally, the bats that we observed making drinking attempts at the turbine towers positioned

their bodies parallel to the turbine tower prior to contact. When bats drink from water sources,

their heads are positioned toward the surface and their ventral surface is orientated parallel to the

surface (Tuttle et al. 2006). This similarity in posture and approach suggests that bats are confusing

the turbine tower surfaces to be water. By orientating their bodies parallel to the wind turbine

tower surface, bats could be picking up their returning echoes in the same manner as they would

from water.

Furthermore, our findings may therefore help explain why migratory bat species

predominately comprise fatalities at wind facilities in North America (Baerwald and Barclay 2009,

Piorkowski et al. 2012). Migrants may be likely to misidentify wind turbine surfaces as water during

migratory periods when they are actively seeking water sources in unfamiliar habitats. While bats

may be able to apply a "fly-and-forage strategy" en-route (i.e., foraging during active migration),

they cannot employ the same strategy to acquire water (Suba et al. 2012). Instead, migrating bats

have to actively fly down to water sources to drink. Migratory bats may therefore be coming into

the area to find water *en route*, and coming into close proximity to wind turbines because they

perceive their smooth surfaces to be water. As little is known about the finer scale movements and behavior of bats during migration, we can only speculate that the bats' initial assessment of features in the landscape is based on vision (Fleming and Eby 2003).

It is generally acknowledged that bats tend to be less active on high illumination nights (i.e., full moon nights), because bats in flight are more visible and therefore susceptible to predation under this condition (Schaub and Schnitzler 2007, Thomas and Jacobs 2013). However, very few studies have been able to verify this phenomenon (Hayes 1997, Santos-Moreno et al. 2010). Although we found that bat activity at wind turbines and water sources was highest on low moon illumination nights, the large amount of variation in bat activity can likely be explained by a combination of factors that includes variation in insect abundance and emergence, weather patterns, and seasonal occupancy of migrating bats (Hayes 1997, Baerwald and Barclay 2011).

Acoustic monitoring

Our acoustic monitoring data further suggests that bats are behaving at wind turbines as if the turbines were a resource. The observed difference in acoustic activity rates at water sources and wind turbine sites confirms that water sources are a primary resource for bats, especially at dusk when bats first emerge from their roosts and appear to fly directly to water. This is not surprising as our study site is located in a very arid, hot environment with daytime temperatures reaching 46 °C during the peak of fall migration when more tree bats are present in the area (Cryan 2003). Thus bats will need, as a priority, to seek water to rehydrate after emerging from their roosts. Furthermore, it is likely that the bats that fly to water sources at dusk are residents in the area; they are familiar with the site and know the locations of key resources. In contrast, migrants are less likely to be familiar with the area, and certainly while in transit will seek out water regularly throughout the night. Our data support this hypothesis as nightly activity patterns indicate that

there may be a mix of resident and migrating bats at wind turbines and cattle ponds. For example, we found a peak in acoustic activity at cattle ponds at dusk (likely due to resident bats) and then we recorded low, but steady levels of acoustic activity across the remainder of the night at both water sources (potentially residents and migrants) and wind turbines. For the latter, we would not expect to see this pattern of activity from bats that are familiar with the area. Instead it is likely to be migrating individuals that are unfamiliar with the area and are coming in proximity with the wind turbines because they perceive them to be a resource. These findings are further supported by seasonal activity patterns, as we recorded large peaks in acoustic activity at both water sources and wind turbines which coincided with the annual fall migration of bats through the area (Cryan 2003, Arnett and Baerwald 2013, Hale unpublished data). Thus, the temporal variation in acoustic bat activity rates gives further support that bats perceived wind turbines as a resource.

The question is therefore, what type of resource do wind turbines represent? As a foraging resource, we would expect bat acoustic activity patterns to coincide with changes in insect abundance. A bimodal pattern in insect abundance when insect activity peaks at dusk and just before dawn was first reported in a study by Hayes (1997). This study was also the first to show that bat nightly foraging activity follows this bimodal pattern (Hayes 1997). As we did not observe this bimodal pattern in our bat acoustic activity, it is unlikely that bats in close proximity to water surfaces and wind turbine tower surfaces are primarily foraging. Thus, if bats were predominantly trawling insects off water surfaces or gleaning insects off wind turbine tower surfaces, we would have recorded higher acoustic rates of activity at these surfaces at dusk and just before dawn, which we did not. As these surfaces do not appear to represent key foraging sites, it supports our hypothesis that wind turbine towers could be perceived by bats as water resources.

Moreover, our acoustic analysis revealed that all six bat species known to be present in the area were active in close proximity to both water surfaces and wind turbine tower surfaces, and that

acoustic activity at cattle ponds was a good predictor of acoustic activity near wind turbines. This finding suggests that different bat species perceive wind turbines to be water sources (i.e., they provide a similar resource).

Among the types of bat acoustic activity recorded, we found four acoustically distinct behaviors at both water sources and wind turbines, and that the percent activity for each behavior appeared to be equivalent between wind turbines and cattle ponds. This proportional similarity in activity further demonstrates that bats were exhibiting comparable patterns of behavior at wind turbines as they did at water sources, and thus treating them as a similar resource. Moreover, we recorded feeding buzzes at both surfaces. Commonly, this type of call is associated with foraging, as bats hone in on target prey. However, a recent study has shown that bats drinking from water sources emit similar terminal buzzes as they approach the water surface (Griffiths 2013). Therefore, the feeding buzzes that we recorded at water surfaces are likely to have been emitted when bats were approaching that water surface to drink. As we also recorded feeding buzzes at the surface of wind turbine towers, this strongly suggests that bats are approaching these surfaces in a similar manner to the water surfaces because they perceive the wind turbine tower surfaces to be water.

Finally, if water sources and wind turbines are so similar, why did we not find a correlation between the number of bats seen in night vision surveys and the number of bats passes recorded in acoustic monitoring surveys that were conducted simultaneously? There are a number of possible explanations for this discrepancy: 1) night vision units can record bats at a greater distance (>80 m field of view) than the acoustic detectors (<30 m detection range); 2) bats do not necessarily echolocate continuously (personal observations); and 3) the acoustic detectors were set up to record calls from water and wind turbine surfaces specifically and the area covered by the detectors at wind turbine towers was much smaller than the area covered at the cattle ponds.

Conclusion

Overall, our study provides strong evidence that bats are coming into contact with wind turbines because they misidentify the smooth turbine tower surfaces to be water. The playback experiment confirmed that returning echoes from turbine towers were comparable to echoes returning from water and supports previous findings that bats cannot distinguish between water and other smooth, manufactured surfaces using echolocation. Furthermore, night vision surveys verified this finding, as bats were observed coming into contact with wind turbine tower surfaces while mimicking the approach and posture of bats drinking at water sources. This behavior revealed that bats were actively attempting to drink from wind turbine surfaces. Additionally, the frequencies of foraging and passing were comparable between sources. This suggests that different types of bat activity near wind turbines, not just drinking, are reflective of activities observed over a water source. Bats may therefore be coming into contact with wind turbines because they misidentify the smooth metal surfaces of turbine towers to be water. In conclusion, if the similarity in ultrasound echoes returning from water surfaces and wind turbine towers is a contributing factor to bat-wind turbine collisions, then any steps to reduce the similarity of the wind turbine surfaces to water should reduce bat fatality rates at wind resource facilities.

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VITA

Personal Aaron Michael McAlexander
Background Charlestown, Indiana
Son of Michael & Ann McAlexander

Education

2004 Diploma, Charlestown High School, Charlestown, IN
2008 Bachelor of Science, Fisheries and Aquatic Sciences, Purdue University,   West Lafayette, IN
2013 Master of Science, Biology, Texas Christian University, TX

Experience

2012-Present Teaching Assistantship, Texas Christian University
2009-2012 Product Spokespersons, Maurice Sporting Goods
2011 (Jul-Dec) Field Technician, Texas Christian University
2011 (Apr-Jul) Field Technician, Oregon State University
2010 & 2011 (Feb-Mar) Field Technician, Oregon Dept. of Fish & Wildlife
2010 (May-Dec) Natural Resources Specialist 1, Oregon Dept. of Fish & Wildlife
2009 (Mar-Oct) Fisheries Naturalist Aide, Indiana Dept. of Natural Resources
2008 (May-Jun) Teaching Assistant, Purdue University
2008 (Jan)- 2009 Fisheries Laboratory Technician, Purdue University
2007 (Aug-Dec) Wildlife Technician, Purdue University
2007 (May-Aug) Fisheries Naturalist Aide, Indiana Dept. of Natural Resources
2006 (Jan)-2007 Fisheries Technician, Purdue University

Publications

Hale, A., A. McAlexander, V. Bennett, B. Cooper. In revision. Evidence that bats perceive wind turbine surfaces to be water. PLoS ONE.

Presentations

Hale, A., A. McAlexander, V. Bennett, B. Cooper. 2013. A test of a novel attraction hypothesis: why are bats attracted to wind turbines? The Wildlife Society Conference. Milwaukee, WI.

McAlexander, A., A. Hale, V. Bennett. B. Cooper. 2013. Do bats perceive wind turbines to be water? Michael and Sally McCracken Student Research Symposium. Texas Christian University. Ft. Worth, TX. *Awarded 1st Place Graduate Student Poster

McAlexander, A., L. Lee, R. Goforth, and M. Sepulveda. 2008. Impacts of concentrated animal feeding operations on fish communities. 69th Midwest Fish and Wildlife Conference. Cincinnati, OH. *Awarded Best Student Poster

Awards

2013 $400- The Wildlife Society travel grant
1st place graduate student poster, Texas Christian University
2008 $500- undergraduate research grant, Purdue University
Best Student Poster, 69th Midwest Fish and Wildlife Conference

Professional Memberships

The Wildlife Society

ABSTRACT

EVIDENCE THAT BATS PERCEIVE WIND TURBINE SURFACES TO BE WATER

by Aaron Michael McAlexander, M.S. 2013
Department of Biology
Texas Christian University

Thesis Advisor: Dr. Amanda M. Hale, Associate Professor of Biology

Committee Members: Dr. Dean A. Williams, Associate Professor of Biology

                             Dr. Brenton G. Cooper, Associate Professor of Psychology

Large numbers of migratory tree bats are being killed at wind energy facilities across North America, and this rapidly growing source of renewable energy may pose a threat to bat populations. In 2012 and 2013 we conducted an ultrasound playback experiment, night vision surveys, and acoustic monitoring to determine if bats could be attracted to the smooth wind turbines surfaces because they perceive them to be water. Our playback experiment revealed little or no differences in the physical characteristics of echoes reflected from water and turbine surfaces. Our video and acoustic surveys indicated that bats behave at wind turbines as they do around water sources. Moreover, we observed bats attempting to drink from turbine towers at rates similar to water sources. Our data suggest that bats may be attracted to wind turbines because the surfaces produce an acoustic signature that is indistinguishable from water.