ASSESSING CHANGES IN BAT ACTIVITY IN RESPONSE TO AN ACOUSTIC DETERRENT — IMPLICATIONS FOR DECREASING BAT FATALITIES AT WIND FACILITIES

by

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Introduction

The release of greenhouse gasses, such as carbon dioxide, through the burning of fossil fuels is resulting in substantial changes to the climate (Cox et al. 2000). Climate change is occurring at a global scale and is affecting the distribution of a wide range of species (Parmesan and Yohe 2003). Renewable energy resources, such as wind power, provide alternatives to the burning of fossil fuels for electrical energy production (USDOE 2015). Wind energy is increasing due to the high potential power production levels, stable pricing, and economic benefits; the benefits of wind energy also include reduced water consumption compared to other energy sources (USDOE 2015). Wind power generating capacity is rapidly expanding within the United States, with the U.S. Department of Energy having a goal of 20% of electrical power produced through wind energy by the year 2030 (USDOE 2008). Wind is the fastest growing electrical energy generation source in the U.S., with a 12% increase in overall capacity in 2015; wind energy accounted for 5.6% of total electricity production in the U.S. during 2015 (Wiser and Bolinger 2016). Texas leads the U.S. in wind power generation, with a total of 17,711 megawatts of generating capacity in 2015 (Wiser and Bolinger 2016). The expansion of wind energy is expected to reduce the production of greenhouse gasses by 14% by the year 2050 (USDOE 2015). Wind turbines generate power locally and can create jobs in rural areas with extensive wind resources, such as in north Texas, generating 88,000 full time jobs in the U.S. in 2015 (Wiser and Bolinger 2016). Although wind energy has many benefits, one of the environmental impacts associated with wind facilities involves bats (Arnett and Baerwald 2013, Hein and Schirmacher 2016).

Bats are killed when they encounter spinning wind turbine blades, and high fatality rates have been observed and estimated across the U.S. and Canada (Arnett et al.2008, Hayes 2013, Huso and Dalthorp 2014, Zimmerling and Francis 2016). The patterns of bat fatalities at wind facilities vary during the season, with higher fatality rates in the fall, and also spatially among wind facilities, with fatality rates generally higher in the east and mid-west than in western states (Hein and Schirmacher 2016, Arnett and Baerwald 2013). Weather also affects the levels of bat fatalities, with higher bat fatalities associated with lower wind speeds (Arnett and Baerwald 2013, Cryan et al. 2014).

The reasons why bats approach wind turbines are largely unknown, but may include searching for foraging or roosting resources (Cryan et al. 2014). There could also be a correlation between the migratory routes used by bats, and the locations where wind turbines are constructed. The hoary (*Lasiurus cinereus*), eastern red (*Lasiurus borealis*), and silver-haired (*Lasionycteris noctivagans*) bats are migratory species, and these three species are the most commonly killed by wind turbines (Arnett and Baerwald 2013, Zimmerling and Francis 2016). Although not all bat species are affected equally, the combination of high bat fatality rates associated with wind energy, and other sources of bat fatalities such as the fungal infection known as white-nose syndrome, caused by the fungi *Pseudogymnoascus destructans*, places the population status of many North American bat species in question (Rodhouse et al. 2015, Frick et al. 2017). Bat population sizes are largely unknown for most species, however, considering that bat populations are characterized by high adult survival rates and low annual reproduction, fatalities from wind turbines are likely resulting in population declines (Barclay and Harder 2003, Hein and Schirmacher 2016, Frick et al. 2017).

Currently, mitigation options that can reduce bat fatalities caused by wind turbines include siting restrictions and curtailment (Arnett et al. 2011, Baerwald 2008, USFW 2012). Siting restrictions limit the location where wind facilities are constructed due to the presence of known bat resources, such as roost, foraging, or commuting areas of endangered species. The U.S Fish and Wildlife Service recommends buffers where no wind turbines are constructed around identified priority habitats for the endangered Indiana bat (*Myotis sodalis*), in order to minimize the potential for fatalities (USFW 2011). There is also evidence that migratory bats use select migration routes, thus, avoiding the placement of wind turbines in migratory corridors could also reduce fatalities (Baerwald and Barclay 2009). These siting restrictions limit the installation of turbines in otherwise suitable locations for the generation of wind energy, limiting wind energy generating capacity. The second form of mitigation is curtailment, which involves slowing or stopping turbines from spinning during times when they are most likely to kill bats. Wind turbines can continue to spin when wind speeds are too low to generate energy. However, most bats are killed during these low wind periods (Arnett et al. 2008). Previous studies have demonstrated that curtailment, through raising the wind speed when the turbines start spinning, or by reducing rotor speeds when turbines are not producing energy, can reduce bat fatalities by over 50% (Arnett et al. 2011, Baerwald et al. 2008, Martin et al. 2017). Wind turbines are being constructed taller with longer blades, and are able to produce energy at lower wind speeds (USDOE 2015), which may result in increased levels of bat fatalities due to the association between bat fatalities and low wind speeds. Curtailment of these more efficient turbines could therefore be more expensive, as there would be more lost power generating potential at low wind speeds. Although siting restrictions and curtailment can minimize bat fatalities, they also affect wind energy production (Arnett et al. 2011, Baerwald 2008, Martin et al. 2017, USFW 2012). For this reason, it would be beneficial to develop mitigation options that would reduce bat fatalities caused by wind turbines, without reducing wind energy generating capacity.

A possible solution for reducing bat fatalities, which does not decrease wind energy production, is deploying acoustic deterrents (deterrents) on wind turbines. Deterrents produce ultrasound, which overlaps with the frequency range of bat echolocation calls. Bats use echolocation to navigate and forage in the dark, and the sound produced by a deterrent is intended to disrupt bats ability to echolocate. Thus, if bats encounter the sound produced by a deterrent installed on a wind turbine and decide to avoid the area, fatalities may be avoided. Previous studies have demonstrated the potential for deterrents to reduce bat activity and fatalities (Szewczak and Arnett 2007, Arnett et al. 2013). Deterrents used during these studies had some limitations, including insufficient coverage of the area around the turbines with ultrasound at a high enough amplitude to effectively deter bats, and weather sensitive electronic equipment that resulted in equipment failures (Arnett et al. 2013). For these, and possibly other reasons, previous deterrents did not reduce fatalities as effectively as siting restrictions or curtailment (Arnett et al 2013). There is, therefore, a need to develop a deterrent that is weatherproof, with increased sound coverage around the wind turbines.

In 2015, we partnered with General Electric (GE) to assist with the development and testing of a pneumatic acoustic deterrent prototype. The design attempts to resolve limitations associated with other deterrents by using compressed gas that is expelled through a custom manufactured nozzle. This deterrent produces multidirectional, broadband, high amplitude ultrasound. The use of compressed gas and nozzles avoids exposing electronic equipment to harsh environmental conditions, with the goal of improving reliability. The deterrent was also designed to pulse on and off, because pulsing may allow for the deployment of additional deterrent nozzles on a single turbine, to improve sound coverage.

In 2015 and 2016, we conducted a ground test of the deterrent at a wind facility in north-central Texas to determine whether the deterrent has the potential to reduce bat fatalities at wind turbines. We performed a paired study at wind turbines and closely associated cattle ponds in 2015. This study provided a comparison between habitat types to determine if bats respond differently to the deterrent while flying near a water source, a known resource for drinking and foraging, compared to flying near a turbine. Research questions during 2015 included: 1) does the deterrent change bat activity/behavior, 2) does bat activity/behavior change with the type of signal produced by the deterrent, 3) does bat activity/behavior change with habitat type, and 4) does bat activity/behavior change with distance from the deterrent? Then, in 2016, we conducted a more focused study of deterrent effectiveness at cattle ponds only. Research questions during 2016 included: 1) does the deterrent change bat activity/behavior, 2) does bat activity/behavior change with the type of signal produced by the deterrent, and 3) does bat activity/behavior change seasonally?

Methods

Study Site

We conducted the field study during 2015 and 2016 at Wolf Ridge Wind, LLC (Wolf Ridge), which is owned and operated by NextEra Energy Inc. in Cooke County, Texas (N 33.72911°, W 97.393545°; Figure 1). This facility began operations in October of 2008 and consists of 75 GE 1.5-MW wind turbines with 80 m towers, 42 m blades, and maximum vertical blade heights of 122 m above ground. The land around the turbines is generally cattle pastures and hayfields with some shrub-woodland habitat. Texas Christian University (TCU) has been investigating bat fatality rates at turbines, potential reasons that bats are approaching turbines, and mitigation measures to reduce bat fatalities at the Wolf Ridge since 2009. Bat species previously documented on Wolf Ridge include hoary, eastern red, silver-haired, tricolored (*Perimyotis subflavus*), evening (*Nycticeius humeralis*), and Mexican free-tailed bats (*Tadarida brasiliensis*; McAlexander 2013).

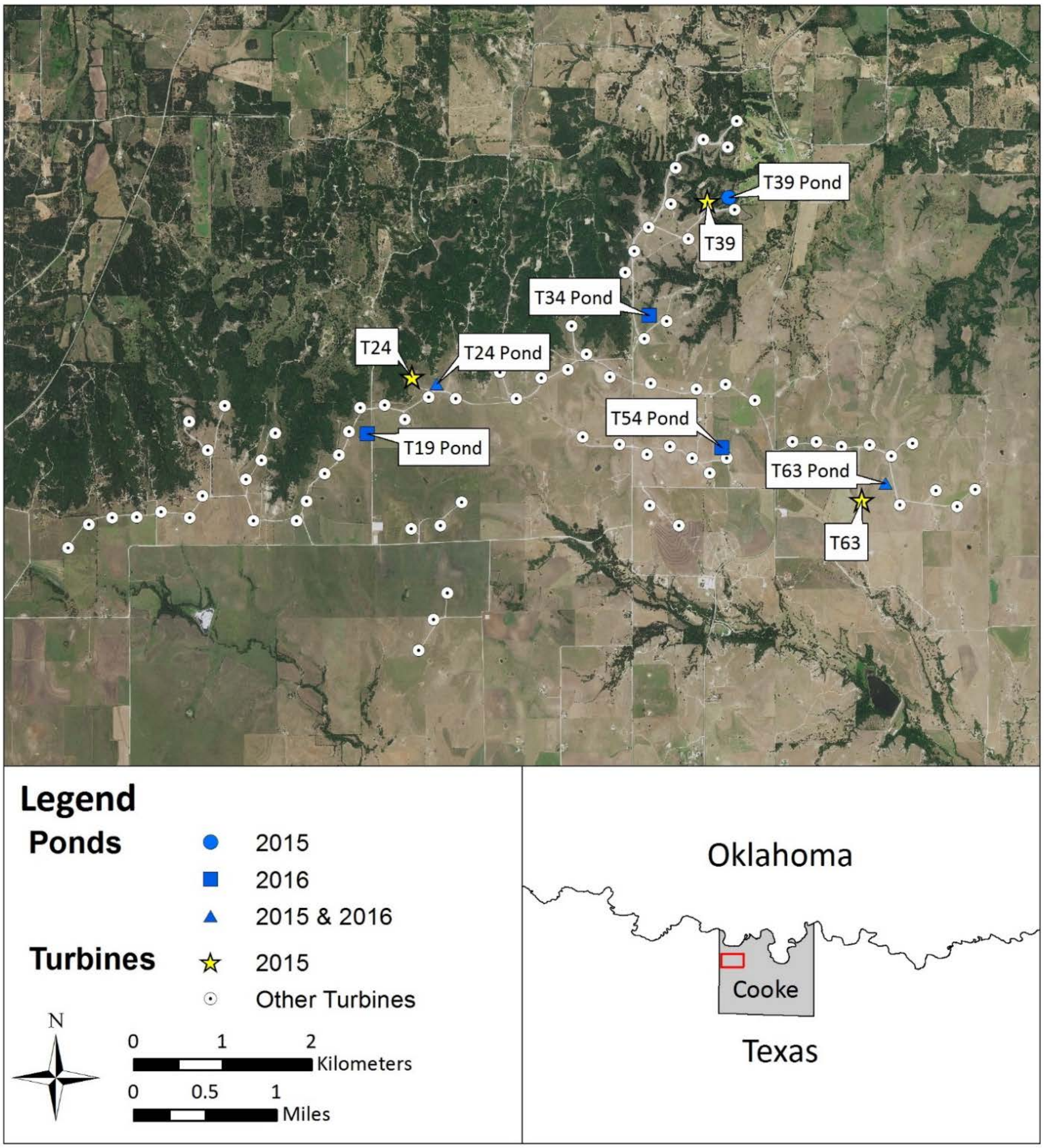

Figure 1. Deterrent testing locations during 2015 and 2016 at Wolf Ridge, Cooke County, Texas (N 33.72911°, W 97.393545°).

The information in the sections below is formatted to first describe deterrent testing conditions that were used during both monitoring years, and then specific differences in the study design are described in the separate methods sections for 2015 and 2016.

Site Conditions

During each survey night, two field personnel were present at a monitoring location; one or two locations were surveyed each night. We collected monitoring location condition data at the start of a survey night including temperature, barometric pressure, relative humidity, wind direction, wind speed, and moon phase. Surveys were not conducted when average wind speeds exceeded 15 miles per hour, as measured using a handheld anemometer, or if there was any precipitation.

Deterrent Setup

The deterrent tested during this study operates by releasing compressed nitrogen through a custom manufactured nozzle. We supplied compressed nitrogen to the deterrent through high pressure hoses that were connected to a set of compressed nitrogen tanks through a specially fabricated manifold. The manifold enabled us to connect multiple nitrogen tanks to the deterrent simultaneously. We used tank mounted pressure regulators to establish and maintain the target pressure at the manifold pressure gauge. We deployed the deterrent on a tripod at 2 m above the ground and oriented the nozzle horizontally toward a focal point, which we established at each monitoring location.

A control box started and stopped the flow of nitrogen through an electronically controlled valve. The control box also varied the deterrent signals (Figure 2). Deterrent signals included continuous “On” and a range of pulsed signals (e.g. 1 sec. on 1 sec. off). We used two deterrents during 2015 and 2016, enabling us to conduct deterrent testing at two locations simultaneously. Deterrent testing was conducted in 10-minute trials. The deterrent operated on the selected signal for the 10-minute trial, followed by a 10-minute quiet period, to allow for any residual effects from the deterrent, on bat activity, to diminish prior to beginning the next trial. Each deterrent signal was tested twice per location each night, for a total of eight trials, weather permitting. We conducted the trials in two sets, so that each of the signals occurred once before any one was repeated; the order of the signals was randomized within each set.

Figure 2. Deterrent testing conducted at Wolf Ridge during 2015 and 2016. a) Nitrogen tanks, regulators, and manifold used for deterrent testing, b) control box and deterrent deployed over a cattle pond and c) tripod mounted deterrent nozzle with electronic valve.

Video Camera Setup

We used a pair of tripod mounted video cameras to record bat activity during the deterrent trials. The cameras were separated by 90° and focused at a location referred to as the "focal point", which was at the middle of the overlapping views from the two video cameras. The focal point generally remained the same throughout the season at each location, but was adjusted at ponds due to fluctuating water levels. We established a focal point at each turbine, located at the base of the turbine 5m in front of the turbine access door, and at each pond, over the water. The overlapping area visible from both cameras simultaneously was termed the "focal area" (Figure 3). The focal area was established so that observed bats were within a known distance range from the deterrent nozzle. Video recordings began just prior to starting each 10-minute deterrent trial, and ended after the deterrent was stopped, so that the entire trial was recorded.

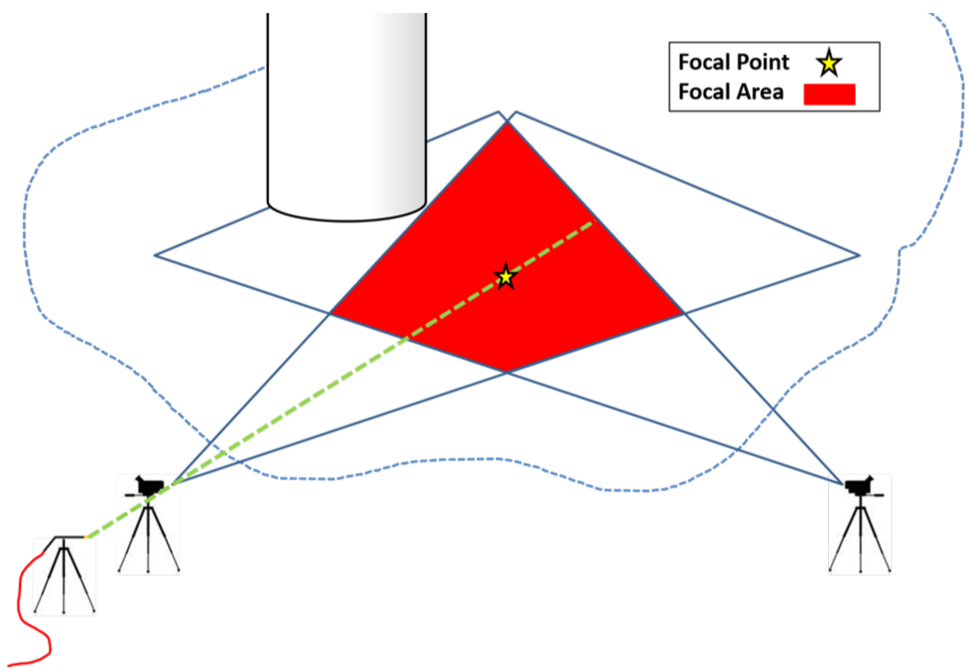

Figure 3. Deterrent and camera setup at turbine (tower base) and pond (dashed blue line) locations during 2015 deterrent testing at Wolf Ridge.

Acoustic Bat Detector Setup

We placed an AR125 ultrasonic bat detector with an FR125 field recorder in close proximity to the cattle ponds and turbines, and oriented the tripod mounted microphone toward the focal point to record bat echolocation calls (Binary Acoustic Technology, Tucson, AZ). The detectors recorded for the entire survey night.

Video Analysis

We used Studiocode video analysis software to synchronize the two videos and assess bat activity for each trial (version 5, Studiocode Business Group, Sydney, AU). Bats were distinguished from large flying insects by wing shape, body shape, wing beating pattern, and flight pattern. In addition, when using thermal cameras, the thermal signature of the homeothermic bats was used to distinguish them from large flying insects. Two independent reviewers watched the videos recorded for each trial. The video analysis software allowed for the videos from both cameras to be watched simultaneously. Each reviewer established a timeline to record each "bat pass". A bat pass was recorded each time a bat was visible in both camera frames simultaneously, meaning it was in the focal area. If a bat left one of the camera frames, the pass was ended. If that bat then reentered both camera frames, it was counted as a separate bat pass. For the purposes of analysis, these passes were treated independently. The field lead reviewed all bat passes documented by one or both reviewers to confirm or reject the presence of a bat; the field lead was blind of the person who previously identified each bat pass. Bat passes that did not contain bats (e.g. flying insects), or contained bats that were not present in both video frames simultaneously, were rejected. We only used confirmed bat passes in subsequent analyses.

For each bat pass, we characterized the flight behavior into one of five categories: 1) “Passing”- making one or less changes of direction during a pass, 2) “Foraging” - making two or more changes of direction during a pass, 3) “Pursuing” - one bat following the flight path of another bat, 4) “Reversal” - changing direction 180 degrees and leaving from the direction it entered the frame, or 5) “Contact” - making contact with the surface of a pond or with the turbine tower.

Acoustic Recording Analysis

Acoustic recordings were processed with Sonobat software (version 3.03, Arcata, California). Each recording was manually reviewed to determine whether echolocation calls were present, and to determine species identification based on echolocation call characteristics. Each separate recording containing bat echolocation calls was counted independently during the analysis to estimate relative levels of activity, with multiple recordings indicative of bats spending more time in the area. Recordings containing multiple overlapping bat calls were counted as >1 bat (e.g. a recording containing two bats was counted twice during analysis). Poor quality recordings (excessive noise, few calls, low amplitude) of high frequency bats (characteristic frequency ≥35 kHz) were excluded from the analysis.

Statistical Analysis

We conducted statistical analysis of the data collected during this study using Minitab (Version 17.2.1, Minitab Inc, State College, Pennsylvania). A 95% confidence interval was utilized for all tests. The number of bat passes observed during the two trials of each deterrent signal were averaged within a survey night at each monitoring location. The mean number of bat passes per 10-minute trial was the response variable used for subsequent analyses. When appropriate, we pooled the results from different deterrent signals or distances together and compared them to the control during analysis. Data were assessed for normality before conducting parametric statistical tests. When data failed to produce normal distributions, we rank-transformed the data (Conover and Iman 1981). We used general linear models (GLM) on the ranked data to test for differences among acoustic signals and distance from the deterrent. We used Fisher's exact test to compare proportions of video behaviors by deterrent signal. We also conducted Spearman's Rank correlations for the number of bat passes per survey night and the number of acoustic recordings per survey night.

2015 Deterrent Testing

Field Surveys

From 17 August through 28 September, 2015, we conducted a paired study to evaluate the effect of the deterrent on north-central Texas bat species. We selected three paired wind turbine and cattle pond locations (Figure 1). Paired locations were selected based on previous research conducted at Wolf Ridge, which identified high numbers of fatalities at the turbines (Bennett and Hale 2014) and high levels of bat activity at the ponds (McAlexander 2016). Ponds were located within 330 m of the respective paired turbine. Surveys rotated nightly between the three paired locations. We completed eight 10-minute deterrent trials at each location during each survey night, weather permitting, beginning at sunset and continuing for 2.5 hours.

We evaluated three deterrent signals, along with a silent "Control". Deterrent signals included "On" with the deterrent on continuously at a constant pressure, "Pulse 1" with the deterrent pulsing on for one second and off for one second at a constant pressure, and "Pulse

2” with the deterrent pulsing on for one second off for two seconds at a constant pressure. The initial manifold pressure for 2015 was 50 psi, which produced a high amplitude ultrasonic “screech” at approximately 48 kHz (Table 1, Figure 4). The order of the deterrent signals was consistent between the paired pond and turbine locations each survey night.

Table 1. Characteristics of the acoustic deterrent signals tested during the 2015 and 2016 field seasons at Wolf Ridge.

Year	Deterrent Signal	Pulse Description	Ramped Pressure	Duty Cycle (%)	Initial Manifold Pressure (psi)
2015	On	Continuous	No	100	50
2016	On	Continuous	No	100	85
2015	Pulse 1	1 sec. on 1 off	No	50	50
2015	Pulse 2	1 sec. on 2 off	No	33	50
2016	Pulse 3	3 sec. on 3 off	Yes	50	85
2016	Pulse 4	2 sec. on 2 off	Yes	50	85
2016	Unramped 2 sec.	2 sec. on 2 off	No	50	85
2016	Unramped 3 sec.	3 sec. on 3 off	No	50	85
2015 & 2016	Control	Off	-	-	-

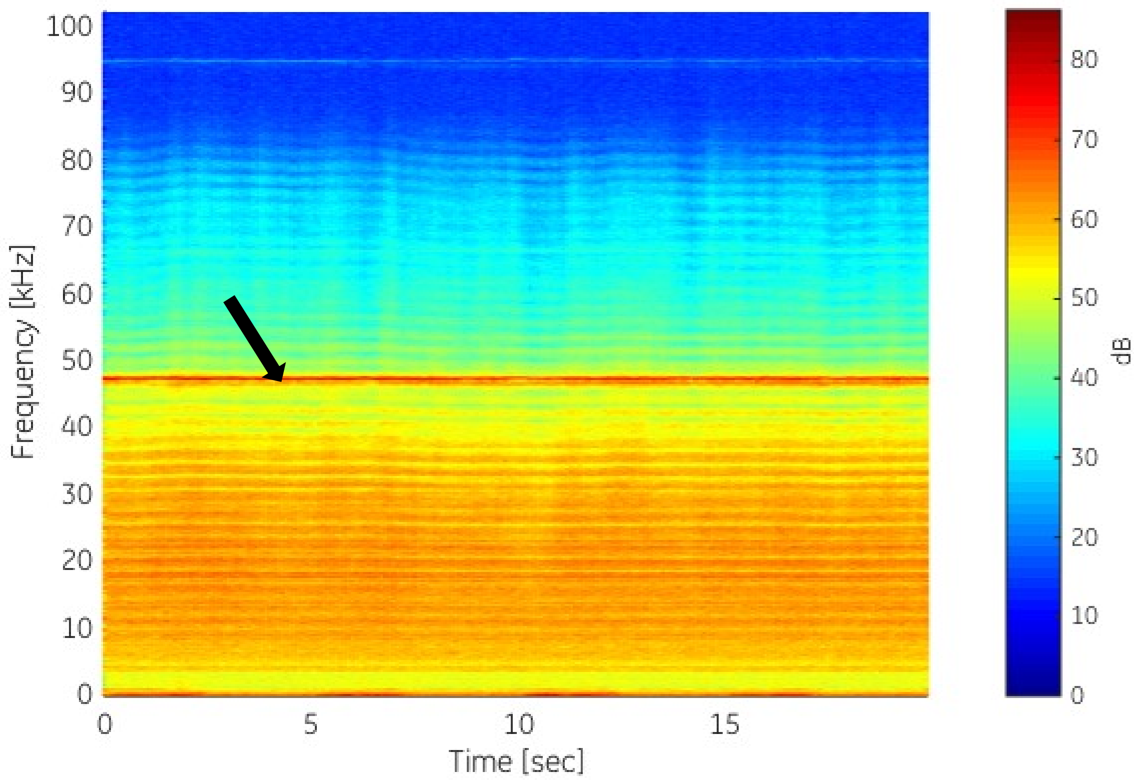

Figure 4. Frequency and amplitude of the sound produced by the deterrent device during testing at Wolf Ridge during 2015, recorded at 10 m from the nozzle. The high amplitude ultrasonic "Screech" is indicated by the arrow.

To determine how bats respond with varying distance from the deterrent, the focal point remained the same and we moved the deterrent to either 10, 20, or 30 m from the focal point. One distance was tested each survey night; the distance tested changed randomly between survey nights, but was consistent at the paired turbine and pond locations within a survey night. Thus, a total of 24 treatment groups were tested during 2015, comprising two location types (turbine, pond), three distances (10, 20, 30 m), and four deterrent signals (On, Pulse 1, Pulse 2, Control).

We used Sony HDR-PJ790V cameras in daylight mode to record the first two trials, as ambient light levels were still high enough (Sony Electronics Inc., Park Ridge, NJ). The same cameras mounted with ATN-NVM3 night vision scopes were used for the subsequent six trials (ATN Corp, San Francisco, CA). Cameras in daylight mode were placed 7 m from the focal point, while night vision cameras were placed 18.5 m from the focal point, due to a narrower field of view using the night vison scopes. Thus, each setup recorded the same 10 m wide field of view at the focal point. One camera was placed in line with the deterrent, while the other was offset at a 90^{o} angle to the side. The videos recorded by the two cameras overlapped in an approximately 10 m wide focal area, centered on the focal point (Figure 5). The resulting focal area was approximately 43 m^2 and covered a range of 5-15, 15-25, and 25-35 m from the deterrent, respectively, for the 10, 20, and 30 m tests (Figure 6). We used two supplemental tripod mounted infrared lights with each night vision camera. We placed the infrared lights to provide the best lighting for each setup, generally 10 m behind the cameras, separated by 90^{o}. The lights were oriented to cross at the focal point, to optimize bat detection. Field technicians started both cameras prior to the beginning of the 10-minute trial, and then an audible signal (whistle) was made at the start time. We used the audible signal to time synchronize videos from the two cameras during video analysis.

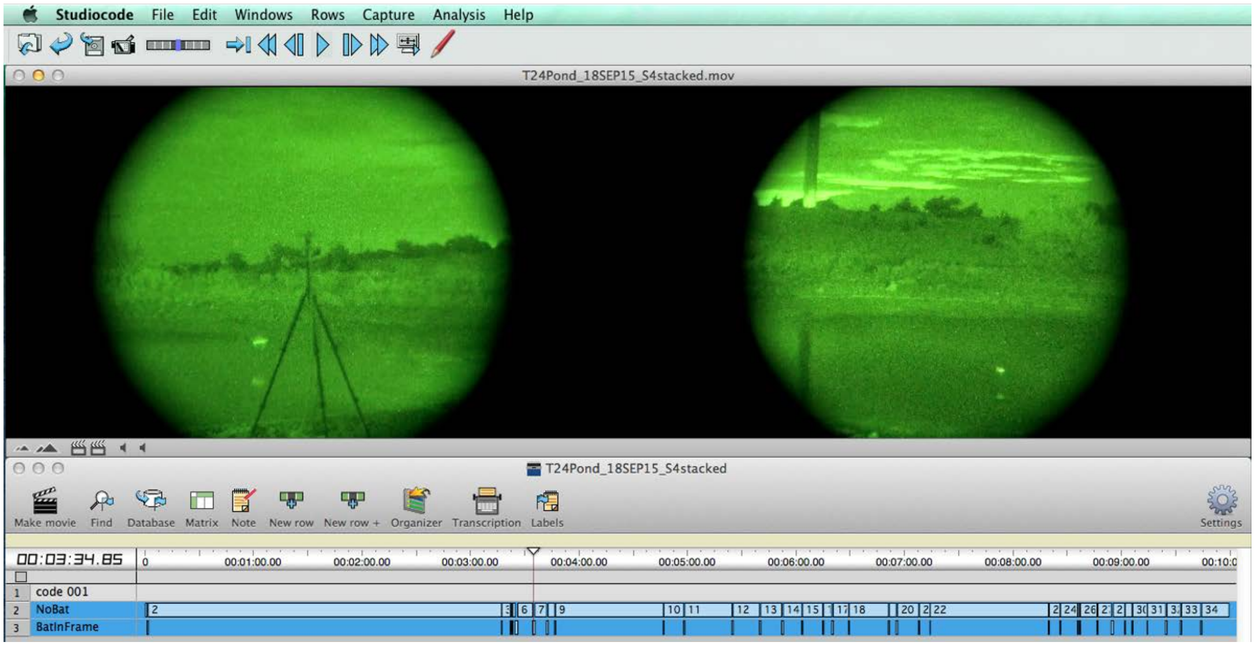

Figure 5. Video analysis window showing overlapping night vision video camera views from 2015 deterrent testing at Wolf Ridge.

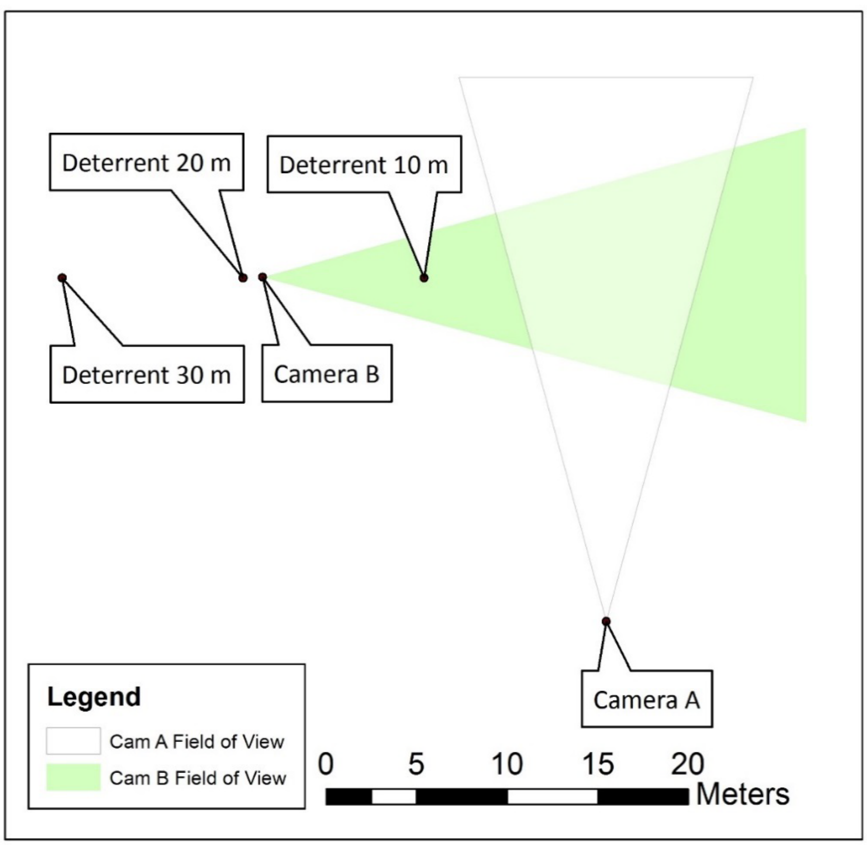

Figure 6. Deterrent and camera setup at ponds during 2015 deterrent testing at Wolf Ridge.

Video Processing and Analysis

We analyzed the data at ponds and turbines separately. In the GLM, deterrent signal (On, Pulse 1, Pulse 2) and distance (10, 20, 30 m) were fixed factors and location (T24, T39, T63 ponds and turbines, respectively) was a random effect. We then analyzed the pooled deterrent signal compared to the control, with deterrent signal (Pooled deterrent, Control) as a fixed factor and location (T24, T39, T63 ponds and turbines, respectively) as a random effect at ponds and turbines separately.

2016 Deterrent Testing

Field Surveys

From 1 April through 17 September, 2016, we continued deterrent testing to evaluate the effectiveness of the acoustic deterrent. Data collected during 2016 was divided into spring (1 April through 9 May), summer (12 May through 29 June), and fall (1 Aug through 17 September) seasons to evaluate whether bat behavior and response to the deterrent varied by season. As described below, the number of treatment groups was reduced, from 24 in 2015, to four in 2016, comprised of a single location type (pond), a single deterrent distance (0-30 m), and four primary deterrent signals (On, Pulse 3, Pulse 4, Control). Field surveys conducted during 2016 utilized methods similar to those used during 2015, with four notable exceptions.

First, because our bat detection rates were much higher at ponds during 2015, in order to maximize the number of bats observed, we only conducted deterrent testing at ponds during 2016. Each of the ponds monitored was closely associated with a turbine (Figure 1). We generally surveyed two ponds simultaneously each survey night during the spring and summer, and one pond during the fall season.

Second, we began the deterrent trials during 2016 at 20 minutes after sunset, instead of at sunset, to better align with bat emergence times observed in 2015. An additional trial was conducted at the end of the survey night, so that eight 10-minute trials were completed before surveys concluded, three hours after sunset. In the same manner as in 2015, the treatments were conducted in two sets, so that each of the four signal trials occurred once before any were repeated. The treatments were randomized within each set. When two ponds were surveyed on a single night, signal order was independent at each location.

Third, the deterrent signals were modified in 2016 to adjust the frequency of the ultrasonic “screech” to better align with the echolocation frequencies of the bat species present at Wolf Ridge. The initial manifold was increased to 85 psi to move the frequency of the deterrent “screech” lower, in order to more thoroughly cover the echolocation range of the bat species occurring in north-central Texas (Table 1). A “Control” and continuous “On” deterrent signal were used in 2016 along with newly developed pulse “Pulse 3”, with the deterrent on for three seconds and off for three seconds with ramped pressure, and “Pulse 4”, with the deterrent on for two seconds and off for two seconds with ramped pressure. The pressure for Pulse 3 and Pulse 4 were ramped, meaning the pressure changed during the pulse, altering the frequency of the ultrasonic “screech” (Figure 7). In addition to the four planned deterrent signals, due to a programming problem, two unramped pulses were included during deterrent testing in the spring season. There was a “2 second unramped” pulse, with the deterrent on for two seconds and off for two seconds, and a “3 second unramped” pulse, with the deterrent on for two seconds and off for two seconds. These signals were not used for the remainder of the season and were replaced by the ramped signals.

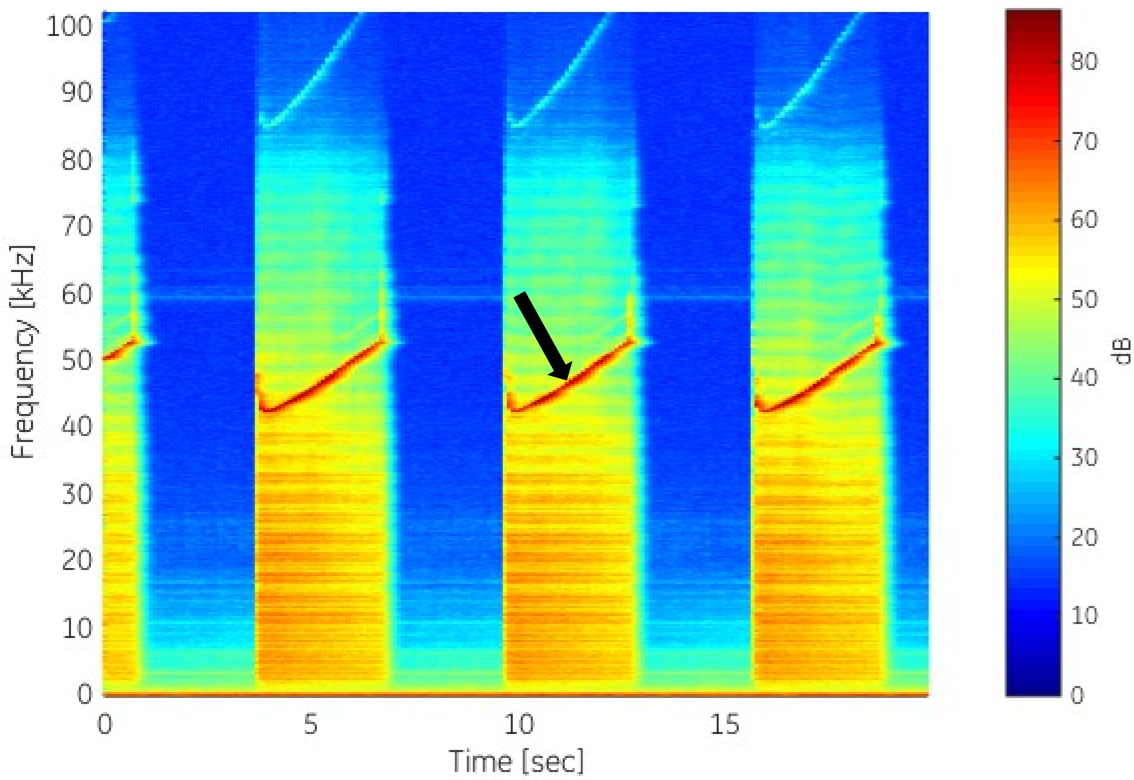

Figure 7. Frequency and amplitude of the sound produced by the deterrent device during ramped pressure pulsing used during 2016 deterrent testing at Wolf Ridge, recorded at 10 m from the nozzle. The frequency of the ultrasonic "Screech", indicated by the arrow, varies due to the ramped pressures.

Fourth, we used Axis Q1922-e and Q1932-e thermal cameras to record bat activity in place of the night vision cameras used during 2015 (Axis Communications AB, Lund, Sweden). Thermal cameras allowed us to use the heat signature produced by homeothermic bats to more easily distinguish them from large flying insects. Both thermal camera models provided the same field of view. We positioned the two thermal cameras 40 m from the focal point, separated by 90^{o}, and oriented horizontally toward the focal point (Figure 8). The cameras were positioned to provide overlapping fields of view that extended from 0 to 31 m from the deterrent, which was placed at the closest intersection of the overlapping views from the two cameras (Figure 8). The overlapping area, visible from both cameras simultaneously, was considered the focal area. The focal area covered approximately 85 m^2 and was mostly or completely over the water at each pond location (Figure 9). The focal area was in the same location with respect to the deterrent during all trials conducted in 2016, so distance was not an explanatory variable during 2016. Thermal cameras were networked together and automatically time synchronized using a field laptop and network router.

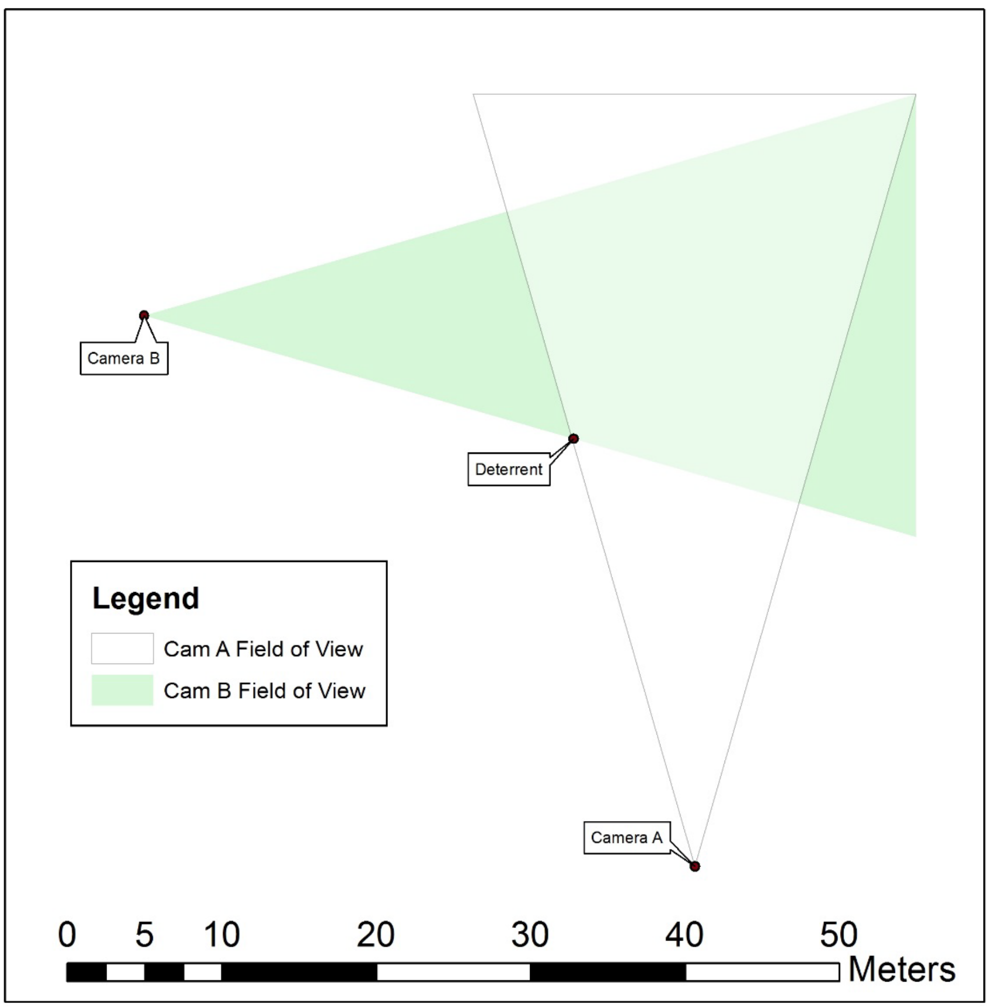

Figure 8. Deterrent and camera setup at ponds during 2016 deterrent testing at Wolf Ridge.

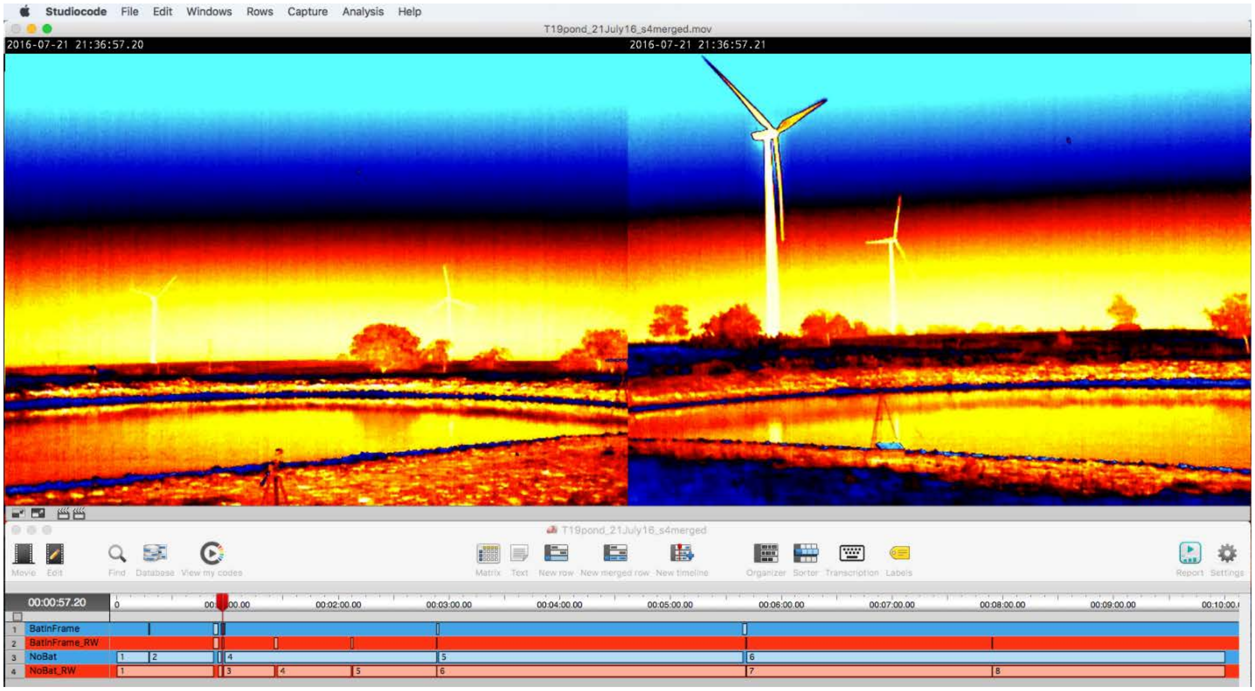

Figure 9. Video analysis window showing overlapping thermal video camera views from 2016 deterrent testing at Wolf Ridge.

Video Processing and Analysis

We conducted video analysis similarly during 2015 and 2016, except videos were automatically time synchronized using the field laptop, instead of audible signals. Thus, both reviewers were generally blind of the deterrent signal used during each of the trials.

In the GLM, deterrent signal (On, Pulse 3, Pulse 4) and season (spring, summer, fall) were fixed factors and location (T19, T24, T34, T54, T63 ponds) was a random effect. We then analyzed the pooled deterrent signals compared to the control, with deterrent signal (Pooled deterrent, Control) and season (spring, summer, fall) as fixed factors and location (T19, T24, T34, T54, T63 ponds) as a random effect. To assess for variation in the treatment effect by season, an interaction (treatment and season) was included in the model.

2015 and 2016 Comparison Methods

Although each set of signals were only utilized during a single year (2015 or 2016, respectively), we conducted an analysis of the combined 2015 and 2016 data to determine if there was any detectible difference in the effectiveness of the device at reducing bat activity between the two years. We used data from all pond surveys during 2015, and only data from the fall season during 2016, because the 2015 data was collected during in the fall. We used a separate GLM for control and pooled deterrent trials, with year (2015, 2016) as fixed factor and location (T19 pond, T24 Pond, T34 Pond, T39 Pond, T63 pond) as a random effect for both models.

2015 Results

Video Analysis

We surveyed paired turbine and pond locations on 33 nights from 17 August to 28 September, 2015. In total, we recorded 447 bat passes from high definition videos during 448 10-minute trials (Table 2). We did not observe any bats in the first daylight video sessions, because ambient light conditions were still too high and bats had not yet emerged from their day roosts. Thus, this set of trials was excluded from the analyses. The second daylight video session and all night vision video sessions were included in the analyses.

Table 2. Number of trials conducted for each deterrent signal type at pond and turbine locations at Wolf Ridge Wind, LLC from 17 August to 28 September 2015.

		Turbine		Pond	
Deterrent Signal	Distance (m)	Trials	Bat Passes	Trials	Bat Passes
Control	10	15	9	19	72
	20	19	5	19	23
	30	18	6	18	44
On	10	16	1	18	20
	20	20	5	20	13
	30	20	10	20	50
Pulse 1	10	18	2	18	9
	20	18	1	18	22
	30	19	20	19	50
Pulse 2	10	16	3	17	10
	20	20	7	20	29
	30	20	5	20	31
Total		**222**	**74**	**226**	**373**

Bat activity was highly variable and sporadic, with 303 (68%) of the deterrent trials yielding zero observed bat passes, while 18 (4%) of the deterrent trials contained 183 (41%) of the total observed bat passes. Of the 448 trials, only nine trials had ≥8 bat passes documented. These nine trials yielded 128 (29%) of the bat passes, while only representing 2% of the total number of trials. These high activity trials occurred only at ponds, and with the deterrent operating at 30 m or during control trials, with a maximum of 41 bat passes during a single trial (Figure 10).

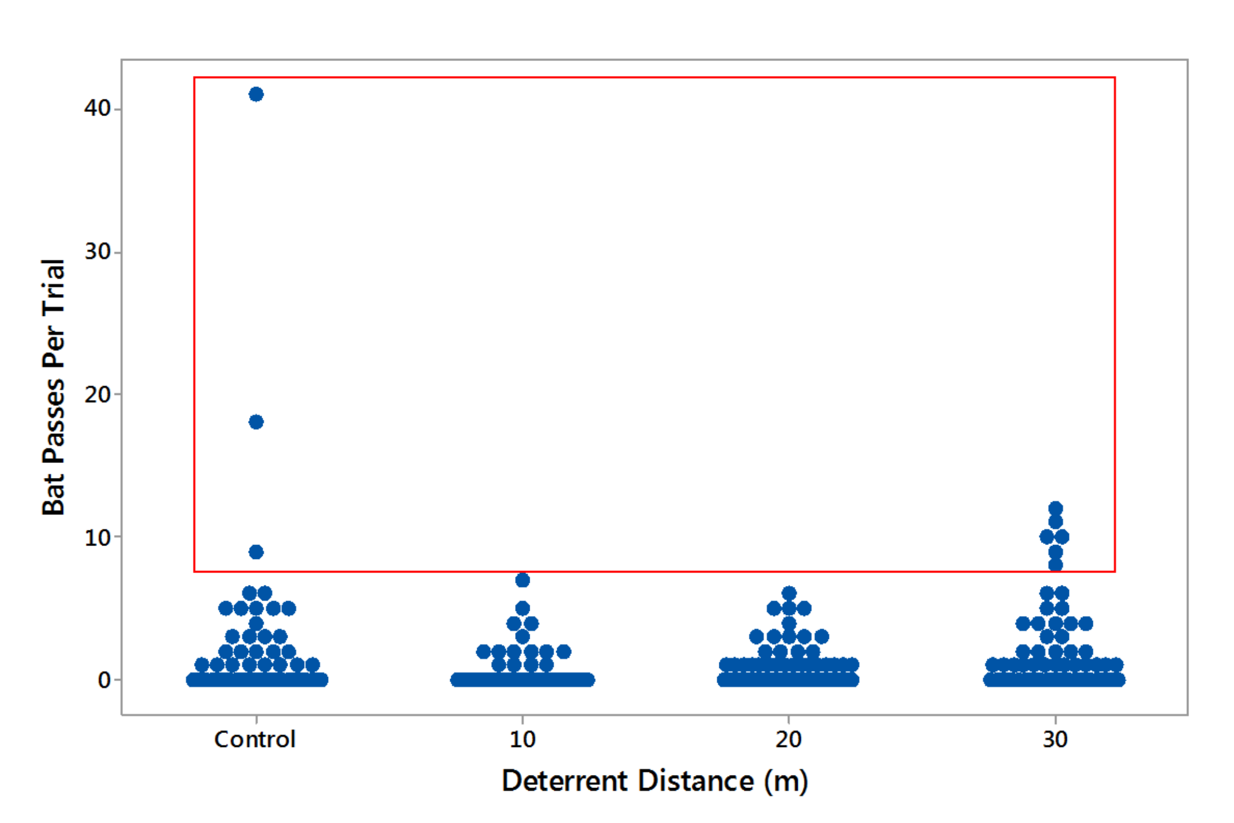

Figure 10. Number of bat passes observed per trial for pooled deterrent signals (On, Pulse 1, and Pulse 2) and during the control trials at three distances from the focal observation point at ponds during 2015. The red rectangle encompasses the top 4% of 10-minute trials, each yielding ≥8 bat passes.

The results of the GLM at ponds indicated that the number of bat passes varied significantly with distance from the deterrent ($F_{2,91}$ = 5.68, p = 0.005), but not with deterrent signal type ($F_{2,91}$ = 0.22, p = 0.80) or location ($F_{2,91}$ = 2.19, p = 0.12). We observed significantly fewer bats with the deterrent at 10 m compared to 30 m (Tukey simultaneous test: t = 3.35, p = 0.003) and no difference between 10 and 20 m (Tukey simultaneous test: t = 1.32, p = 0.37) or between 20 and 30 m (Tukey simultaneous test: t = 2.00, p = 0.12). The GLM at turbines indicated that the number of bat passes did not vary with distance from the deterrent ($F_{2,89}$ = 0.64, p = 0.53), signal type ($F_{2,89}$ = 0.17, p = 0.85), or location ($F_{2,89}$ = 2.8, p = 0.07). The results of the GLM at ponds indicated that the number of bat passes did not vary between the control and pooled deterrent signal for the combined 10 and 20 m distances ($F_{1,39} = 0.12$, $p = 0.73$) or by location ($F_{2,39} = 0.74$, $p = 0.48$). The 10 and 20 m distances were pooled because we did not detect a significant difference in the reduction in bat activity between those distances; the 30 m was significantly different so it was excluded. The GLM at turbines indicated that the number of bat passes did not vary between the control and pooled deterrent signal for the combined 10 and 20 m distances ($F_{1,39} = 0.0$, $p = 0.96$) or by location ($F_{2,39} = 0.59$, $p = 0.56$). The reduction in mean observed bat passes for the pooled deterrent treatments compared to the controls is shown in Figure 11 and Table 3 for turbines and ponds. Although a similar reduction in the mean number of bat passes was observed at ponds and turbines at 10 m for pooled deterrent trials, compared to the control, 80.4 and 75.8% respectively, the differences were not statistically significant at ponds or turbines at any of the distances ($P>0.05$ in all cases).

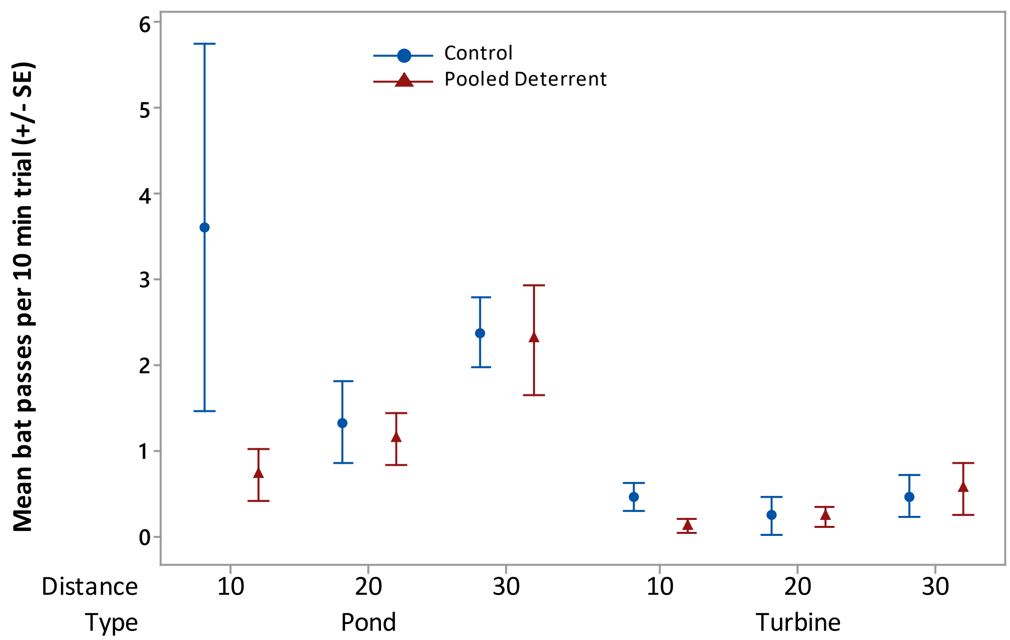

Figure 11. Mean number of bat passes per ten minute trial (±SE) for control and pooled deterrent trials, by distance category at ponds and turbines during 2015. Survey nights per location type and distance was 11.

Table 3. Percent reduction in observed bat passes, by habitat type and distance during the 2015 field season at Wolf Ridge.

Type	Distance (m)	Control	Pooled deterrent	Percent reduction
Pond	10	3.60	0.71	80.40
	20	1.32	1.12	14.90
	30	2.36	2.28	3.50
Turbine	10	0.45	0.11	75.80
	20	0.23	0.22	4.00
	30	0.46	0.54	-19.10

Behavior

Most bats observed were “Foraging” and “Passing” at ponds, 40 and 52% respectively, and turbines, 27 and 65% respectively, during deterrent trials. We observed “Reversals”, “Contact” and “Pursing” in 0-7% of the bat passes. During control trials, there was not a significant difference in the proportion of bats detected “Foraging” or “Passing” at ponds and turbines (Fisher’s exact test: $P>0.05$ in both cases). As differences in flight behavior could reveal differences in how bats respond to the deterrent, we also looked for differences in behavior between the pooled deterrent treatments and the control. We found that the proportion of each behavior was not significantly different between the pooled deterrent treatments (On, Pulse 1, and Pulse 2 pooled) and the control (Fisher’s exact test: $p > 0.05$ in all cases) when pooling deterrent trials for the 10 and 20 m distances at ponds and turbines separately. Although results were not significant, behavioral trends at ponds and turbines were similar, with lower proportions of bats “Foraging” with the deterrent operating, and higher proportions of “Passing” during pooled deterrent trials (Figure 12).

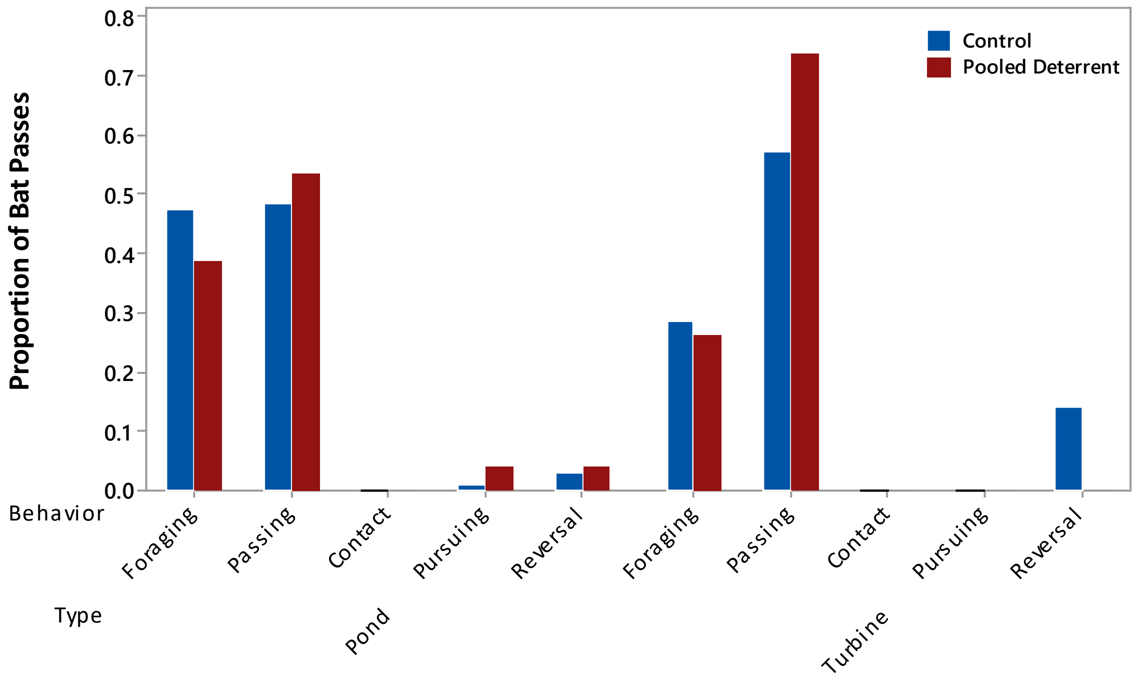

Figure 12. Proportion of behaviors observed during bat passes for control (n=95), recorded during 38 trials, and bat passes for pooled deterrent (N=103) recorded during 111 trials at ponds and for control (N=14), during34 trials, and bat passes for pooled deterrent (N=19) recorded during 108 trials at turbines for the combined 10 and 20 m distances.

Acoustic Analysis

The number of acoustic recordings per detector night, along with the number of bat passes observed with the night vision cameras, is shown in Figure 13. There was a positive correlation between acoustic recordings and bat passes, which was statistically significant (Spearman's roh = 0.75, p = <0.001), indicating that the level of bat activity recorded using video and acoustics were correlated. As observed in the video analysis, more bat calls were recorded at pond locations than at turbines. Also similar to the video analysis, bat acoustic activity was highly variable among survey locations and survey nights during the deterrent trial period. We detected five of the six species previously documented species using acoustic detectors during deterrent testing in 2015; the hoary bat was not detected during 2015. We also detected an additional species, the canyon bat (*Parastrellus hesperus*). The average number of acoustic recordings per acoustic detector night at ponds is shown in Table 4.

Table 4. Average acoustic recordings per night for each species at ponds (n=32 nights) and turbines (n=31 nights) during 2015 deterrent testing at Wolf Ridge.

	Pond		Turbine	
Species	Mean	SE Mean	Mean	SE Mean
Lasiurus borealis	2.22	0.70	0.32	0.17
Lasiurus cinereus	0.00	0.00	0.00	0.00
Lasionycteris noctivagans	0.22	0.17	0.03	0.03
Nycticeius humeralis	12.81	3.59	1.06	0.67
Parastrellus hesperus	4.19	2.71	0.03	0.03
Perimyotis subflavus	4.13	2.08	0.10	0.07
Tadarida brasiliensis	0.00	0.00	0.06	0.06

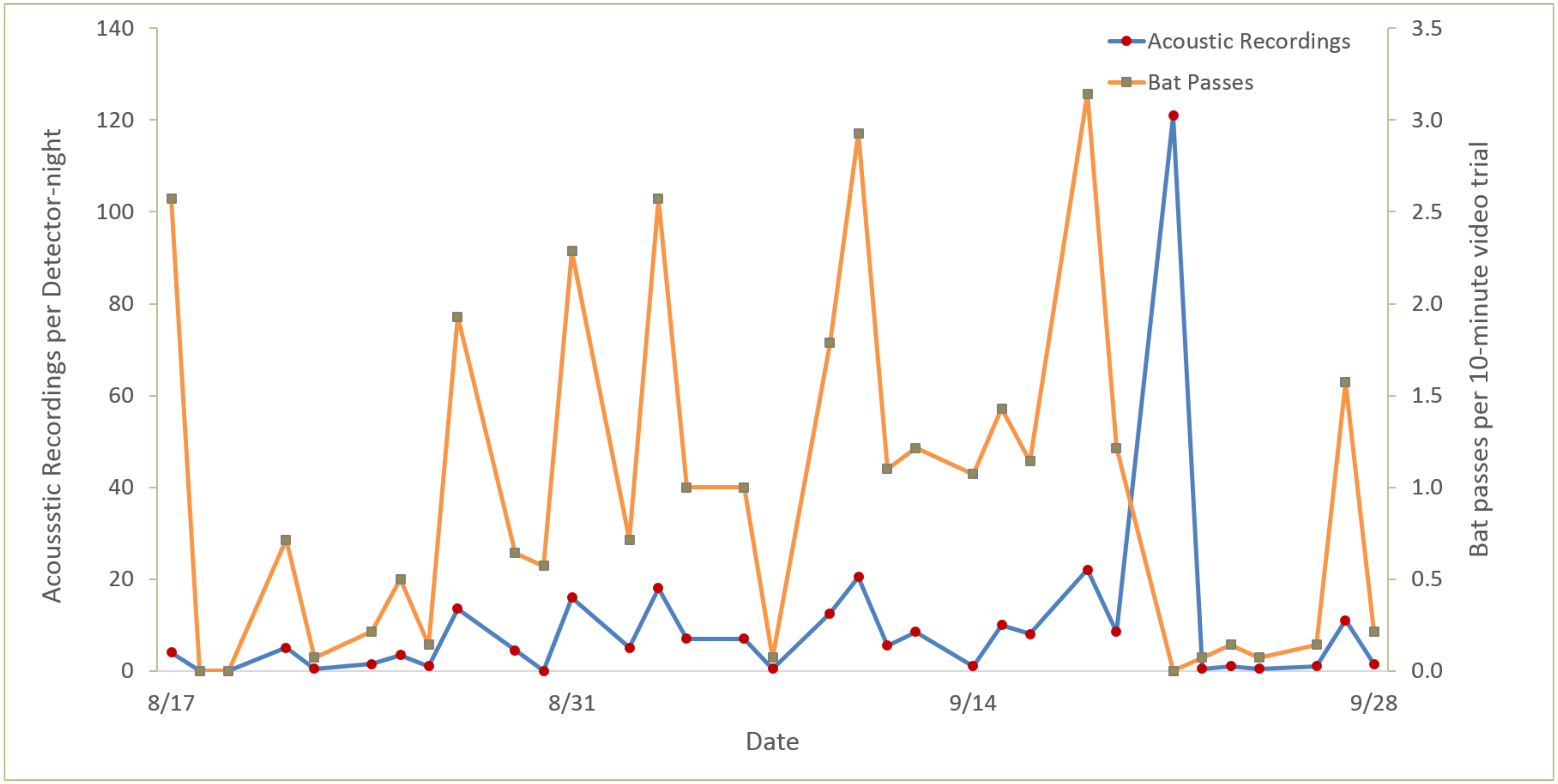

Figure 13. Acoustic recordings per detector night and bat passes counted during video analysis during 2015 deterrent testing at Wolf Ridge.

2016 Results

Video Analysis

We conducted deterrent testing on 50 nights between 1 April and 17 September, 2016, at Wolf Ridge cattle ponds. A single pond was surveyed on 19 nights and two ponds were surveyed on 31 nights, for a total of 81 pond nights. We recorded 492 bat passes during 601 10-minute trials. Deterrent testing results from the spring, summer and fall seasons are summarized in Table 5.

Table 5. Number of deterrent trials by season and signal and the number of bats detected using thermal cameras during deterrent testing at Wolf Ridge in 2016.

Season	Deterrent Signal	Trials	Video Bat Passes
Spring	Control	18	74
	On	18	9
	Pulse 3	10	3
	2 Sec Unramped	15	5
	3 Sec Unramped	6	2
Summer	Control	103	74
	On	107	9
	Pulse 3	103	19
	Pulse 4	104	12
Fall	Control	29	149
	On	29	54
	Pulse 3	30	52
	Pulse 4	29	30
	Totals	**601**	**492**

Bat activity during 2016 was highly variable and sporadic within and among survey nights, with 467 (78%) of the deterrent trials yielding zero bat passes, while 16 (3%) of the trials contained 272 (55%) of the total bat passes. High activity trials ($\geq$8 bats) observed during 2016 occurred on five occasions while the deterrent was operating, while 11 control trials contained eight or more bats, with a maximum of 46 passes during a single trial. Thus, even though there were three times more deterrent signal trials (n=451) than control trials (n=150) there were more than twice as many high activity passes during control trials (Figure 14).

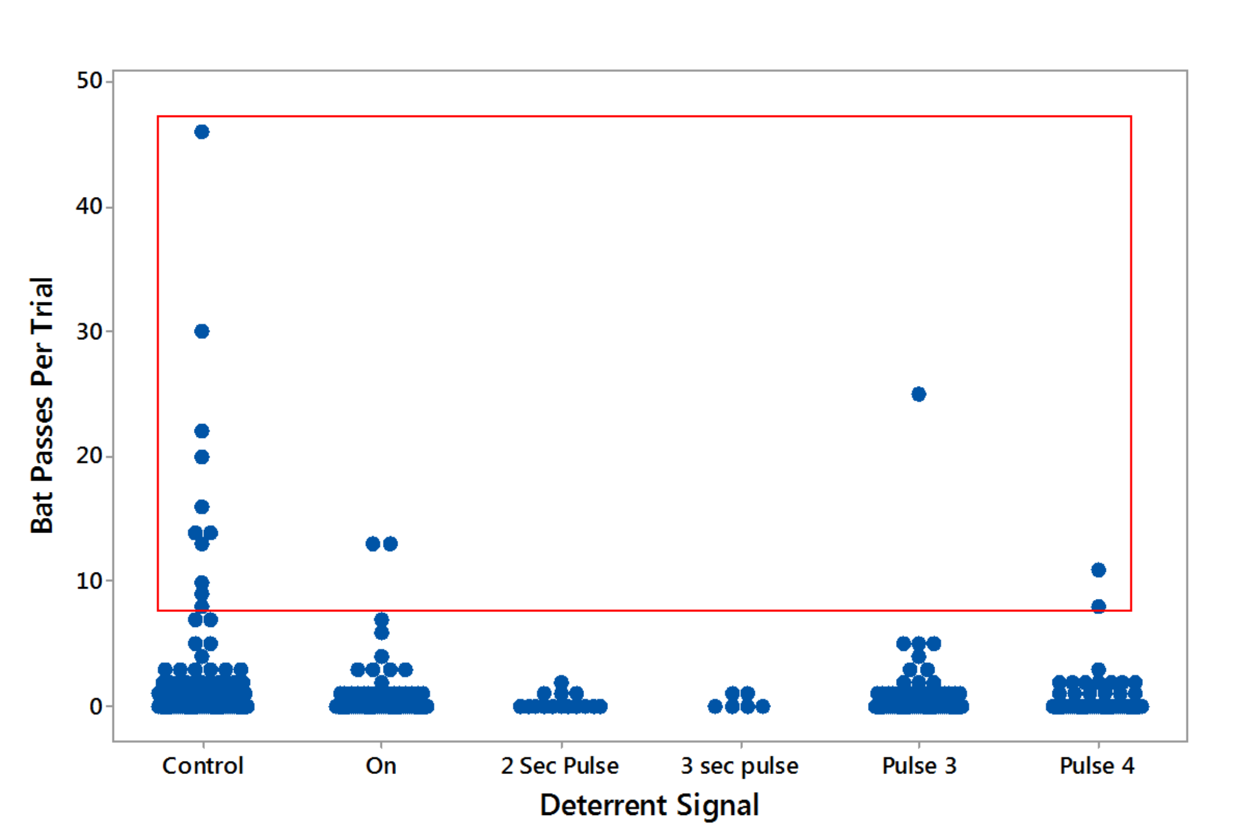

Figure 14. Number of bat passes observed per trial by deterrent signal at ponds during deterrent testing at Wolf Ridge in 2016. The red rectangle encompasses the trials with ≥8 bat passes during a 10-minute trial.

The results of the GLM at ponds indicated that the number of bat passes did not vary among the deterrent signals ($F_{2,214}$= 1.71, p = 0.18), or between the different ponds ($F_{4,214}$= 1.24, p = 0.29), while the number bat passes were significantly different among the three seasons ($F_{2,214}$= 25.70, p <0.001). The results of the GLM indicated that the number of bat passes was significantly lower during pooled deterrent trials, compared to the control ($F_{1,148}$= 9.99, p = 0.02), there was also a significant difference among the three seasons ($F_{2,148}$= 21.10, p < 0.001), and also among the pond locations ($F_{4,148}$= 2.76, p = 0.03). When evaluating the interaction among treatment and season, there was not a significant difference in treatment effect among the three seasons ($F_{2,150}$= 0.15, p = 0.86; Figure 15). Bat activity was highest during the fall and lowest during the spring. Mean reduction in bat activity, by season, for the pooled deterrent trials, compared to the control, ranged from 72-91%. (Table 6).

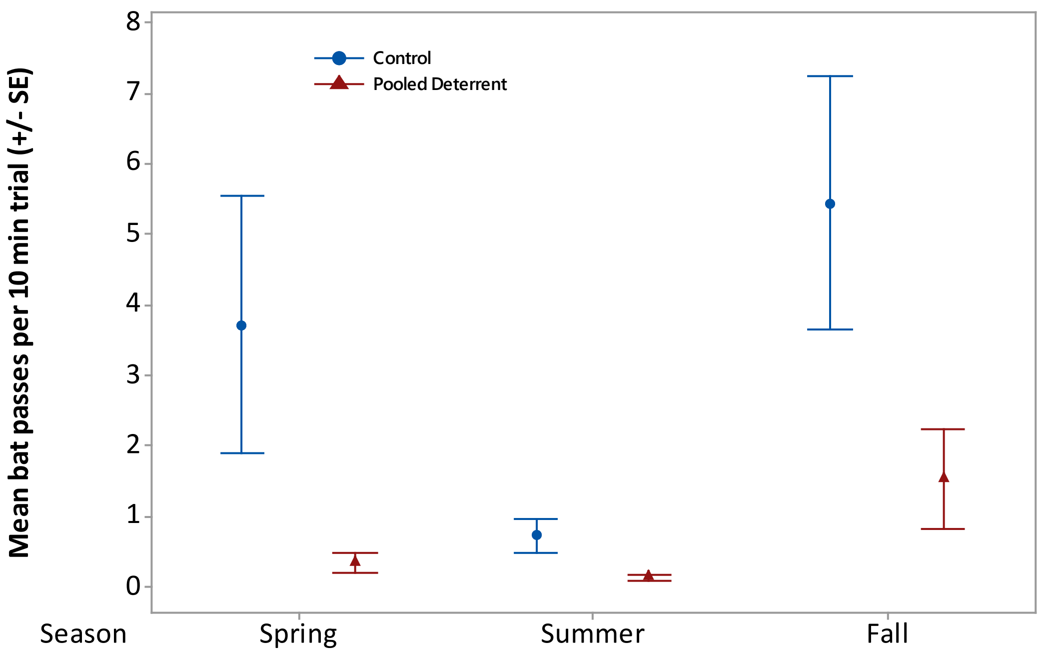

Figure 15. Average bat passes per ten minute trial for control and pooled deterrent trials by pond night, separated by season, for deterrent testing at Wolf Ridge during 2016. Bars are one standard error from the mean.

Table 6. Percent reduction in bat passes calculated from the average number of bat passes observed using thermal cameras during deterrent trials for control and pooled deterrent signals during 2016.

Season	Control	Pooled Deterrent	Percent Reduction
Spring	3.70	0.34	91
Summer	0.72	0.12	84
Fall	5.43	1.52	72

Behavior

Bat behaviors observed during review of thermal videos included relatively low proportions of “Pursuing” and “Reversals” (<1-2%), and moderate proportions of “Contact” (10-15%; Figure 16). Most bats observed were “Foraging” or “Passing” over ponds during deterrent trials. Bats exhibited significantly lower proportions of “Foraging” flight patterns during pooled deterrent trials compared to control trials (Fisher’s exact test: $p = 0.015$) and significantly higher proportions of “Passing” flight patterns (Fisher’s exact test: $p < 0.001$) for pooled deterrent treatments (On, Pulse 3, Pulse 4) than during control trials. None of the other flight behaviors (Pursuing, Contact, and Reversal) were significantly different when comparing the deterrent treatments and control (Fisher’s exact test: $p > 0.05$ in all cases; Figure 16, Table 7).

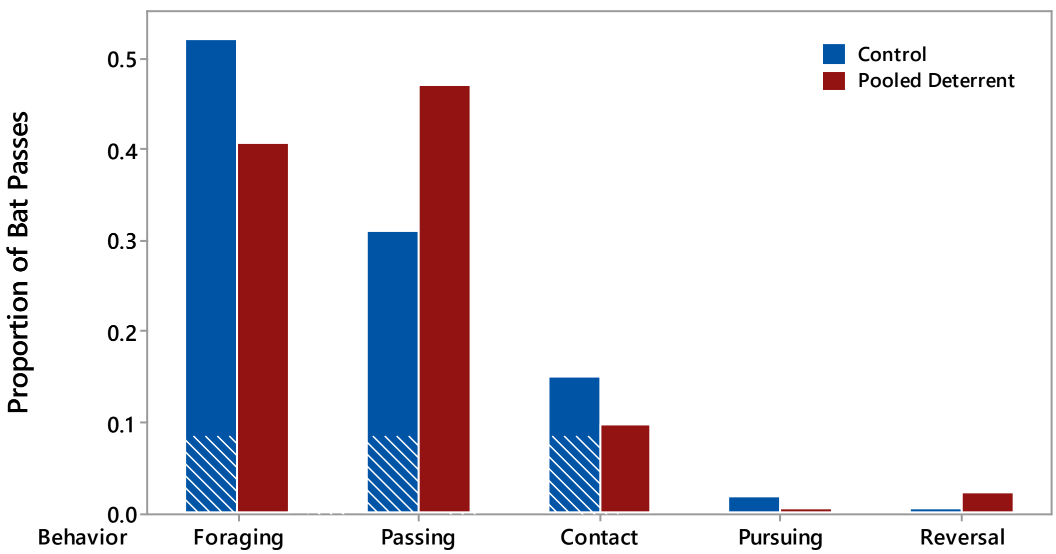

Figure 16. Proportion of behaviors observed during bat passes for control (n=296), recorded during 150 trials, and bat passes for pooled deterrent (N=190) recorded during 451 trials. Bats were “Foraging” a lower proportion of the time and “Passing” a higher proportion of the time during pooled deterrent trials at Wolf Ridge during 2016.

Table 7. Proportion of bat behaviors observed during control and pooled deterrent trials during 2016 deterrent testing at Wolf Ridge.

Treatment Type	Behavior	Total Bat Passes	Proportion
Control	Foraging	154	0.52
	Passing	92	0.31
	Contact	44	0.15
	Pursuing	5	0.02
	Reversal	1	0.00
Pooled Deterrent	Foraging	76	0.41
	Passing	88	0.47
	Contact	18	0.10
	Pursuing	1	0.01
	Reversal	4	0.02

Acoustic Analysis

The number of acoustic recordings per detector night at T24 pond, along with the number of bat passes observed with the thermal cameras, is shown in Figure 17. . Seasonal changes in species composition was only assessed at T24 pond because we had consistent acoustical data from this location throughout the season. There was a positive correlation between acoustic recordings and observed bat passes, which was statistically significant (Spearman's roh = 0.41, p = <0.023), indicating that the level of bat activity recorded using video and acoustics were correlated. Our analysis of the acoustic data showed a total of seven species present during deterrent testing in 2016, including all of the bat species previously reported at Wolf Ridge, and again documenting the presence of the canyon bat. These results are separated by species in Figure 18. Similar to the results from the video analysis, acoustic bat activity was higher during the spring and fall, and lower during the summer monitoring period.

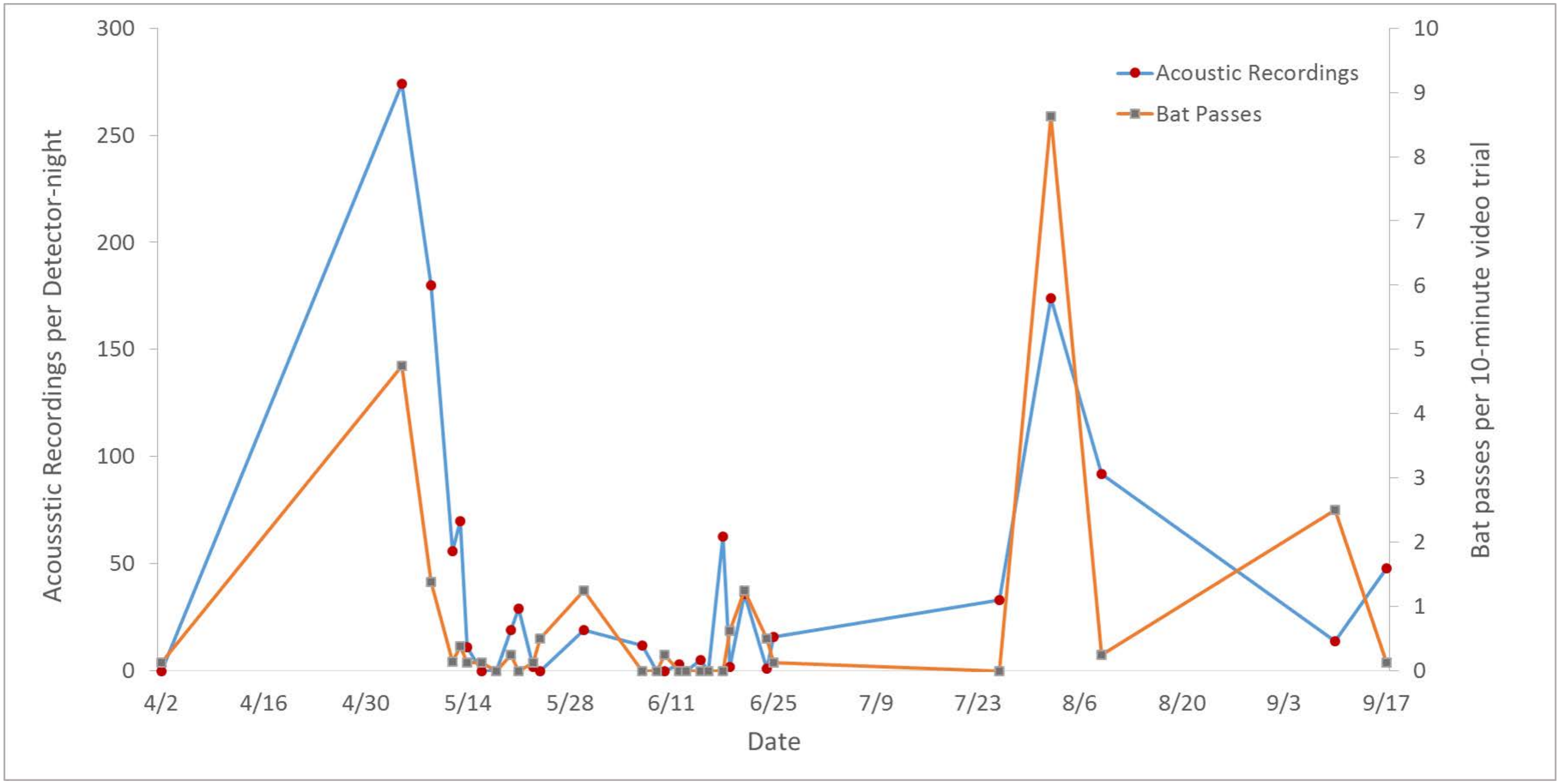

Figure 17. Acoustic recordings per detector night and bat passes counted during video analysis at T24 Pond during 2016 deterrent testing at Wolf Ridge.

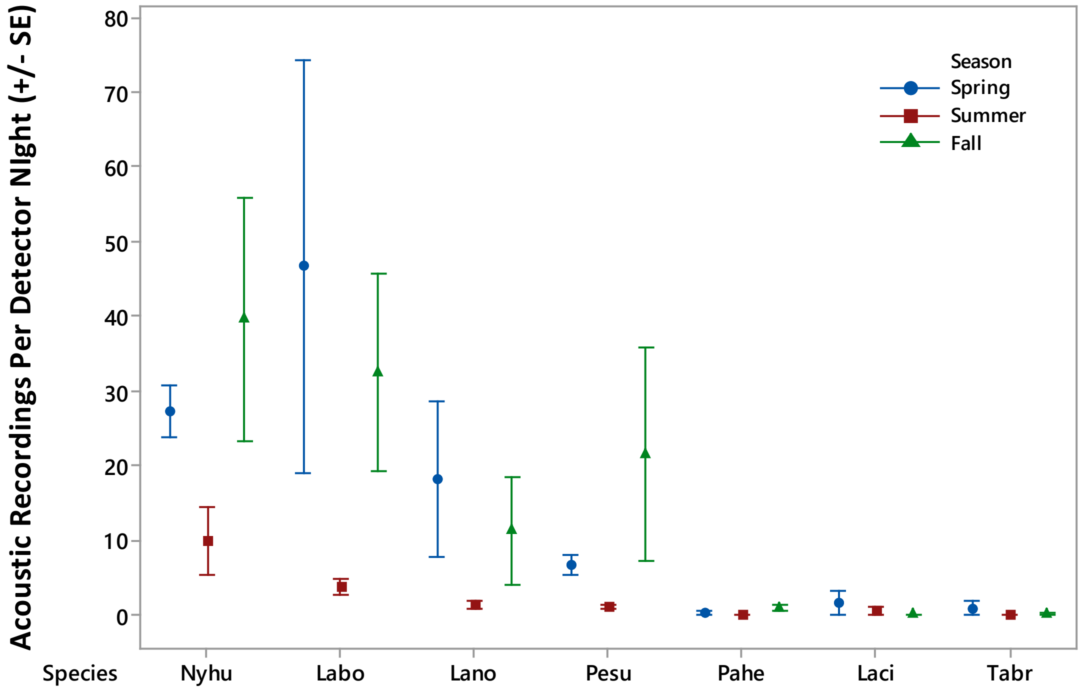

Figure 18. Acoustic recordings per detector night by season at T24 pond during 2016 deterrent testing at Wolf Ridge. Species are listed using a four letter abbreviation of the scientific name, in order of abundance.

2015 and 2016 Comparison Results

Mean bat passes for control trials during 2015 was 2.4 bats per-10 minute trial, while control trials during 2016 had an average of 5.4 bats per 10-minute trial. The average number of bat passes during pooled deterrent trials was 1.4 bats per 10-minute trial in 2015, and 1.5 bats per 10-minute trial in 2016 (Figure 19). The results of the GLM indicated that the number of observed bat passes was not significantly different between the two years for control trials ($F_{1,41} = 2.31$, $p = 0.14$) or for pooled deterrent trials ($F_{1,42} = 0.01$, $p = 0.91$).

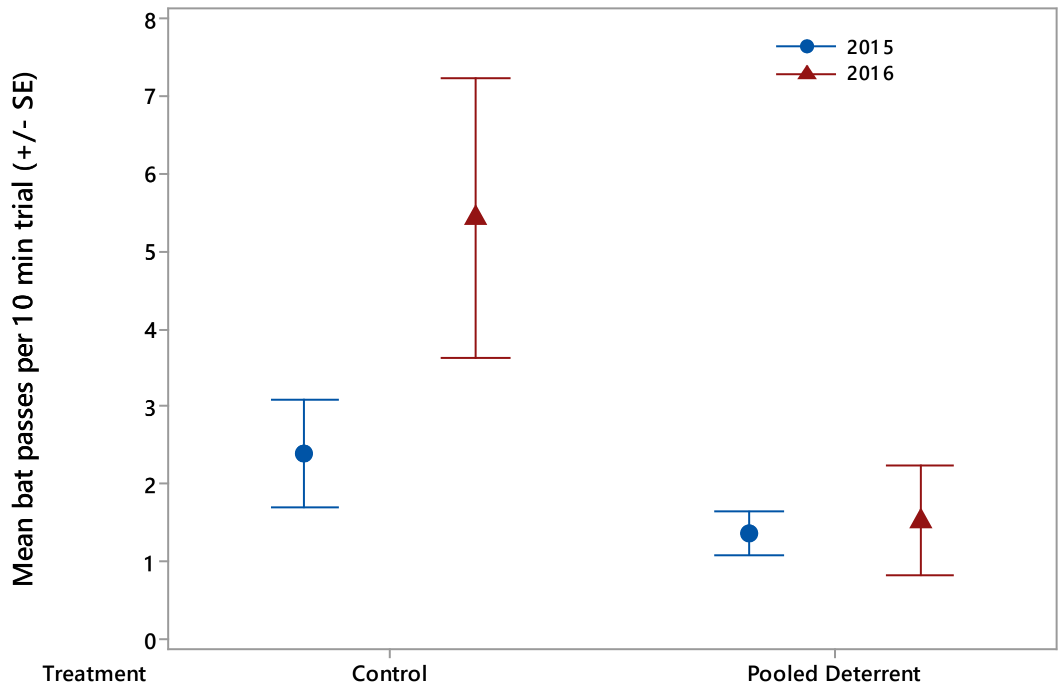

Figure 19. Comparison of deterrent effectiveness during 2015 and 2016 testing at Wolf Ridge.

Discussion

Overall, our research showed that an acoustic deterrent can reduce bat activity and alter bat behavior. We also found that the effectiveness of the deterrent is not influenced by signal (continuous, pulsing) or habitat type (pond, turbine), but is affected by distance.

In both survey years, we recorded similar rates of reduction in bat passes observed with the deterrent operating, although the results were only statistically significant in 2016. The lack of statistical significance in 2015 was likely due to the larger number of treatment groups tested (24 in 2015 vs. ~4 in 2016) and the highly variable levels of bat activity observed. Furthermore, our observed reduction in bat activity in 2016 (72-91%) was similar to the reduction (93%) recorded in a previous deterrent study also conducted over ponds (Szewczak and Arnett 2007). We also noted that in the afore mentioned study, the field of view applied extended from the deterrent device out to 12 m and covered an area of approximately 57 m^2. In contrast, our study included an area extending out to 31 m from the deterrent and covered an area of approximately 85 m^2 in 2016. Therefore, our deterrent produced a similar reduction in bat activity over a larger area, demonstrating that the device may more effectively cover the rotor swept zone. In addition, data collected during 2015 and 2016 indicate that the deterrent may prevent or minimize large peaks of bat activity. This finding may be important, as patterns of bat fatalities at some wind farms show high numbers of fatalities occurring over short periods of time (Arnett et al. 2008). If the deterrent is effective at minimizing these peaks in bat activity from occurring, then bat fatality rates could be reduced once the deterrents are installed on wind turbines.

Our study also demonstrated the importance of ultrasonic frequency range and amplitude generated by the deterrent. In 2015 we found that although our device produced a high amplitude screech at 48 kHz, this screech occurred above the characteristic low frequency of bats at our study site (Figure 4). In particular, the minimum call frequency of the eastern red bat, one of the bats most commonly killed by wind turbines, fell beneath the screech in an area that also had the lowest amplitude of sound produced by the deterrent. As a result, modifications were made in 2016 to reduce the frequency of the “screech” to closer to 40 kHz. In addition, the pulsed signals used were ramped in order to vary the frequency of the high amplitude screech, to cover more of the acoustic range of species such as the eastern red bat (Figure 7). In order to determine if this modification was effective, we compared our results from both years. We found that while there was no significant difference in bat activity reduction between the two years with the deterrent operating, the higher mean number of bats recorded in the control trials in 2016 suggests that the deterrent in this year more effectively reduced bat activity. We recommend direct in field comparisons of the deterrent signals used during 2015 and 2016 to definitively determine if a difference in effectiveness resulted from the modified deterrent signals used during 2016.

We also noted that the effectiveness of the deterrent may have been influenced by the plasticity in bat echolocation repertoires. We anecdotally found among our acoustic data collected that during deterrent testing, bats with characteristic low frequency echolocation calls above 35 kHz increased the frequency of their calls in response to the deterrent (Figure 20). In support of our results, a study conducted on for Mexican free-tailed bats showed that these bats alter their echolocation calls in response to sounds produced by natural gas extraction compressors (Bunkley et al. 2015). This shift in frequency that we observed demonstrates that bats may be able to acoustically avoid the sound of the deterrent, and highlights the importance of a broad frequency range, particularly, a range that covers the frequencies used by the bat community present at a particular wind facility.

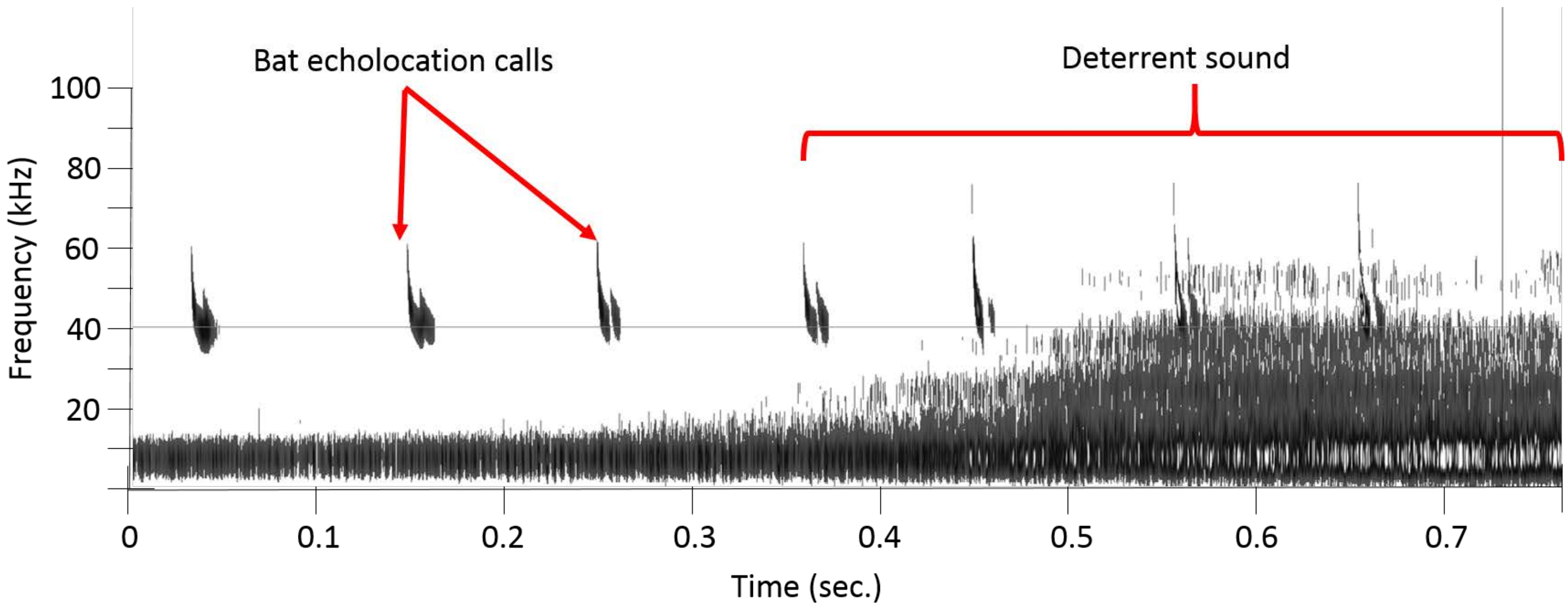

Figure 20. Eastern red bat shifting echolocation call characteristics in response to deterrent sound. Recording made during deterrent testing at a pond during 2016

Although the Wolf Ridge study site was selected, in part, because of the presence of multiple species of tree bats (hoary bats, eastern red bats, and silver-haired bats), the most commonly detected species at Wolf Ridge during 2015 and 2016 was the evening bat. These bats are residents that are not commonly found during fatality searches at Wolf Ridge (Bennett and Hale 2014). Nevertheless, evening bat echolocation characteristics are very similar to eastern red bats, so they may act as a suitable surrogate for deterrent effectiveness on eastern red bats. Another limitation to assessing the effectiveness of the deterrent was the lack of abundance of the two other species commonly reported as wind turbine fatalities (silver-haired bats <1% in 2015, 18% in 2016, and hoary bats 0% in 2015, <1% in 2016) and there are no suitable surrogates for these species at our study site. Thus, additional surveys in areas with greater silver-haired and hoary bat abundance would be necessary to evaluate the effectiveness of the deterrent on these species.

A further consideration would be amplitude of the deterrent sound. While we did not investigate the influence of amplitude in this study, we observed that variation in amplitude across frequencies may have influenced the effectiveness of our deterrent. We recommend that future studies into deterrent testing considers the 65 decibel (dB) threshold recommended by Arnett et al. (2013). Clearly identifying the decibel threshold for effective bat deterrence would be important in determining the placement of the deterrent devices to provide effective sound coverage of the rotor swept area of the wind turbines, especially because a change of only 3 dB represents a doubling of the sound level.

Another feature that may contribute to deterrent effectiveness is alteration of bat behaviors, in particular, behaviors that require complex echolocation calls (e.g., more frequency modulation; Altringham 2011). We observed reduced complex “Foraging” flight behavior and increased simple “Passing” behavior with the deterrent operating. This reduction indicated that the deterrent may have reduced the bats’ ability to effectively forage, meaning they may spend less time in the deterrent signal area. In support of our findings, there is previous evidence that deterrents reduce foraging abilities of bats (Spanger 2006). Although there were not significant differences in the proportions of other complex flight behaviors (“Contact” or “Pursuing”) flight behaviors while the deterrent was operating, an equivalent trend in reduction was observed. Furthermore, comparison of the proportions of more simple flight behaviors, such as “Reversals”, were also not significantly different. We also noted that “Reversals” made up a higher proportion of the deterrent bat passes observed, indicating that bats may be exhibiting this behavior in response to the deterrent sound. Thus if bats are, for example, foraging around wind turbines, and the deterrent influences complex echolocation, this effect may reduce foraging, which may in turn result in bats spending less time in the rotor swept zone. Our study therefore indicates that any observed changes in flight behavior with the deterrent operating could have important consequences for potential fatality reductions. Further investigations could potentially use three dimensional flight mapping to document differences in flight behaviors.

Our acoustic recordings also supported that complex echolocation calls may be influenced by the deterrent. When evaluating acoustic recordings we noted that, in certain instances, the acoustic deterrent masked the bat echolocation calls. In order for the deterrent to be effective at masking, the amplitude of the deterrent must be greater than the amplitude of the returning echoes to the bats. Our study indicated that our deterrent may mask these returning echoes, as we observed instances where either bat calls were either obscured by the deterrent sound or bats stopped echolocating (Figure 21). Either way, this demonstrates that the deterrent noise has the potential to inhibit bat echolocation.

We also noted that the sound produced by the deterrent device not only included sound in the ultrasonic frequency range (20-60 kHz), but also sound in lower frequency ranges (<20 kHz). Although previous deterrent designs have focused on mainly on ultrasound, perhaps the inclusion of lower frequency sounds may influence the effectiveness of the deterrent (Arnett et al. 2013). The rationale behind this suggestion is that bats can also hear and communicate in lower frequencies (Reyes 2015). Furthermore, low frequency sounds could result in avoidance behaviors, as previous research has indicated that bats use low frequency noise to detect predators, or that the sounds could reduce a bat’s ability to detect predators (Bennett and Zurcher 2013, Schaub et al. 2008). Thus, it is possible that some of the avoidance behavior observed in response to the deterrent tested at Wolf Ridge could be associated with these lower frequency sounds. We therefore recommend that future studies evaluate the effect of lower frequency sounds on bat activity, especially as 1) lower frequency sounds attenuate less with distance, so would remain louder at greater distances from the deterrent, and 2) such sounds may not only deter bats but other species (e.g. birds and invertebrates).

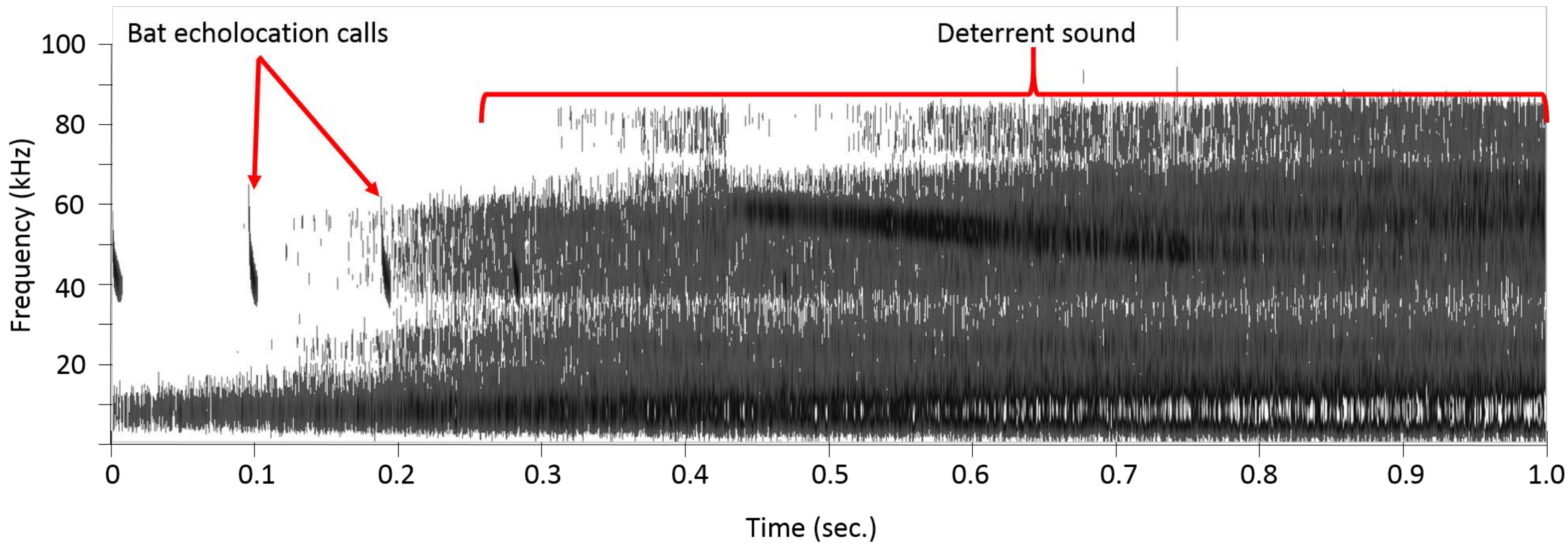

Figure 21. A representative bat call recording with bat calls visible prior to deterrent starting, then not visible. Recording made during deterrent testing at a pond during 2016.

Another feature that may have influenced the effectiveness of the deterrent was habitat type. We addressed this factor by conducting a paired study design at ponds and turbines in which we explored whether bats were behaving at these two different habitat types. In particular, we were concerned that bats may respond to the deterrent differently near the turbines compared to over the ponds. Our study indicated similar trends in response to the deterrent at ponds and turbines even though far fewer bats per trial were observed at the turbines. Consequently, we conducted surveys only at ponds during 2016 in order to better detect treatment effects. Although our study demonstrated similarities among these two habitat types, we still have concerns that bat behavior around turbines, particularly in the rotor swept zone, may be different enough to influence the effectiveness of the deterrent and therefore recommend deterrent studies in the rotor swept zone.

In addition to exploring the effectiveness of the deterrent, we investigated whether signals could be pulsed and remain effective. When comparing the pulsing signals to the continuous on signal, we did not detect a difference in the rate of reduction in bat passes observed during either year, supporting the use of pulsed signals to allow for additional deterrent nozzles to operate using the same amount of infrastructure (i.e., air compressors). The ability to install multiple nozzles may subsequently increase coverage, and therefore increase the effectiveness of the deterrent for reducing bat activity, potentially resulting in reduced fatalities.

Finally, we explored whether bat activity in response to the deterrent varied with distance. We found that the reduction in bat activity was significantly higher with the deterrent at 10 m than at 30 m at ponds. This reduction in effectiveness with distance is likely due to the attenuation of sound, especially high frequency ultrasound (Szewczak and Arnett 2007). Attenuation is an important determinant of deterrent effectiveness, especially as the length of many wind turbine blades already exceed 50 m, and some offshore wind turbines have blade lengths up to 80 m (USDOE 2015). With increases in the size of the rotor swept zone, the location and number of deterrent nozzles would need to be increased in order to cover the same proportion of the rotor swept zone at a sufficient sound level to deter bats. To resolve the reduction in effectiveness of the deterrent due to attenuation would require the installation of multiple deterrent nozzles on the turbine nacelle, tower, and possibly along the length of the turbine blades.

A further implication for reduction in effectiveness of the deterrent with distance is associated with high levels of relative humidity. A previous deterrent study was conducted at relative humidity ranging from 76.8-86.5% (Arnett et al. 2013). They noted that ultrasound attenuates more quickly at higher humidity. In comparison, during deterrent testing at Wolf Ridge, relative humidity ranged from 27-87%, with an average of 45% in 2015. During 2016, relative humidity in the spring season averaged 47%, in the summer the average was 70%, and in the fall the average was 52%. As humidity at Wolf Ridge was generally lower than in the Arnett et al. (2013) study, attenuation would have been lower. The deterrent may, therefore, be more effective at deterring bats in lower humidity areas.

Our study revealed two other considerations that could influence the assessment of deterrent effectiveness; 1) season and 2) variations in nightly bat activity. First, bat activity varied significantly among the seasons, with lower activity during the summer, compared to the spring and fall. This variation in activity corresponds to bat migration, with the highest activity levels recorded in the fall migration period. Thus, we recommend that evaluations of deterrent effectiveness be conducted during the fall migration. Second, we found that bat activity varied dramatically, from zero to 69 bat passes observed at a location during a single survey night. This variation may have been due to migratory bats moving through our study site, creating these pulses in activity, or inactivity, that strongly influenced our ability to detect treatment effects.

One aspect of our study design that may have affected our results was that compressed nitrogen, supplied using gas cylinders, was used to operate the acoustic deterrent, due to the availability of compatible hardware for the project. However, the deterrent is designed to operate using air supplied by compressors once deployed on wind turbines. Air is about 78% nitrogen, 21% oxygen, and small amounts of other gasses. The difference in the composition of the gas expelled through the nozzle could change the sound produced. Furthermore, the difference between the density of nitrogen and air, with nitrogen being about 3% lighter than air, varies less than the difference in air density over the range of temperatures that will occur during deployment of the deterrent on wind turbines. Thus, the sound produced during our study was expected to be within the range of sounds produced once the deterrent is operating on compressed air.

Another aspect of our study design that may have affected our results was whether multiple trials (deterrent and control) conducted during a single survey night were independent (e.g., did the first deterrent treatment impact bat activity in subsequent trials). In the same way, differences between the effectiveness of the various deterrent treatments, if present, could be better detected using a completely independent sampling design. However, controlling for the other extraneous variables, especially inter-night and inter-location variation in levels of bat activity, in a natural environment, could prove difficult.

A third aspect of our study design that may have affected our results was the use of different camera types (night vision vs. thermal). The thermal cameras had several advantages over the night vision. First, the resolution of the thermal cameras and greater ability to detect bats, relative to the night vision cameras, allowed a larger focal area to be monitored simultaneously in front of the deterrent (i.e., night vision ~43 m^2 and thermal ~85 m^2). Another advantage of the thermal cameras was in distinguishing bats from insects. The thermal signature associated with bats observed using thermal cameras allowed us to distinguish between bats and large flying insects with greater confidence, and also increased video processing efficiency. Finally, the thermal cameras used during 2016 were networked together and time synchronized with a computer. Synchronization made the timing of the paired videos align more accurately during video analysis. For these reasons, we recommend that thermal cameras be used for this type of behavioral study.

Conclusion

Our research is supported by previous studies indicating that deterrents could help to reduce bat fatalities at wind energy facilities (Szewczak and Arnett 2007, Arnett et al. 2013). The reduction rate in bat passes observed during our deterrent trials are similar to the rates of bat fatality reduction documented during curtailment studies at wind turbines (Arnett et al. 2011, Baerwald et al. 2008, Martin et al. 2017). Thus, if the rates of reduction in bat passes observed during the deterrent trials, translates into similar rates of fatality reduction once the devices are deployed on wind turbines, then this deterrent may be as effective at reducing bat fatalities as curtailing wind turbines at low wind speeds.

The results from this study will be used to inform the number and orientation of deterrent nozzles and the deterrent signal utilized when the deterrent is tested in the rotor swept zone of wind turbines during future research. These future studies will ultimately determine if the reductions in bat passes observed at Wolf Ridge during deterrent testing translate into reductions in bat fatalities at sufficient levels for the deterrent to be considered an alternative to siting restrictions and curtailment. Alternatively, the deterrent could be used in coordination with these and other methods to achieve the targeted reductions in bat fatalities, while still allowing wind energy to be an economic, clean, and renewable source of energy.

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Vita

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Abstract

ASSESSING CHANGES IN BAT ACTIVITY IN RESPONSE TO AN ACOUSTIC DETERRENT — IMPLICATIONS FOR DECREASING BAT FATALITIES AT WIND FACILITIES

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Wind energy is a renewable resource with many environmental benefits. However, one environmental impact from wind energy is on bats, because bats are killed when they fly into the path of spinning turbine blades. Estimates of bat fatalities at wind facilities across the U.S. exceed 500,000 per year. One potential way to reduce bat fatalities at wind facilities is with acoustic deterrents. These devices, including the newly designed acoustic deterrent tested during this study, produce sound to deter bats. At a wind farm in north-central Texas, we assessed changes in bat activity at wind turbines and closely associated cattle ponds in response to the acoustic deterrent. The acoustic deterrent reduced the level of bat activity by up to 90%, indicating it has the potential to reduce bat fatalities when installed on wind turbines.