DOES A TEXTURED COATING ALTER BAT ACTIVITY AND BEHAVIOR IN PROXIMITY TO WIND TURBINE TOWERS?

By

BRYNN HUZZEN

Bachelor of Science, 2016
University of Florida
Gainesville, Florida

Submitted to the Graduate Faculty of
the College of Science and Engineering
Texas Christian University
in partial fulfillment of the requirements
for the degree of

Master of Science

May 2019

Acknowledgments

I would like to thank the United States Department of Energy, Nextera Energy Resources, and the Adkins Fellowship Fund from the Biology Department at TCU for the funds that made this research possible. I would also like to thank the technicians from the Bat Lab who gave some or all of their summer for this project: Ryan Conley, Martin McQueen, Emily Inglis, Michael Kaufman, and Matthew Lackey. In addition, I'd like to thank many members of the Environmental Science department for countless venting sessions and comic relief when very much needed: Madison Peppers, Jimmy Greene, Ellen Hall, Kristen Debone, Alyssa Austin, Michaela Donahoo, Alec Laurenti, and Izzy Agpalo. I'd also like to especially thank Katie Smith and Martin McQueen for their irreplaceable friendships and support. I don't believe I would have made it through this program without them.

In addition, I would like to thank my advisor Dr. Tory Bennett for her continuous guidance throughout this project, and the innumerable things she has taught me about bats, academia, scientific writing, and life. I would also like to thank Dr. Amanda Hale for her help and advice throughout this project, especially her statistical assistance. Additionally, I'd like to express my gratitude to Dr. John Horner for always having his door open to me, listening and advising me, and his extremely helpful feedback for this thesis.

Lastly, I'd like to thank my family and friends for their support and understanding through this stressful two years. I promise to be a better friend, daughter, sister, cousin, and granddaughter after this!

Table of Contents

List of Figures

List of Tables

Introduction

Wind power is a fast-growing source of renewable energy and has become prominent and widespread around the world (Ren21 2017; Wiser & Bolinger 2017). While the benefits of wind energy include reducing our reliance on fossil fuels and lessening their environmental impacts, it has become evident that there are some disadvantages to this form of energy generation. For example, large numbers of bat fatalities have been reported at wind farms globally and the majority of these comprise migratory and highly mobile bat species (Arnett *et al.* 2008; Lehnert *et al.* 2014; Roscioni *et al.* 2014). Many fatality monitoring programs have been conducted in recent years to understand and assess the magnitude of this threat (Kunz *et al.* 2007; Arnett *et al.* 2008; Piorkowski & O'Connell 2010; Baerwald & Barclay 2011). From these studies, it has been estimated that hundreds of thousands of bats are being killed every year by wind turbines in North America alone (Arnett & Baerwald 2013; Zimmerling & Francis 2016; AWWI 2018), with peak fatalities occurring during bat migration (Arnett *et al.* 2008; Baerwald & Barclay 2011; Jameson & Willis 2014). Furthermore, such studies have revealed that three species of tree-roosting bat make up approximately 75% of wind turbine fatalities in North America: hoary (*Lasiurus cinereus*), eastern red (*Lasiurus borealis*), and silver-haired bats (*Lasionycteris noctivagans*; Arnett & Baerwald 2013; AWWI 2018). While the implications of such high levels of mortality are unknown, it has been predicted that if trends continue bat populations will inevitably be impacted (Frick *et al.* 2017). There is, therefore, a pressing need for strategies that minimize both the proximate (i.e., direct cause of mortality) and ultimate (i.e., why bats are coming into close proximity with turbines) causes of bat fatalities.

Currently, it is not entirely understood why bats are interacting with wind turbines, but there are three proposed hypotheses: 1) interactions are purely incidental and any fatalities that occur are representative of local bat abundance; 2) resources, such as roosting sites, mating opportunities, commuting/migration routes, foraging sites, or water sources are available in close proximity to wind turbines; and 3) the wind turbines themselves provide or are perceived to provide a resource for bats (Cryan & Barclay 2009). As the majority of fatalities appear to involve solitary tree-roosting bats and occur in areas with little or no known resources, this suggests that such species may be attracted to wind turbines (Bennett & Hale 2018).

A number of studies provide support for the attraction hypothesis (Cryan *et al.* 2014). For example, a study by Bennett et al. (2017) found bat feces in turbine door slats, indicating bats were using wind turbines as night roosts. Another study by Jameson and Willis (2014) suggested that bats are attracted to tall anthropogenic structures during migration and found that the bat calls recorded at such structures were primarily composed of social calls indicative of mating behavior. Cryan *et al.* (2014) suggested that bat behavior around wind turbines was similar to behavior observed at tall trees, such as searching for roosts, potential mates, or insect prey. Furthermore, two studies examined the stomach contents of bat carcasses retrieved from beneath wind turbines (Valdez & Cryan 2013; Foo *et al.* 2017). They found that many of the stomachs were not only full (a sign of recent foraging), but also contained a similar composition of invertebrates to those captured on and around the wind turbines (Valdez & Cryan 2013; Foo *et al.* 2017). Finally, a study by McAlexander (2013) explored the behavior of bats at turbines and recorded bats approaching tower surfaces with the same posture as they would when drinking at nearby water sources. This body of evidence suggests that bats are interacting with turbines because the turbines themselves provide or are perceived to provide one or more resources for bats. Thus, to prevent bats from coming into contact with wind turbines, we must understand what characteristics of the turbines may be attracting bats.

Several studies have hypothesized that turbine tower surfaces may be a source of attraction. For example, a study by Long *et al*. (2011) found that the light-colored painted surfaces of turbine towers attracted insects and hypothesized that this in turn would provide a foraging resource for insectivorous bats. Moreover, additional studies have shown that bats cannot acoustically distinguish artificial smooth surfaces (such as metal, wood, plastic, or glass) from water (the only smooth surface found in nature) and reported that naïve bats would repeatedly attempt to drink from such surfaces (Greif & Siemers 2010; Russo *et al.* 2012). As wind turbine towers are smooth metal surfaces, it could be hypothesized that bats misperceive those surfaces to be water. McAlexander (2013) conducted a playback experiment using artificial bat calls played at local water sources and turbine tower surfaces. The study revealed that there was no significant difference between echoes returning from either surface. This finding therefore supported the aforementioned hypothesis. Furthermore, as wind turbine towers are smooth surfaces, they could also act as acoustic mirrors (Geipel *et al.* 2013; Greif *et al.* 2017). The acoustic mirror effect is a phenomenon in which bats use smooth surfaces to more readily locate and capture prey (Geipel *et al.* 2013). As echoes returning from these surfaces are free of noise, prey identification is more effective and the acoustic mirror effect can thereby increase foraging success. As a result of the acoustic mirror effect, many bat species are known to forage above and from water surfaces as well as from smooth leaves (Geipel *et al.* 2013; Clare & Holderied 2015; Greif *et al.* 2017). In addition, studies by Foo *et al.* (2017) and Bennett *et al.* (2017) both showed evidence that bats forage around wind turbines, potentially because they offer high-efficiency foraging resources.

Thus if the smooth surfaces of wind turbine towers are attracting bats, we further hypothesize that changing the surface texture could reduce bat activity in proximity to turbine towers and, therefore, reduce the risk of bats coming into contact with moving blades. A potential mitigation strategy would be to identify a texture that reduces bat activity, is cost effective, and can be applied to turbine towers during both the operational and manufacturing stages. One crucial caveat to texture design would be to ensure that the texture coating would not be perceived as an alternative resource for bats. For example, the texture should not have similar characteristics to tree bark. Moreover, given the variable ecological and behavioral differences between bat species (Altringham 2011), we would also need to determine if a texture coating could be effective for most, if not all, at-risk bat species.

To address these issues, Yuen (2015) conducted a playback experiment testing synthetic echolocation calls from a representation of different bat species on a selection of different textures. These textures were: 1) a smooth painted surface using the paint typically applied to General Electric wind turbine towers; 2) a painted wood-chip surface; and 3) three surfaces with a paint/sand mixture applied. Between these latter surfaces, the sand particles differed in size. Yuen (2015) then compared the characteristics of echoes returning from each surface and determined that among these surfaces, echoes demonstrated species-specific differences. Yuen (2015) further generalized these species differences into two categories; high and low frequency bat species. High frequency bats were defined as those that echolocated at frequencies above 35 kHz (including eastern red, evening (*Nycticeius humeralis*), and tri-colored (*Perimyotis subflavus*) bats) and low frequency bats as species that echolocated at frequencies below 35 kHz (including hoary, Mexican free-tailed (*Tadarida brasiliensis*), and silver-haired bats). The study indicated that high frequency bats should be able to distinguish between smooth painted surfaces and surfaces with small particle sizes, whereas low frequency bats would only distinguish between smooth and textured surfaces when the largest particle size was present. In addition to this study, Bienz (2016) explored wild-caught bat interactions between smooth and textured surfaces in a controlled flight facility. This behavioral study found that, while high frequency bats made contact with water and smooth surfaces, they did not make contact with textured surfaces supporting Yuen (2015)'s results. Bienz (2016) also revealed that at surfaces with the largest particle sizes, high frequency bats approached gaps between the particles. In contrast, where large particles had clustered together, bats were able to land on and cling to these particles (Bienz 2016). Thus, the results of both studies indicated that a textured surface for multiple species not only had to be a mixture of small and large particle sizes, but it also would need a high density of small particles interposed with a low density of evenly distributed large particles to limit gap size. In 2016, a texture meeting these characteristics was developed and tested in a flight facility in a second behavioral study. In this controlled environment, bats had little or no contact with the textured surfaces and reduced activity in proximity to these surfaces in comparison to their equivalent smooth surface. Given these results, the next step was to apply this texture to wind turbine towers at an operational wind farm and explore the responses of wild bats to textured turbines.

The objective of our study was, therefore, to execute a paired behavioral survey at smooth and texture-treated wind turbine towers at an operational wind farm in north-central Texas. For this study, we used video and acoustic technology to observe bat activity and behavior at wind turbine towers and predicted if the texture treatment was effective, bat activity would be lower at textured turbines compared to the smooth. In addition, we conducted fatality monitoring surveys to determine patterns in bat fatality and potentially determine if there was a relationship between bat activity and fatality. If our results support predictions and a cost-effective texture treatment could be applied to both at operational wind turbines and turbines during the manufacturing process, then such a treatment may be an effective mitigation strategy to reduce bat fatalities at wind farms worldwide.

Methods

Study site

We conducted surveys at Wolf Ridge Wind, LLC (hereafter referred to as Wolf Ridge; N 33°43’53.538”, W 97°24’18.186”). Wolf Ridge is owned and operated by NextEra Energy Resources and consists of 75 1.5-MW General Electric wind turbines (model: GEA14954C15-MW). These turbines have a cut-in speed of 3.0 m/s and cut-out speed (10 minute average) of 20 m/s (General Electric 2009). The turbine blades measured 42 m in length, the rotor-swept zone is 5,346 m^2 with a hub height of 80 m.

The area encompassing the wind resource site consists of two distinct habitats (Fig.1). To the north of the property, scrub woodland surrounds an underlying watershed leading to the Red River escarpment. The southern, eastern, and western parts of the site are subject to continued disturbance as a result of agricultural practices, including cattle grazing, native hay harvesting and winter wheat (*Triticum aestivum*) cultivation. In total the wind resource area extends over 48 km^2, with wind turbines spaced approximately 1 ha apart.

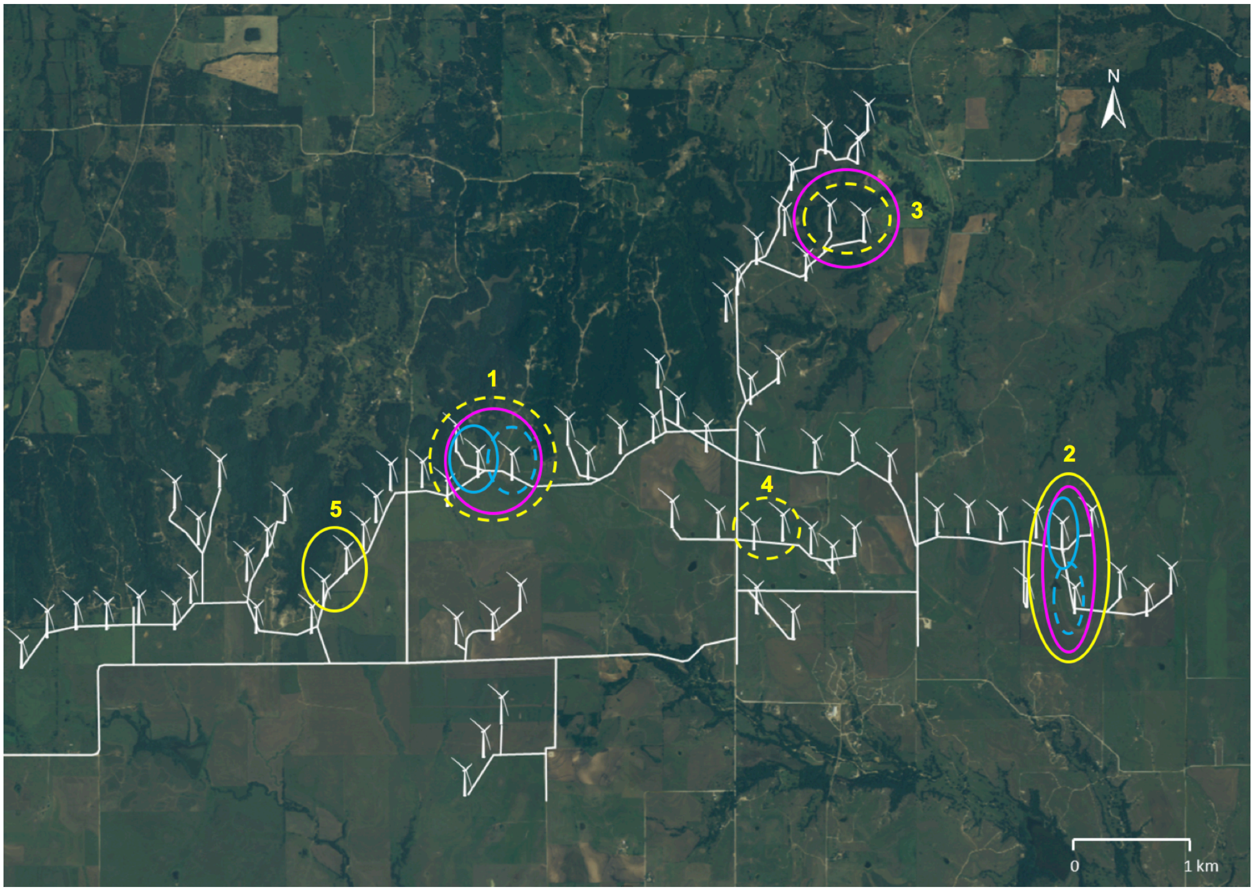


Figure 1: Map of Wolf Ridge Wind, LLC in north central Texas. Wind turbine pairs labeled 1-5 and circled in yellow show the paired turbines with high numbers of bat fatalities recorded in fatality monitoring surveys from 2009 to 2014. The dashed yellow outline denotes turbine pairs that were included in the feasibility study undertaken in 2016. Paired turbines circled in pink represent turbines surveyed in 2017 prior to texture application. Paired turbines circled in blue represent turbines surveyed after the texture application. Within each pair, a solid blue outline identifies smooth turbines (towers without the texture coating), while a dashed blue outline delineates towers with texture coating.

Since Wolf Ridge became operational in December 2008, researchers at Texas Christian University (TCU) have been examining both the direct and indirect impacts of wind turbines on bats at the site. Surveys conducted include fatality monitoring from 2009 to 2014, acoustic surveys from 2009 to 2017, behavioral studies at turbines and nearby ponds from 2012 to 2017, acoustic deterrent testing from 2015 to 2016, and invertebrate sampling surveys in 2012, 2013, and 2015. From both acoustic and fatality monitoring, 6 bat species have been identified at Wolf Ridge. Six species have been consistently reported every year: eastern red, hoary, silver-haired, tri-colored, evening, and Mexican free-tailed bats, while a 7th species, the canyon bat (*Parastrellus hesperus*), has been acoustically recorded with increasing frequency since 2012.

Preliminary Feasibility Study

To determine if the application of a texture coating successfully reduced bat activity in proximity to wind turbine towers, we sought to compare bat activity and behavior between a subset of smooth and textured turbine towers. To maximize data collection, we conducted a feasibility study in 2016 to refine our study design by 1) identifying pairs of turbines that have historically similar high levels of bat activity, 2) establishing when peaks occur in both seasonal and nightly bat activity at our study site, and 3) determining optimal equipment set-up.

Identifying paired turbines

Using data from fatality monitoring surveys, we first identified turbines with high levels of bat fatality. We then selected ten turbines (five pairs; Fig. 2) based on four criteria: 1) turbines within a pair were approximately 1 ha apart; 2) the number of bat fatalities per tower within a pair were similar; 3) location of pairs was broadly distributed across the study site; and 4) the area surrounding all turbines comprised short grass extending 50 m from the turbine base to maximize carcass detection.

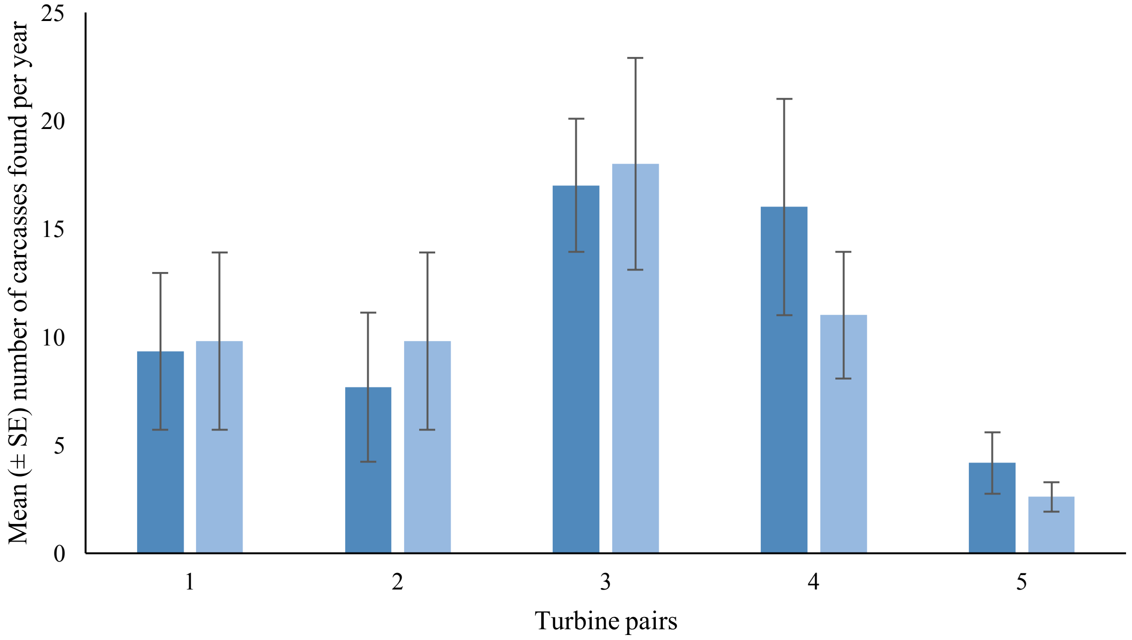


Figure 2: Average (± SE) number of bat carcasses found per year at turbine pairs 1-5, shown in Fig. 1, during fatality searches at Wolf Ridge from 2009 to 2014. The shades of blue indicate the 2 turbines within each pair.

As fatality levels within each of the five pairs selected were similar (Fig. 2), we considered it appropriate to survey three of the five original pairs (pairs 1, 3, and 4) in our feasibility study. These three pairs were selected based on landowner access and turbine operations at the time of the surveys. We then conducted behavioral surveys using night vision and thermal camera technology along with acoustic bat detectors at these selected turbine tower surfaces from July to mid-August 2016.

The results of the behavioral surveys, shown in Fig 3, demonstrated that observed levels of activity were comparable between each of the selected pairs. To confirm this, we used a series of paired *t* tests and found no significant difference in the number of bats observed per hour between turbines in each pair (Pair 1: *t*=0.17, *df*=3, *P*=0.876; Pair 3: *t*=3, *df*=1, *P*=0.205; Pair 4: *t*=-1.77, *df*=4, *P*=0.151).

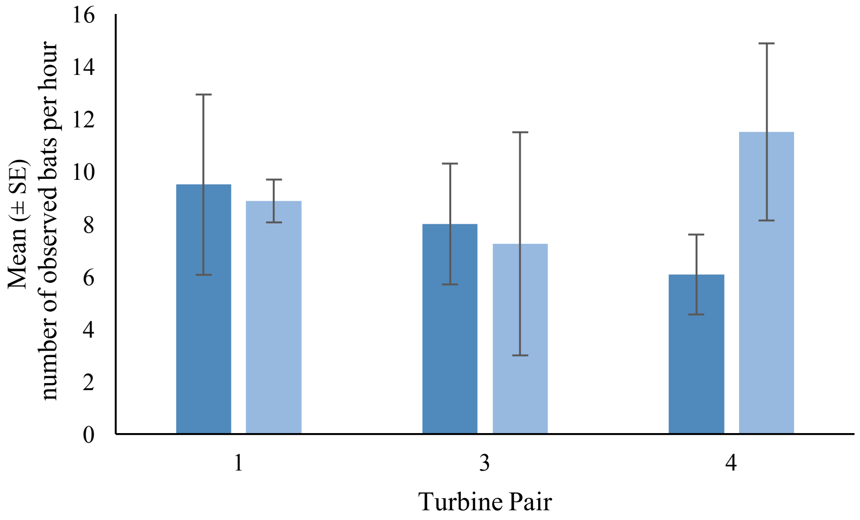


Figure 3: The mean number (± SE) of observed bats per hour recorded at each turbine pair studied at Wolf Ridge from 9 July to10 August 2016 during the feasibility study. The shades of blue indicate the 2 turbines within each pair. Turbine Pair 1 was surveyed for 5 nights, Turbine Pair 3 for 4 night, and Turbine Pair 4 for 7 nights.

Establishing survey timing

To optimize data collection, our surveys needed to coincide with peaks in bat activity, both across the survey period (i.e., seasonally) and within a survey night. All previous surveys at Wolf Ridge demonstrated a peak in bat activity between the months of July and September (McAlexander 2013), which coincided with the fall migratory period (Arnett & Baerwald 2013; Weller *et al.* 2016; Fig. 4). Furthermore, within a night, bat activity has been found to peak within a 3-hour period starting at dusk (Hayes 1997; Baerwald & Barclay 2011; McAlexander 2013). To explore survey timing further, we recorded bat activity between 20 minutes after sunset (i.e., dusk) and 200 minutes after sunset in our feasibility study. We found that bat activity peaked within the 3 hours after dusk, confirming that this survey period was appropriate (Fig. 5).

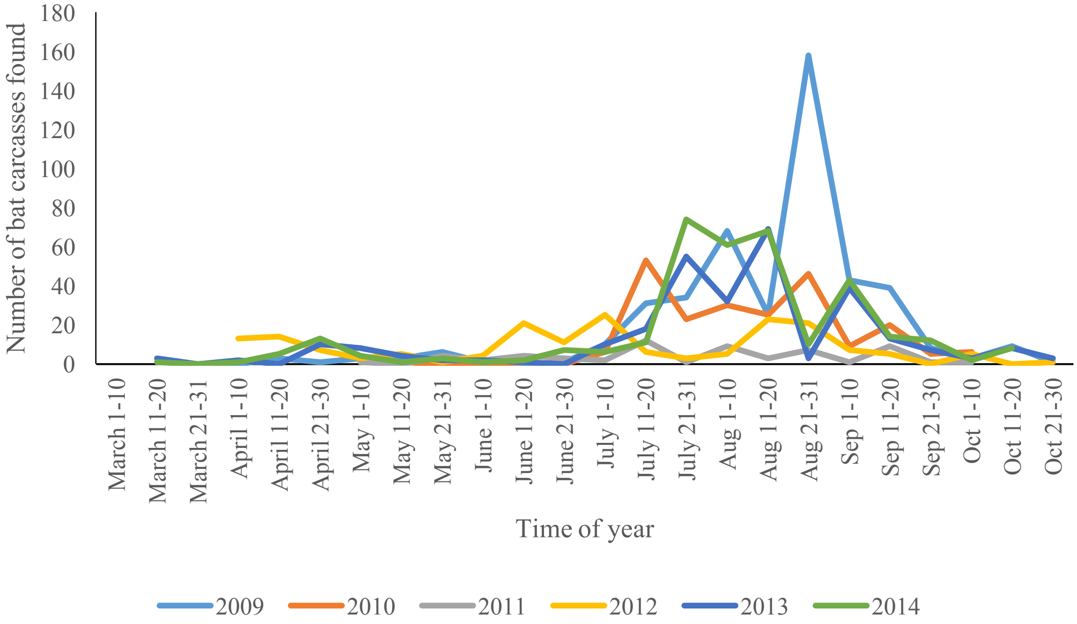


Figure 4: The pattern of bat fatality, demonstrated by the number of bat carcasses found during fatality searches at Wolf Ridge in previous years. Note that search method and sample size varied among years.

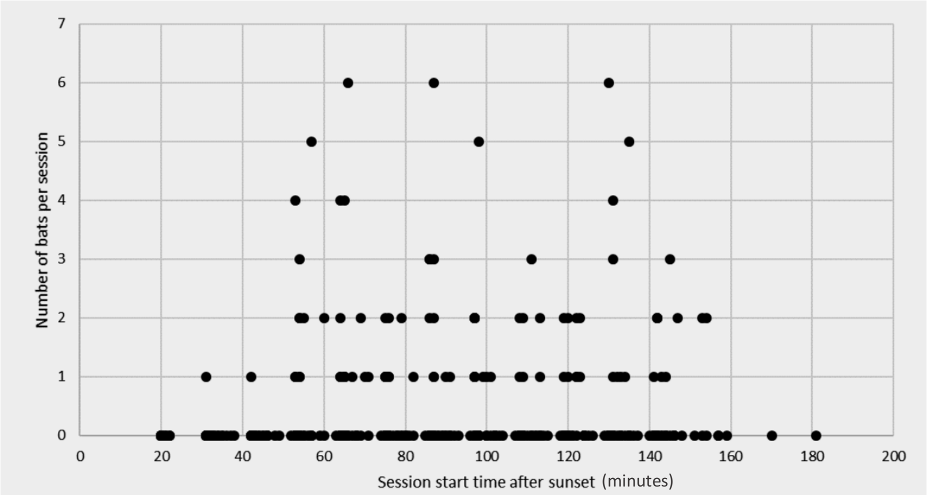


Figure 5: Bat activity in the 200 minutes after sunset during the 2016 feasibility study at Wolf Ridge.

Optimizing equipment set-up

To date, two different video technologies are available that can be used to survey bat activity at wind turbines: night vision (Warren *et al.* 2006; Fuller *et al.* 2012) and thermal imaging (Blowers *et al.* 2015; Matzner *et al.* 2015; Hayman *et al.* 2017). These methods vary both in their image resolution and field-of-view. To determine which technology could maximize bat observations and identify specific behaviors in proximity to turbine towers, we tested both night vision and thermal technology in our feasibility study.

As night vision technology had been used for similar behavioral surveys at our study site in the past, we continued to use the set-up in which night vision cameras were placed 2 m from the base of the turbine tower and angled upward toward the bottom of the nacelle (the cover that houses generating components; McAlexander 2013). For the thermal cameras, which we had not used before, we first determined the optimal distance and angle at which bats could be observed in close proximity to wind turbine towers. Previous studies using thermal cameras to assess bat activity at wind farms tended to focus on activity in the entire rotor swept zone (RSZ) rather than the tower surface (e.g., Horn *et al.* 2008; Cryan *et al.* 2014). While farther camera distances offer a wider field-of-view to maximize visible areas around the turbines, a narrower field-of-view could increase bat detectability. Subsequently, we placed a thermal camera 2 m, 25 m, 50 m, and 95 m from the tower base, adjusting the angle to optimize the view of the tower when necessary, to assess whether distance impacted the number of observable bats (see Fig. 6). We found that at distances of 2 m, bats were more visible at the turbine towers, while still providing a field-of-view in which approaching bats could be seen (Fig. 6A).

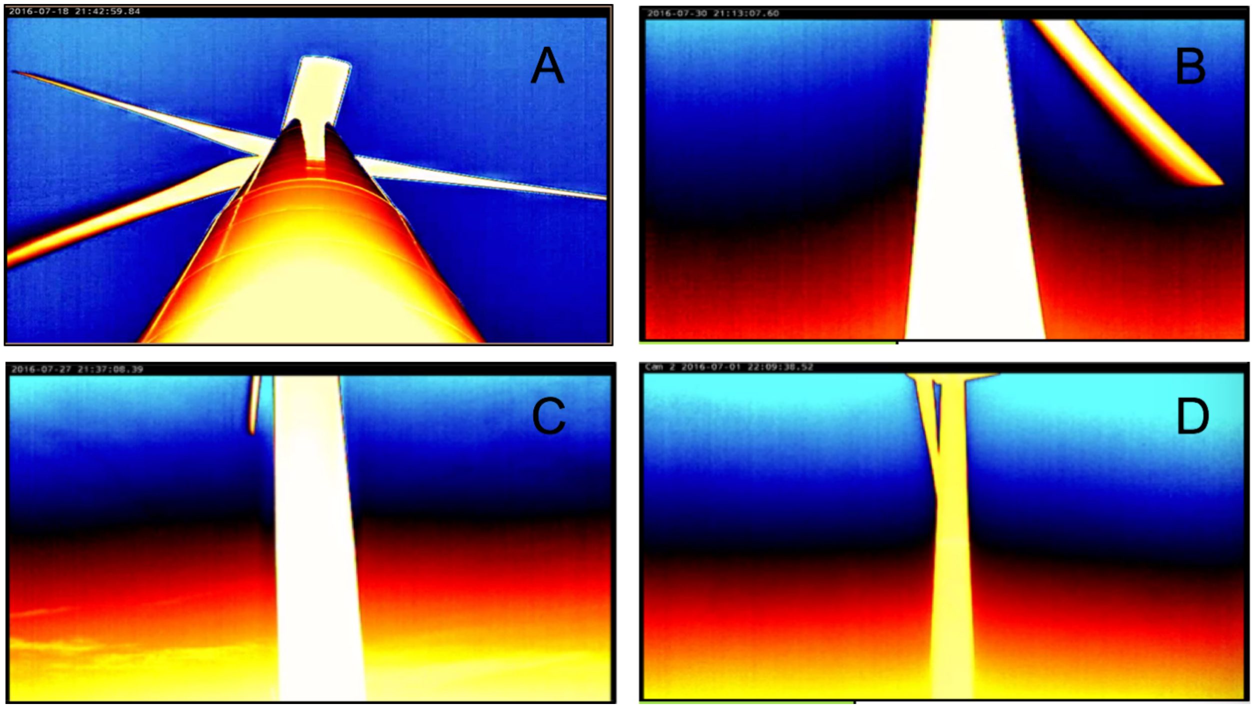


Figure 6: Field-of-view of thermal camera placed A) 2 m from turbine base; B) 25 m from turbine base; C) 50 m from the turbine base; and D) 95 m from the base of the turbine during the 2016 feasibility study at Wolf Ridge.

We also noted that when using thermal cameras, the heat signature from the turbine towers was greater than that of the bats, which resulted in bats disappearing from view as they passed in front of the tower. Thus, the use of thermal cameras alone could potentially limit our ability to observe specific bat behaviors at or near the tower surface. As bats could be detected more clearly when approaching turbine towers using thermal cameras and bat behavior was more visible using night vision technology, we concluded that using both technologies simultaneously would maximize data collection.

Paired Behavioral Survey

To determine how free-flying bats respond to texture-coated towers at operational wind turbines, we conducted a series of behavioral surveys from 16 May to 22 September 2017. First, we undertook preliminary bat activity surveys at three sets of paired turbines from 20 May to 18

June 2017 (Fig. 1). We then created a texture coating application plan designed to match the size, distance, and density of particles from previous experiments (Yuen 2015; Bienz 2016), and the texture coating was applied at two of the three sets of paired turbines between 19 and 24 June 2017 (Fig. 7). The coating was applied around the entire turbine tower from 10 to 43 m above ground, thus incorporating the lower portion of the RSZ. Within each pair, the texture coating was applied to one turbine and the other was used as a smooth for comparison. While the texture application plan detailed identical texture applications to all turbine towers in our study, the manual application process was subject to error, as multiple layers of materials were used and applied at great height. In fact, the amount of materials used during the texture application differed between the turbines in both pairs, and the final textures were not identical between turbines. We continued to survey bat activity and behavior at these 2 pairs of turbines from 24 June to 22 September 2017.

Figure 7: Texture coating application at a wind turbine at Wolf Ridge in June 2017.

Surveys were conducted up to 5 nights per week, weather permitting. Each turbine pair was surveyed on rotation and during a night, surveys were conducted at both turbines within a pair simultaneously using night vision technology, thermal cameras, and ultrasonic acoustic recorders (using the setup determined in our feasibility study above).

Night vision technology

Two night vision set-ups were placed approximately 2 m from the base of a turbine, one on the leeward and one on the windward side of the turbine tower (Fig. 8). Each set-up comprised an

ATN NVM14 night vision scope attached to a Sony HDR-PJ790 video camcorder on a Manfrotto MT055XPRO3 tripod. Note that during the first trial of the night, we used only the Sony camcorders as the night vision cannot function during low light levels. The scopes were then attached to the Sony camcorders for the second trial onwards. The night vision/camcorders were angled upward, with a field-of-view that incorporated the turbine tower from approximately 10 m above the gravel pad to the ventral surface of the nacelle hub (80 m high). The equipment set-up also included two ATN Super Long Range Infrared Illuminator IR450 lights on VELBON EF tripods. These lights were placed approximately 1 m from either side of the night vision/camcorders, and also angled upward to effectively illuminate the turbine tower surface (Fig. 6A). Additionally, we placed a Pettersson ultrasound detector D240x next to each night vision/camcorder set up to provide an audible indication that a bat was present in real time during recorded trials. These detectors have a range of 35 m and were set at a frequency of 40 kHz to capture ultrasonic calls between 20 and 60 kHz, encapsulating the frequency range for all the known local bat species.

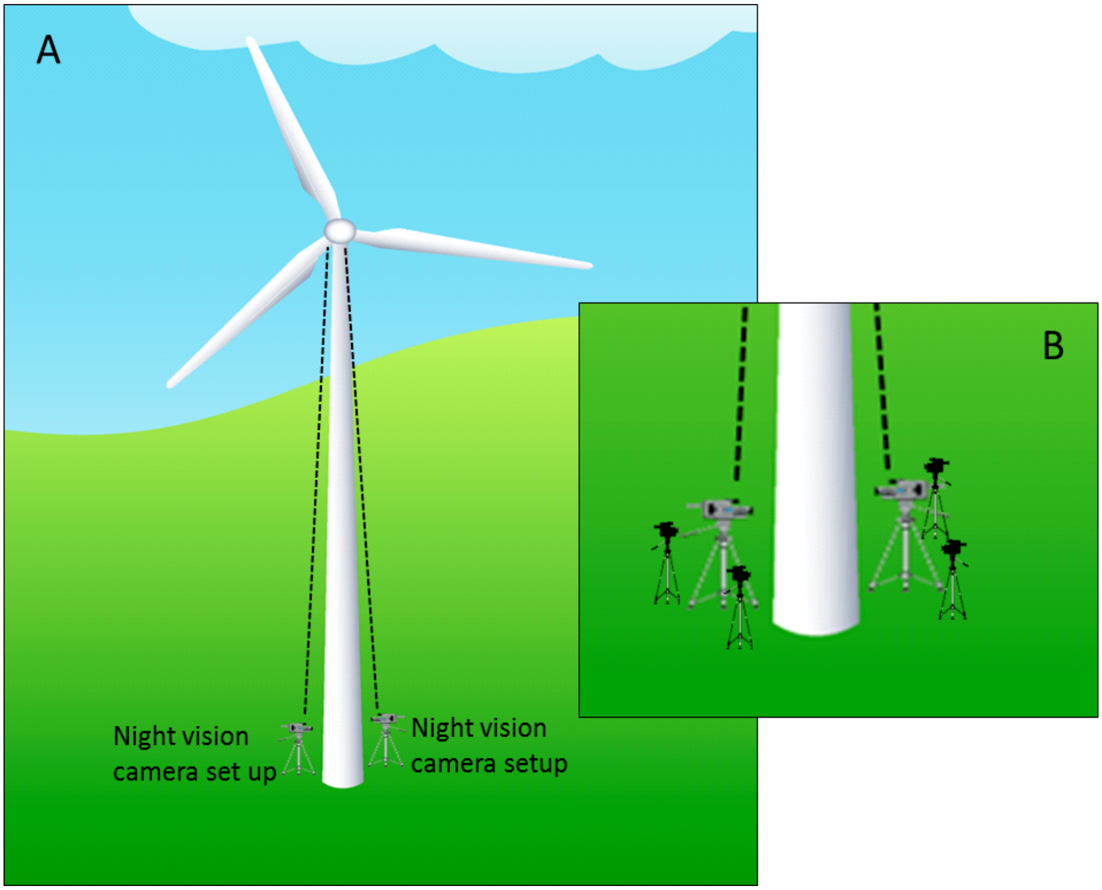


Figure 8: Diagram of night vision/camcorder set-up for bat behavioral surveys at wind turbine towers at Wolf Ridge. **A** depicts a broad view of the equipment set-up, whereas **B** shows a more detailed view of night vision/camcorder set-up with IR lights on either side to illuminate turbine towers.

Thermal cameras

Two thermal cameras were set up at each turbine directly adjacent to the night vision/camcorders, with one on the leeward and one on the windward side of the turbines (Fig. 9). Each thermal camera set-up consisted of an Axis Q1932-E 19MM thermal camera mounted on a Manfrotto MT055xPRO3 tripod. The cameras were angled upward in the same fashion as the night vision/camcorders, again extending up the tower to the ventral surface of the nacelle (Fig. 9B and C).

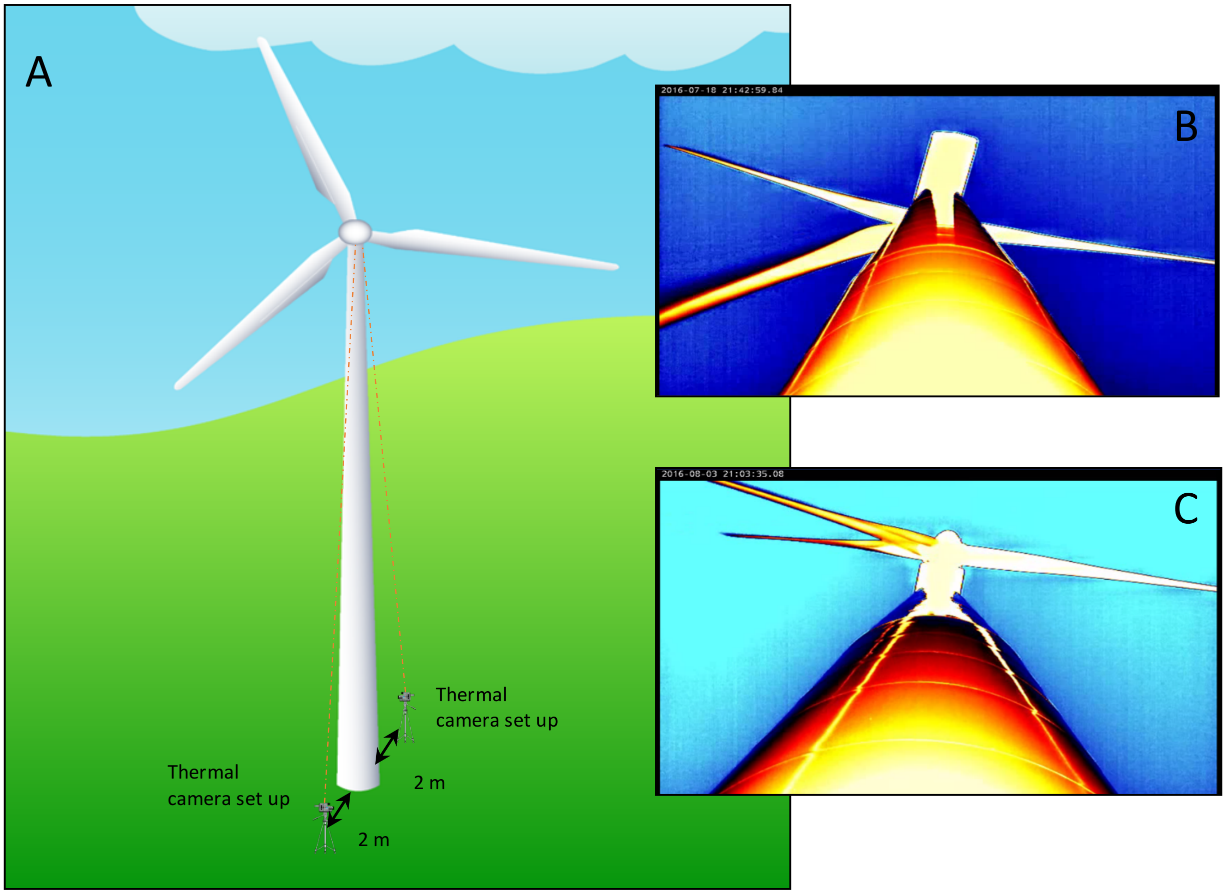


Figure 9: Thermal camera set-up for behavioral surveys at Wolf Ridge. **A** Thermal cameras were set up 2 m from tower base on leeward and windward sides. **B** Field-of-view from the leeward camera, and **C** Field-of-view from the windward camera.

Thermal cameras were connected to an HP Compaq 8510w laptop computer via Ethernet cables and a Netgear ProSAFE 8-Port Fast Ethernet PoE Switch. A car battery attached to a Cen-Tech Power Inverter powered the laptop and the thermal cameras through the Netgear Ethernet switch. Each laptop contained Axis computer software used to synchronize the internal clocks of the thermal cameras and to start and stop recordings. Laptops were placed within 5 m of the leeward cameras and screens were covered during recorded trials to prevent light from potentially affecting bat activity.

Acoustic recordings

Ultrasonic acoustic recording equipment was set up to record bat activity and allow for potential species identification. An AR-125 bat detector, microphone, and iFR IV Field Recorder (with a detection range of ~45 m, a threshold set at 18.0, time expansion at 10.0, a duration at 4.0 seconds, and a frequency range set at 20-110 kHz) were placed at the base of each turbine tower (Fig. 10). The microphone was mounted atop a standard tripod and angled upward towards the nacelle. Detectors were turned on prior to beginning nightly surveys and turned off when surveys were completed.

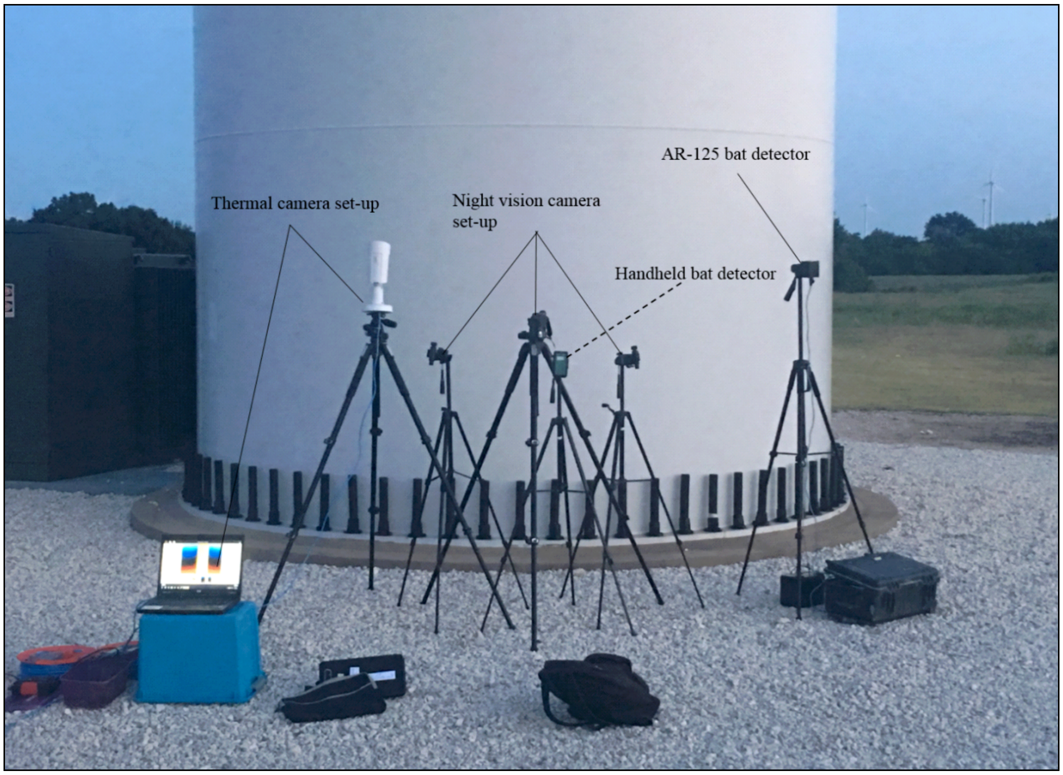


Figure 10: The equipment set-up for the leeward side of a wind turbine tower to examine bat behavior at Wolf Ridge. Note that one laptop powers both thermal cameras and that only one AR-125 is placed at each turbine surveyed.

Additional data collected

As research has shown that weather and environmental conditions can have an impact on bat activity and potentially influence the results of behavioral surveys (Scanlon & Petit 2008), we recorded the following data at the start of each survey night: temperature (^{o}C), wind speed (km/h), gust speed (km/h), wind direction (cardinal), humidity (%), dew point (^{o}C), barometric pressure (in.), cloud cover (full, partial, or clear), moon phase, and moon illumination (%). We also recorded temperature, wind speed and gust speed, cloud cover, and whether or not the moon was visible between each trial. Moreover, surveys were not conducted if wind speeds averaged greater than 24 km/h, if precipitation occurred, or if lightning struck within 80 km of survey location.

Survey trials

During a survey night, 1-2 technicians conducted 12 10-min video recording trials beginning approximately 20 minutes after sunset at both turbines within a pair. Timing and completion of all 12 trials were subject to weather and equipment malfunction. At the beginning of each trial, we synchronized all video recordings using a visual cue, such as a hand swipe over the camera lenses. Thermal camera recordings were saved through a Sony 32 MB micro-SD card onto the HP laptops in .mts file format. We then converted these recordings to .mp4 files using “Any Video Converter Free” software. All night vision HD video recordings were downloaded each night and converted to .mp4 files, using “My Memories Home” software. All these data, along with sound files in .wav file format from the iFR IV recorder, were stored on external hard drives at the end of each survey night.

Video and acoustic analysis

We processed all recorded footage using Studiocode video analysis software (version 5, Studiocode Business Group, Sydney, AU). In Studiocode, corresponding thermal and night vision/camcorder videos were synchronized onto a single timeline using the visual cue (see methods above). Footage from both cameras could then be viewed and analyzed together. We watched each 10-min trial and manually recorded when any bat-like object was observed. Note that flying objects were not included if they passed over the top of the nacelle (over 80 m high), as this study specifically concentrated on bat activity at turbine towers. We then re-watched these bat-like objects and systematically determined whether they were ‘confirmed bats’, ‘possible bats’ or ‘non-bats’ using a Bat Identification Key (Appendix A).

Next, we categorized the proximity of all confirmed and possible bats from the turbine towers, hereafter referred to as proximal activity. For this, we defined three distance categories: ‘far’ (>2 m from the tower surface), ‘close’ (<2 m from the tower surface), and ‘contact/close contact’ (i.e., the bat appeared to touch the tower surface). We utilized distance markers on the turbine tower (such as the flange) and the presence/absence of a reflection of the bat on the tower surface as visual aides to confirm bat proximity. Finally, we identified bat behaviors, hereafter referred to as behavioral activity. Preliminary analysis of video footage from the 2016 feasibility study enabled us to define 9 specific bat behaviors, five of which occurred in both ‘far’ and ‘close’ distance categories, while the remaining four occurred in the ‘contact/close contact’ category (total of 14 behaviors across all distances). The ‘far’ and ‘close’ behaviors included: *passing* – when a bat flies across the field-of-view in a relatively straight flight path (≤1 turn); *reversing* – when a bat enters the field-of-view and turns back the way it came without passing the tower; *looping* – when a bat turns around at or after passing the front or back of the tower and returns the way it came; *chasing* – when one bat closely follows another; and *foraging* – when a bat flies in a zig-zag pattern with ≥2 changes in direction, i.e., turns. The ‘contact/close contact’ behaviors included: *skimming* – when a bat flies low over the tower, with its body parallel to the surface and may or may not make contact; *sweeping* – when a bat flies low over the tower and makes contact with an outstretched wing tip; *colliding* – when a bat flies directly into the tower; and *gleaning* – when a bat hovers briefly over the surface of the tower before making contact with the surface (i.e., to potentially grab a food item, such as an insect) and then flies away.

For the acoustic files recorded, we used SonoBat Scrubber (version 4.vi) to filter out noise files and retain potential bat calls. With the remaining files, we used SonoBat Software for Bat Call Analysis (v. 3.03) to manually identify all calls to species, where possible. We then identified behaviors exhibited (commuting, foraging, feeding buzz, or communication). Finally, we matched ‘confirmed’ and ‘possible bats’ from the video footage with acoustic calls identified to species that occurred within ±5 seconds of an observed object.

Fatality monitoring surveys

To determine whether bat abundance and activity patterns observed in the paired behavioral study corresponded with periods when bats were most at risk from wind turbine collisions, we also conducted fatality monitoring surveys from May to September 2017. Ten turbines were selected for these surveys based on 1) their distribution across the site; 2) a history of bat fatality; and 3) a search area that consisted of mostly gravel, bare ground and low vegetation (<15 cm) within 50 m of the turbine tower to increase searcher efficiency. Of these 10 turbines, we included all 6 turbines surveyed during the pre-texture application stage (see Fig. 1). We performed surveys 2-5 times per week and began approximately 30 minutes after sunrise, weather permitting. Surveys were delayed or cancelled if visibility was impaired (i.e., fog, heavy precipitation, or a solar eclipse) or if lightning struck within 80 km of the survey location. Furthermore, the order in which the turbines were searched was rotated each day.

In teams of 2-3, we searched for bat carcasses on the gravel, pad, and surrounding area at each turbine. Gravel searches were initiated 80 m from the tower using a laser range finder, and we then investigated the area around the tower using the rope method, (as described in Baerwald *et al*. 2009). For this, we attached a rope around the turbine tower approximately 2.5 m above ground level, from which we attached a second rope that extended 45 m from the tower. This second rope was attached at specified cardinal directions (i.e., between N and E, between E and S, etc.; hereafter referred to as the starting angle). Surveyors were spaced at approximately 4.5 m intervals along the rope, and we slowly walked around the turbine holding the rope taut while methodically scanning the ground for carcasses (Fig. 11). This technique created a spiral search path centered around the base of the turbine (Fig. 12). The starting angle and direction (clockwise or counter-clockwise) were rotated each search day to minimize the occurrence of potential "blind spots" within each search plot.

Figure 11: Field technicians searching for bat carcasses in the 45 m radius area around a wind turbine at Wolf Ridge.

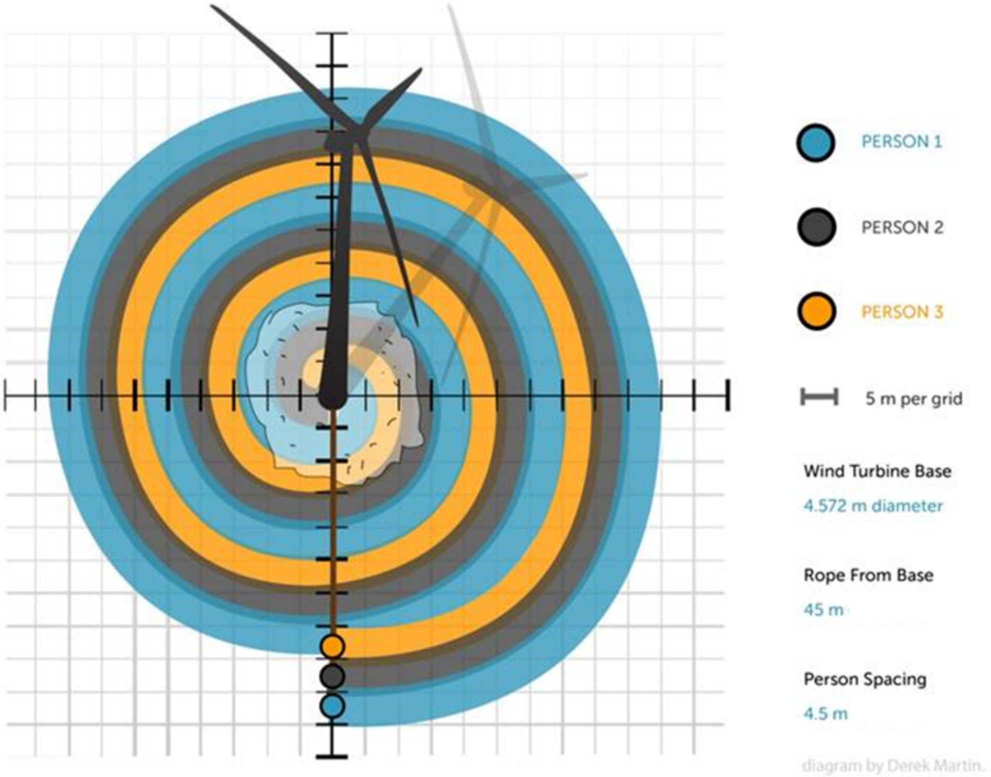


Figure 12: Spiral search pattern implemented for fatality monitoring surveys at Wolf Ridge.

Any carcasses found were marked with a 30 cm wire stake flag during the search, which we returned to once the search was completed. We processed each carcass by first recording the GPS location using LocusMap application on a smart phone, as well as the degree and distance of the carcass from the turbine tower using compass and laser range finder. We then took a photograph of the carcass, as a record of placement and condition of the carcass, along with substrate on which it was found. We recorded the substrate type (e.g., gravel or non-gravel), percentage of bare ground, and vegetation height (cm). In addition, we noted body condition (e.g., fresh or decaying), body parts present, tissues present, status of eyes (e.g., round, fluid-filled, partially dehydrated, flat, sunken, or empty), any signs of trauma, any signs of scavenging, and any scavengers present on the carcass (such as ants or fly larvae). Finally, we estimated a time since death (i.e., <1 day, <2 days, <4 days, <6 days, >6 days) based on the above information. All carcasses were given a unique identification consisting of the sample number, turbine number, surveyor, and date (e.g., 1T21BH12MAY17), placed in quart-sized zip-lock bag, and temporarily stored in a cooler. At the end of daily fatality searches, we identified the species, sex, age, and breeding condition, and measured weight (g) and forearm length (mm). Bat carcasses were then placed in a freezer and stored at 4° C.

Data analysis

To compare bat activity between smooth and textured turbines at our site, we first had to determine if we could include 'possible bat' observations in our analyses. For those flying objects that we categorized as 'possible bats', we speculated that these objects may have been bats. To do this, we visually examined the activity patterns of 'confirmed' and 'possible bats' and combined these categories if they followed the same trend in activity across the survey period. Note that we treated each 'possible' and 'confirmed bat' as an independent observation throughout our analyses. For all subsequent statistical analyses, we used Minitab software (version 18, Pennsylvania, USA with an $\alpha=0.05$).

Bat activity at wind turbine towers - To determine if bat activity patterns remained consistent with activity recorded in the feasibility study (Fig. 3), we constructed a fixed effects general linear model (GLM) with turbines nested within pairs to ascertain any significant differences in observed bat activity between the turbines. Then, for the post-texture application stage, the GLM enabled us to discern if there was a difference in bat activity between turbine pairs. Due to differences in the texture application, we did not combine smooth and textured data, but treated turbine pairs separately in our analyses. Thus, we conducted paired *t* tests to reveal more detailed differences in bat activity between smooth and textured turbines within each turbine pair. Finally, we repeated the above analyses using the bat acoustic calls recorded.

To determine if differences in recorded bat activity patterns were caused by differences in the bats active at each tower, we used the acoustic calls to examine species-specific activity between smooth and textured turbines in each pair. For this, we used a series of Wilcoxon's signed rank tests to compare the difference in the number of species-specific bat calls recorded per hour at each turbine pair. Note that bat species with <10 calls recorded at one or both turbines within a pair were excluded from this analysis.

Proximal activity at wind turbine towers - To examine whether proximal bat activity differed between smooth and textured turbines, we compared the proportion of all observations ≤2 m of the turbine tower (categorized as 'close' and 'contact/close contact' distances, see Methods). We first used these proportions to test whether proximal activity was consistent between turbines in each pair during the pre-texture application stage using Fisher's exact tests. We then repeated these tests using the post-texture application stage proportions to determine if the texture influenced the proximity of bats to the turbine towers. We then used bat acoustic calls matched with observations to discern if activity in proximity to turbine towers was potentially driven by specific species using a Fisher's exact test. Note that bat species with <10 calls recorded at one or both turbines within a pair were excluded from this analysis.

Behavioral activity at wind turbine towers - To understand differences in behavioral activity between smooth and textured turbines, we visually examined the mean number of bats per night exhibiting each behavior (e.g., passing, foraging, etc.) within each distance category across all turbines. Next, we used a series of Fisher's exact tests to test for any significant differences in the proportions of each behavior exhibited at the textured turbine compared with the smooth in each pair. Note that we excluded behaviors from our analyses in which <10 bats were observed at one or both turbines. We then repeated these analyses using the behaviors identified in the recorded bat calls.

Bat fatalities - To determine if our study supported the theory that bat activity is associated with bat fatality (Weller & Baldwin 2012), we calculated Pearson's correlation coefficients to determine if the patterns of observed and acoustic bat activity across all turbines correlated with the occurrences of bat fatalities.

Results

Across the survey period, we surveyed 72 nights between 20 May and 22 September, 2017. The data from two nights were not included because ≤6 trials were recorded (for more details, see Table 1). Overall, we observed 1032 'confirmed bats' and 619 'possible bats' (see Appendix B). We successfully recorded 736 10-min trials during the pre-texture application stage (20 May – 18 June) when 3 turbine pairs were surveyed and a total of 2541 10-min trials in the post-texture application stage (24 June – 22 September) when 2 turbine pairs were surveyed (Table 1). In addition, we recorded 1215 bat calls on the acoustic recorders over the entire survey season, and identified all 7 bat species known to be present at the site: eastern red (*n* =370 calls), hoary (*n* =214 calls), silver-haired (*n* =77 calls), tricolored (*n* =209 calls), canyon (*n* =8 calls), evening (*n* =325 calls), and Mexican free-tailed (*n* =12 calls) bats. Of the 1651 objects identified as 'confirmed' or 'possible bats,' we matched 1054 to particular species when bat calls were recorded within 5 sec of the observations.

Table 1: Number of survey nights with >1 hr of recordings at each turbine pair during the pre- and post-texture periods of data collection from 20 May to 22 September 2017. Within a turbine pair, **A** is the smooth turbine tower and **B** the potential texture-treated tower. Note that grey shading indicates that Turbine Pair 3 was not included in our study following the post-texture application stage.

Total number survey nights		**Pre-texture application**	**Post-texture application**
Turbine Pair 1	**A**	5	27
	B	5	27
Turbine Pair 2	**A**	6	27
	B	5	27
Turbine Pair 3	**A**	5	N/A
	B	5	N/A

As outlined in Methods, we first visually examined whether activity patterns of 'confirmed' and 'possible bats' were similar across the survey period. As the patterns of 'possible bat' observations were consistent with 'confirmed bat' observations at each turbine surveyed, we concluded that the former may have been bats (Fig. 13; also see Appendix C). We therefore combined these two categories for the proceeding analysis. We also noted in both observed and acoustic bat activity across the survey period that corresponding peaks in activity occurred at turbines within a pair (Fig. 14). These peaks were most noticeable between July and September during the fall bat migration season, demonstrating that the post-texture application stage occurred when bat activity was highest at our site.

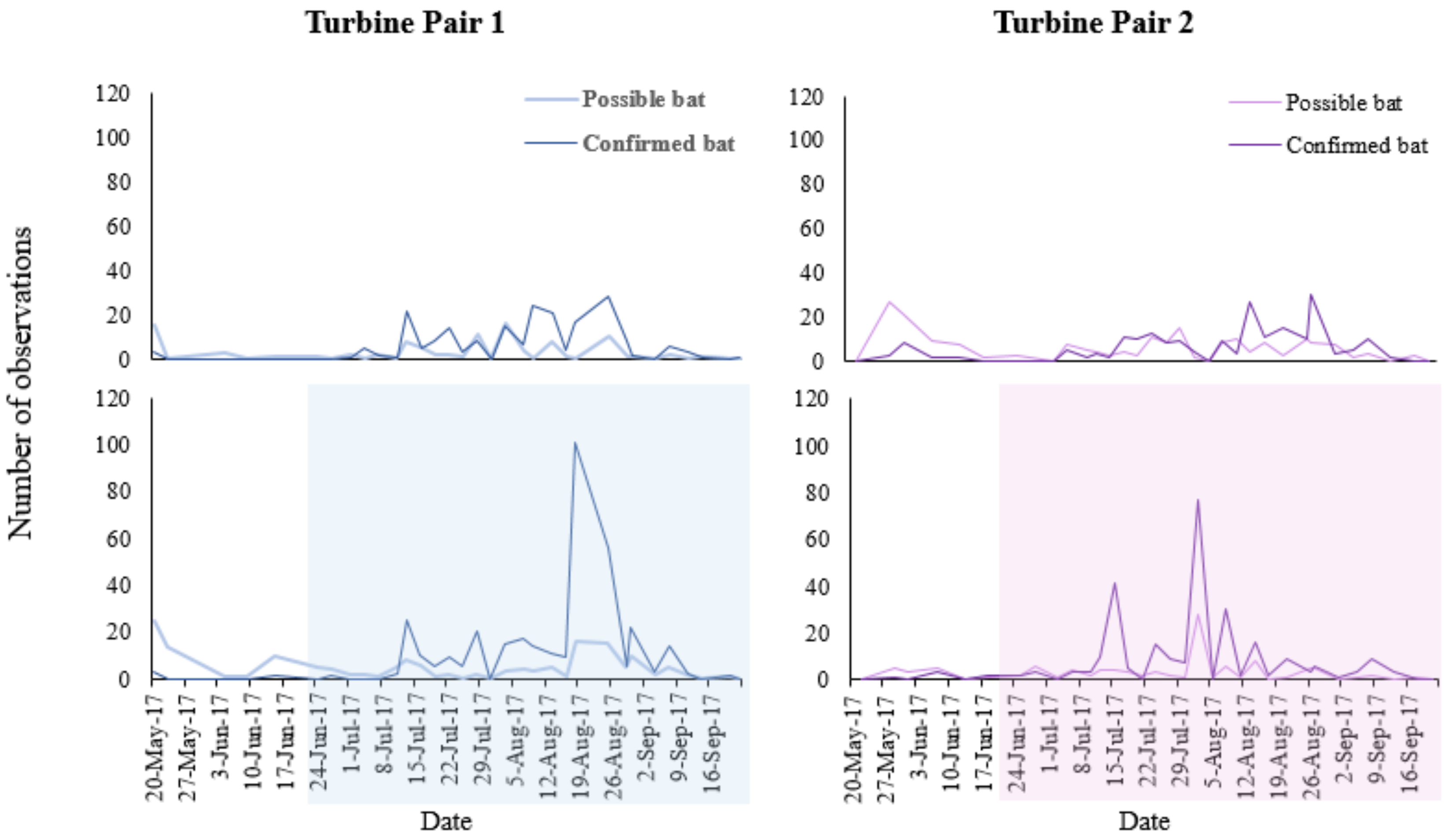


Figure 13: ‘Confirmed bat’ and ‘possible bat’ observations at each turbine surveyed at Wolf Ridge over 70 survey nights. Blue indicates Turbine Pair 1, whereas purple represents Turbine Pair 2. The shading highlights the post-texture application stage, indicating the textured turbine within each pair.

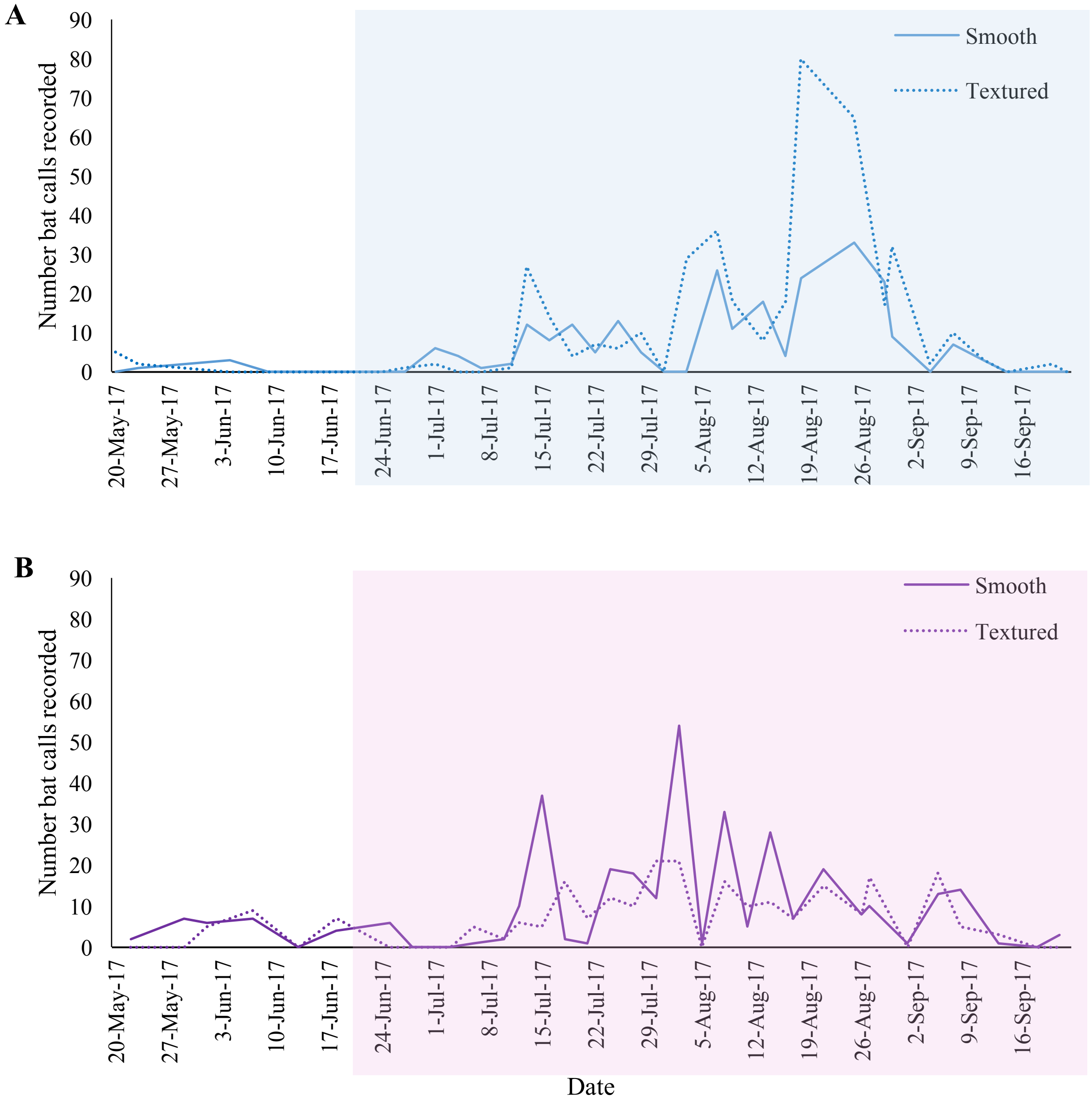


Figure 14: Acoustic bat activity at both turbine pairs over the survey period at Wolf Ridge over 70 survey nights. **A** The pattern of bats calls recorded at Turbine Pair 1; **B** The pattern of bat calls recorded at Turbine Pair 2. The shaded area within each chart indicates data collected during the post-texture application stage.

Bat activity at wind turbine towers

Next, we compared bat activity between all turbines during the pre- and post-texture application stages. Across the 3 pairs of turbines surveyed during the pre-texture stage, the mean number of bats observed per hour ranged from 2.2 to 7.9 over 16 survey nights (Fig. 15).

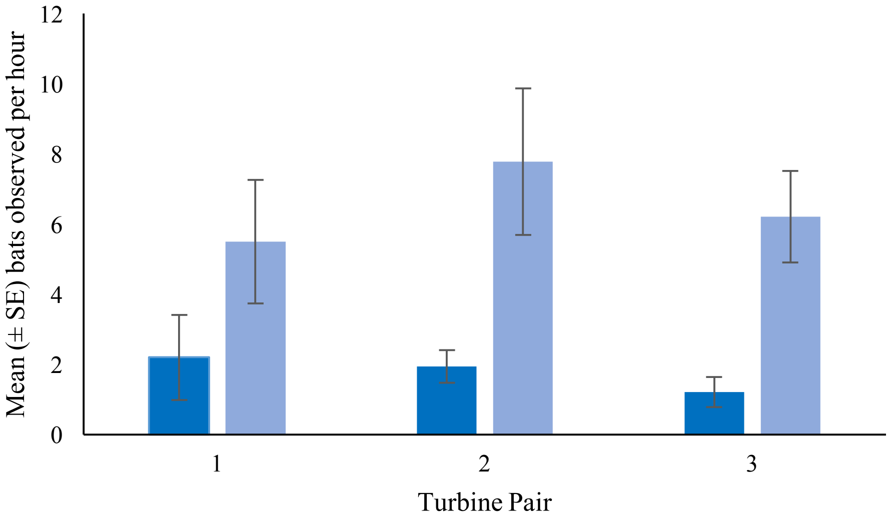


Figure 15: The mean (± SE) number of bats observed per hour during the pre-texture application stage over 16 survey nights from 20 May to 18 June 2017. The shades of blue indicate the 2 turbines within a pair.

We then used a fixed effects GLM with turbine pairs as the main effects and turbines nested within pairs to compare the mean observed bats per hour (using the ln+1 transformation). There was no significant difference in observed bat activity between the turbines ($F_{2,3} = 0.26$; $P = 0.77$).

During the post-texture application stage, we continued to survey two pairs of turbines across the season. These surveys included Turbine Pair 1 and Turbine Pair 2. Turbines shown as dark blue in Figure 15 remained controls (hereafter referred to as ‘smooth’), while the turbines shown in lighter blue had the texture coating applied (hereafter referred to as ‘textured’). The mean number of bats observed per hour during the post-texture application stage ranged from 5.3 to 8.5 over 54 survey nights (Fig. 16).

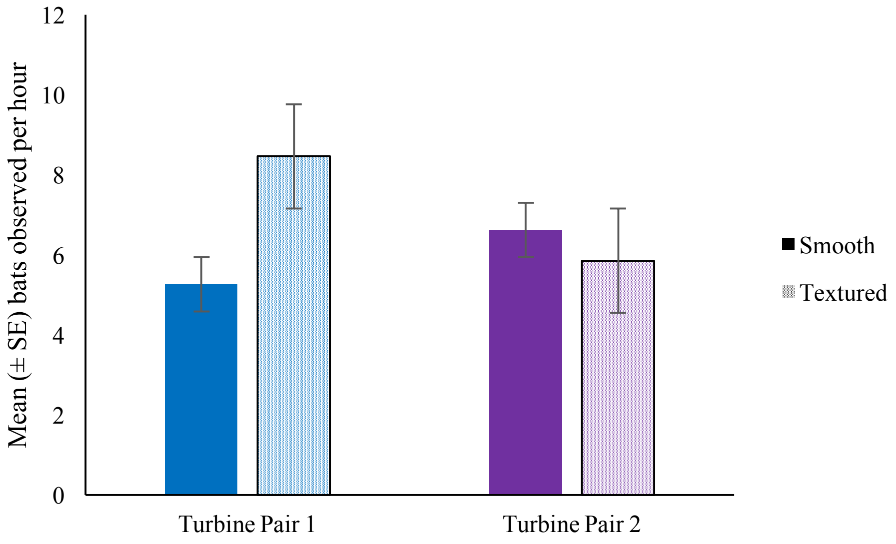


Figure 16: The mean (± SE) number of bats observed per hour at the smooth (solid bars) and textured (patterned bars) turbines over 27 survey nights for each pair from 24 June to 22 September 2017. Blue represents Turbine Pair 1, while purple represent Turbine Pair 2.

Next, we tested for differences in the observed bats per hour between textured and smooth turbines. For this, we compared the mean number of observed bats per hour (using the ln+1 transformation) using a fixed effects GLM with turbine pairs and turbine type (i.e., smooth or textured) as the main effects, and with turbines nested within pairs. The number of bats observed per hour was not significantly different between turbines ($F_{1,2} = 0.02$, $P = 0.881$). To reveal more detail between smooth and textured turbines within each pair, we then conducted two paired *t* tests to reveal any differences in observed bats per hour. There were no significant differences in observed bats per hour between smooth and textured turbines at either Turbine Pair 1 ($t = -1.98$, $df = 26$, $P = 0.058$) or Turbine Pair 2 ($t = -0.35$, $df = 26$, $P = 0.729$).

We then repeated these analyses using bat calls recorded to compare acoustic bat activity between the surveyed turbines during the pre- and post-texture application stages. During the pre-texture stage, the mean number of bat calls recorded per hour that ranged from 0.6 to 2.2 at each turbine (Fig. 17).

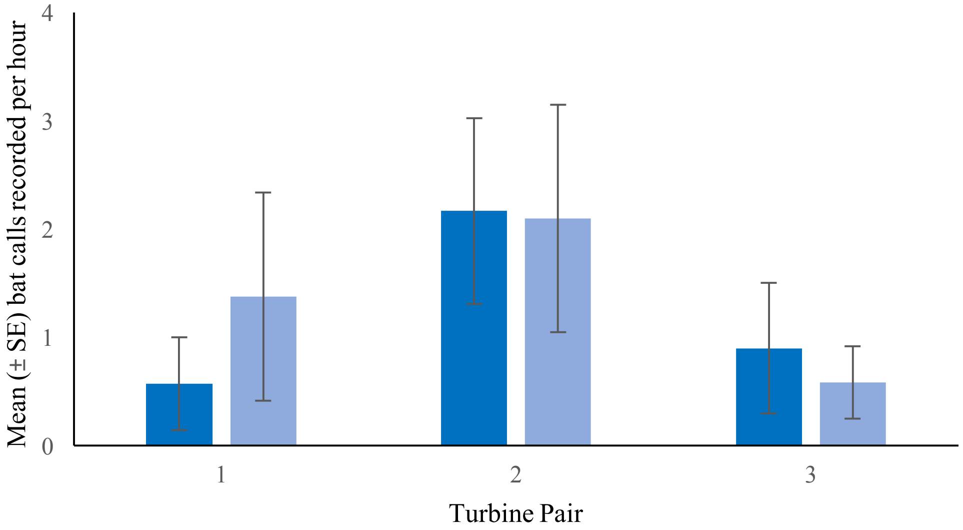


Figure 17: The mean (± SE) number of bat calls recorded per hour during the pre-texture application stage over 16 survey nights from 20 May to 18 June 2017. The shades of blue indicate the two turbines within a pair.

Using a fixed effects GLM with turbine pairs as the man effect and turbines nested within pairs, we found no significant difference in acoustic bat activity between turbine pairs during the pre-texture application stage ($F_{2,3} = 1.11$; $P = 0.364$).

During the post-texture application stage, the mean number of bat calls recorded per hour ranged from 3.8 to 7.3 at each turbine (Fig. 18). To then examine whether the number of bat calls recorded across the post-texture application stage was significantly different between all turbines, we used another GLM and tested the mean number of bat calls recorded per hour (using the ln+1 transformation) with turbine pairs and turbine type (i.e., smooth or textured) as the main effects, and turbines nested within pairs. This test revealed no significant difference in the number of acoustic bat calls recorded ($F_{1,2} = 0.00$, $P = 0.99$). We then conducted 2 paired t-tests to reveal any differences in recorded bat calls per hour (using the ln + 1 transformation) between smooth and textured turbines in each pair. These tests revealed no significant difference at either Turbine Pair 1 ($t = -1.63$, $df = 26$, $P = 0.115$) or Turbine Pair 2 ($t = 1.02$, $df = 26$, $P = 0.315$).

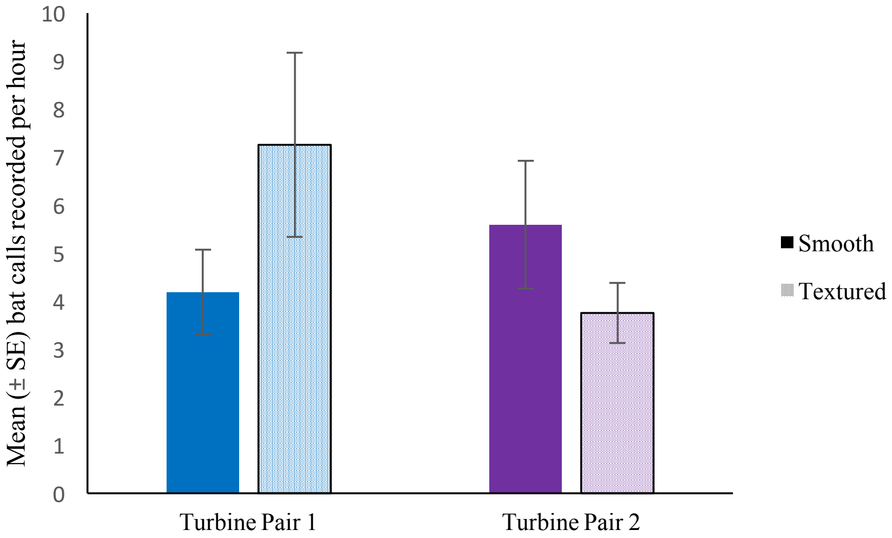


Figure 18: The mean (± SE) number of bat calls recorded per hour at the smooth (solid bars) and textured (patterned bars) turbines over 27 survey nights for each pair from 24 June to 22 September 2017. Blue represents Turbine Pair 1, while purple represent Turbine Pair 2.

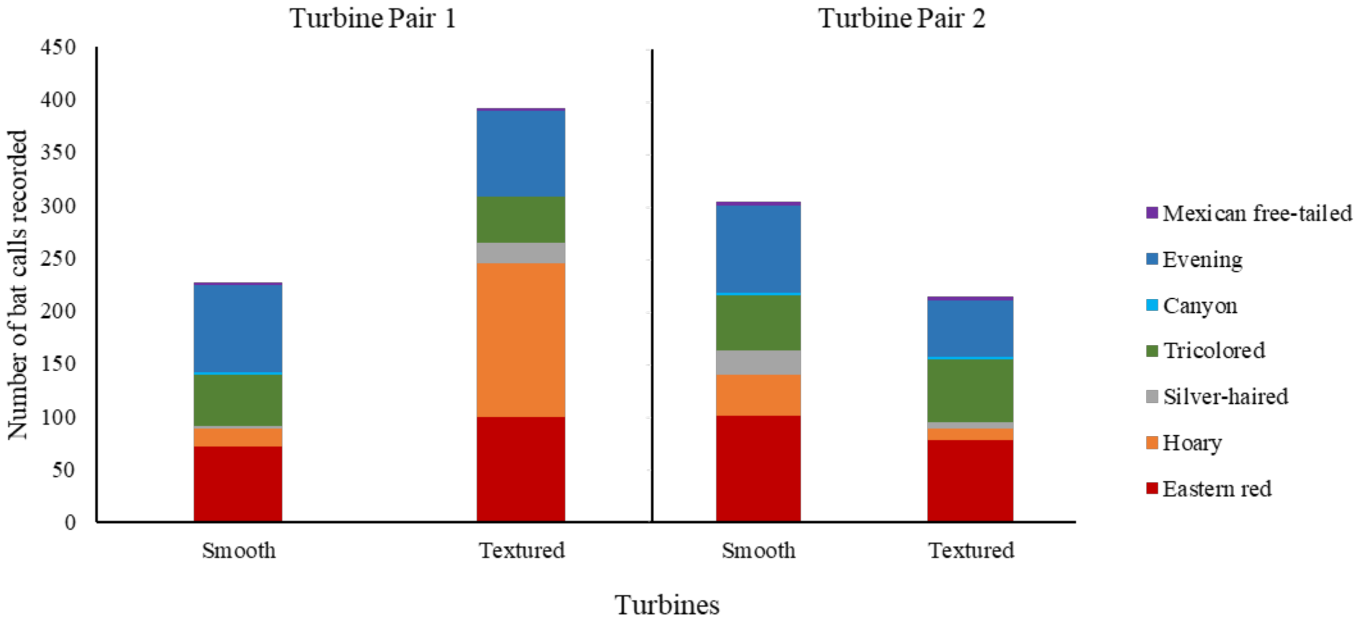
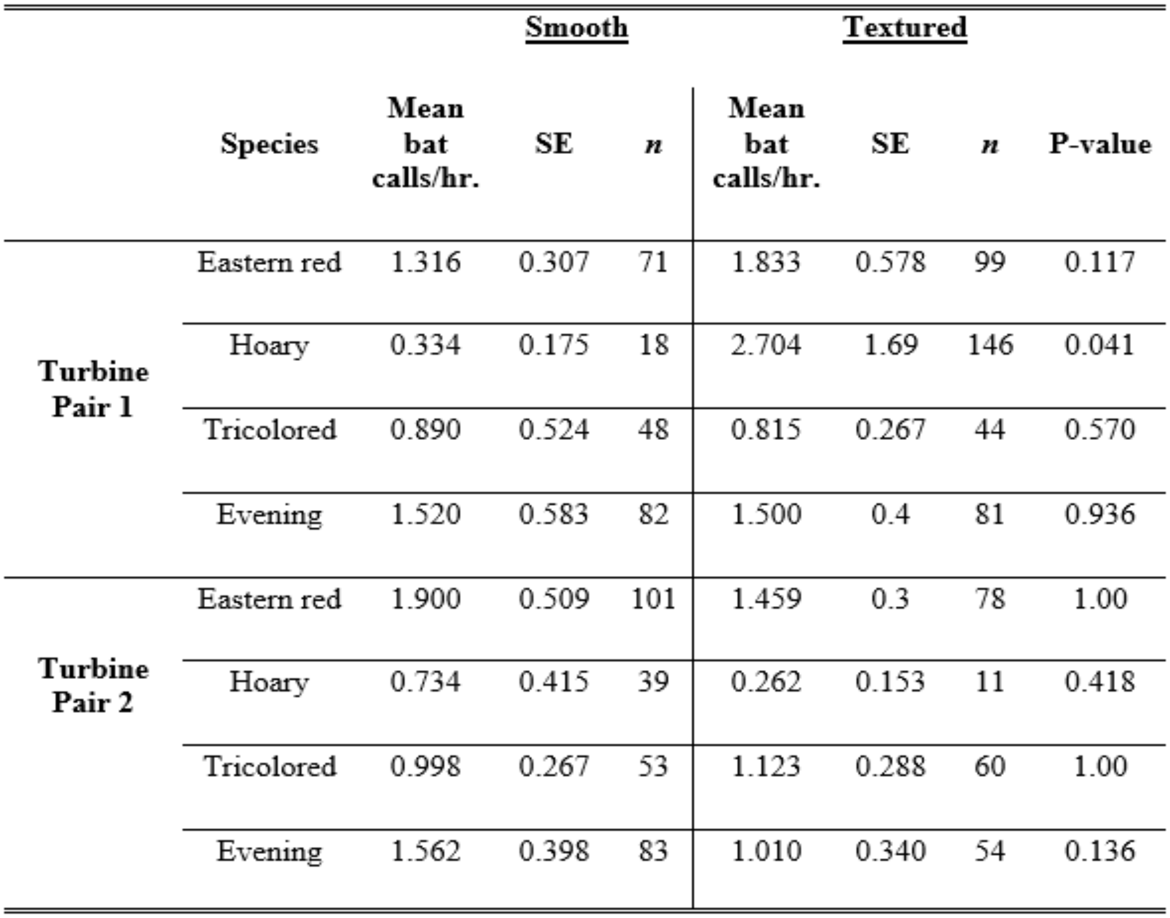


Figure 19: The number of acoustic calls recorded per hour for each bat species at Wolf Ridge wind turbine towers during the post-texture application stage. Each turbine pair was surveyed 27 nights from 24 June to 22 September 2017.

Our acoustic analysis also revealed potential variation in species-specific acoustic bat activity recorded at each turbine, with potential differences among hoary, silver-haired, tricolored, and eastern red bats (Fig. 19). To assess if the pattern of bat activity recorded was driven by certain species, we conducted a series of Wilcoxon's signed rank tests comparing the difference in the number of species-specific bat calls recorded per hour between smooth and textured turbines. Our findings revealed significantly higher hoary bat activity at the textured turbine in Turbine Pair 1, and no significant differences in species-specific activity at Turbine Pair 2 (Table 2).

Table 2: The results of a series of Wilcoxon's signed rank tests comparing the differences between species-specific bat calls recorded per hour at the textured versus smooth turbines in each wind turbine pair surveyed at Wolf Ridge during the post-texture application stage from 24 June to 22 September 2017. Each turbine pair was surveyed 27 nights. The '*n*' signifies the number of bat calls recorded. Note that species with <10 bat calls recorded at one or both turbines within a pair were excluded from the analysis.



		Smooth			**Textured**			
	Species	**Mean bat calls/hr.**	**SE**	***n***	**Mean bat calls/hr.**	**SE**	***n***	**P-value**
Turbine Pair 1	Eastern red	1.316	0.307	71	1.833	0.578	99	0.117
	Hoary	0.334	0.175	18	2.704	1.69	146	0.041
	Tricolored	0.890	0.524	48	0.815	0.267	44	0.570
	Evening	1.520	0.583	82	1.500	0.4	81	0.936
Turbine Pair 2	Eastern red	1.900	0.509	101	1.459	0.3	78	1.00
	Hoary	0.734	0.415	39	0.262	0.153	11	0.418
	Tricolored	0.998	0.267	53	1.123	0.288	60	1.00
	Evening	1.562	0.398	83	1.010	0.340	54	0.136

Proximal activity at wind turbine towers

To determine if proximal bat activity differed between smooth and textured turbines, we first confirmed that such distance-related activity was consistent between turbines in each pair during the pre-texture application stage. Note that as we observed <10 bats categorized as ‘contact/close contact’ across our entire survey period (see Appendix B), we proceeded to combine ‘contact/close contact’ observations with ‘close’ observations for the following analyses (hereafter referred to as ‘all close’). The proportion of bat passes categorized as ‘all close’ ranged from 0.04 to 0.26 per turbine (Fig. 20).

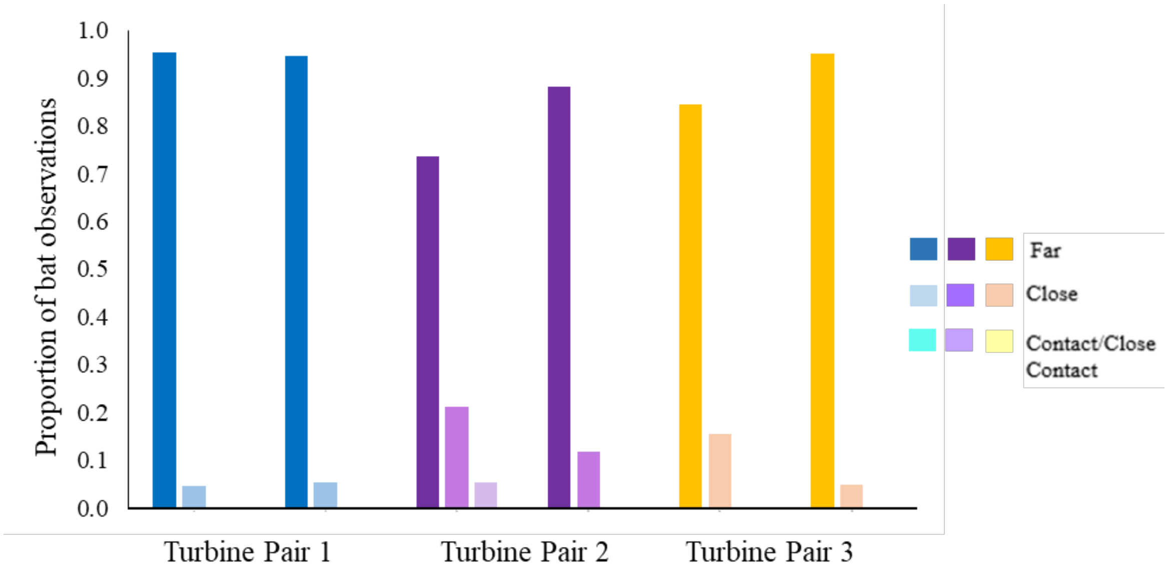


Figure 20: The proportion of bats observed in each distance category at each turbine studied over 5-6 survey nights during the pre-texture application stage from 20 May to 22 September 2017. Turbine Pair 1 is shown in blue, Turbine Pair 2 is in purple, and Turbine Pair 3 is in yellow.

Using a set of 3 Fisher’s exact tests, we compared the proportion of ‘all close’ observations during the pre-texture application stage between turbines in each pair and found no significant differences in bat activity (Table 3). Then, to determine if the texture influenced proximal bat activity, we compared the proportion of 'all close' observations between the smooth and textured turbines in each pair across the post-texture application stage. The proportion of bat passes categorized as 'all close' ranged from 0.24 to 0.36 per turbine (Fig. 21)

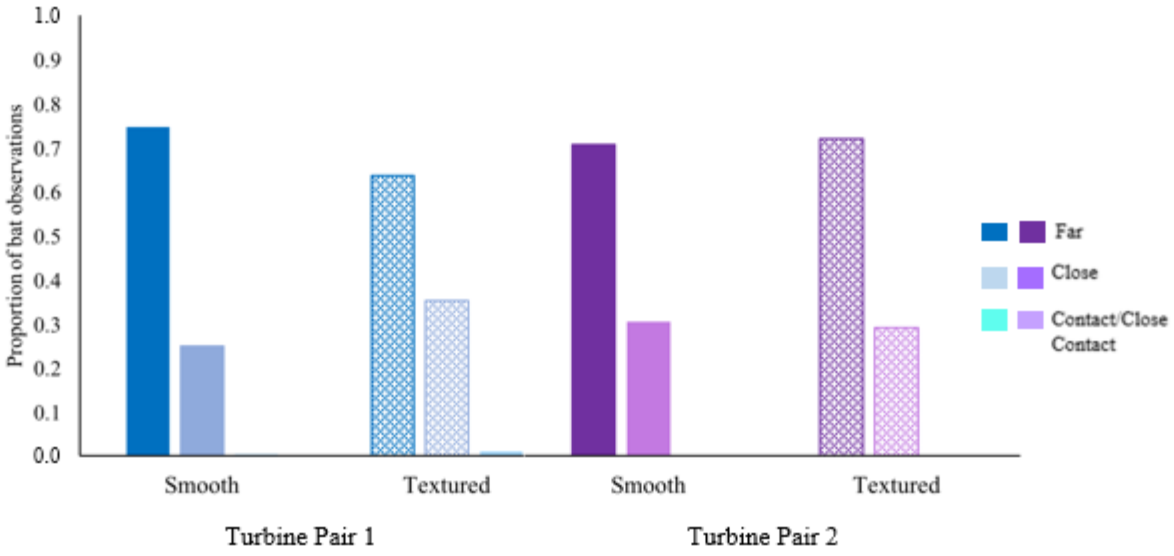
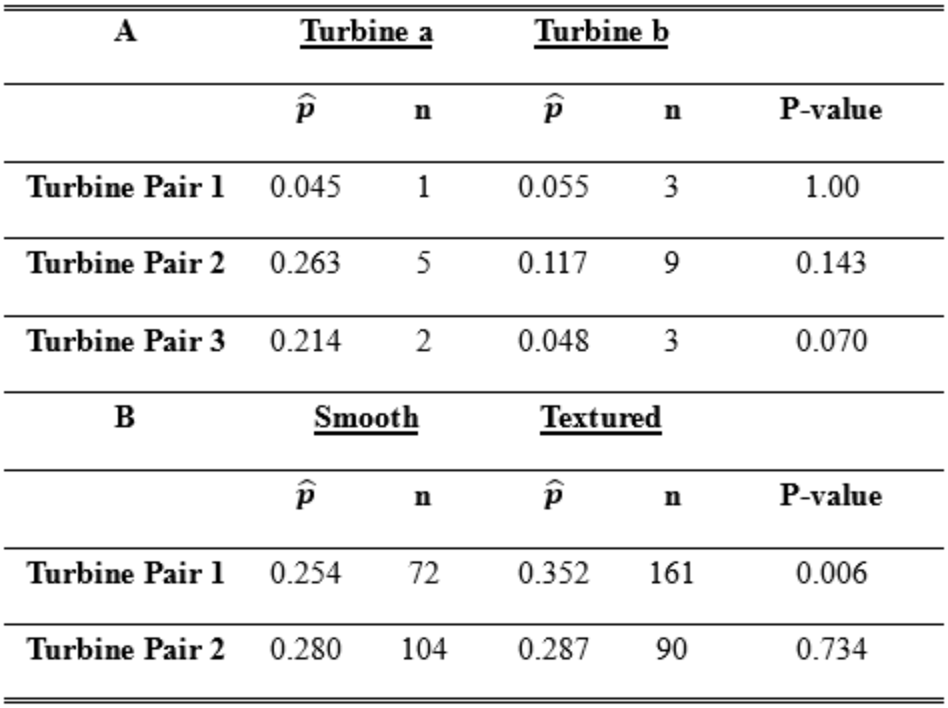


Figure 21: The proportion of observations in each distance category at each turbine studied over 27 survey nights during the post-texture application stage from 24 June to 22 September 2017. Turbine Pair 1 is shown in blue, while Turbine Pair 2 is shown in purple. The patterned bars indicate the textured turbine in each pair.

We conducted a set of 2 Fisher's exact tests to compare these proportions between smooth and textured turbines in each pair. At Turbine Pair 1, there was a significantly higher proportion of 'all close' observations at the textured turbine compared with the smooth, and there was no significant difference for Turbine Pair 2 (Table 3).

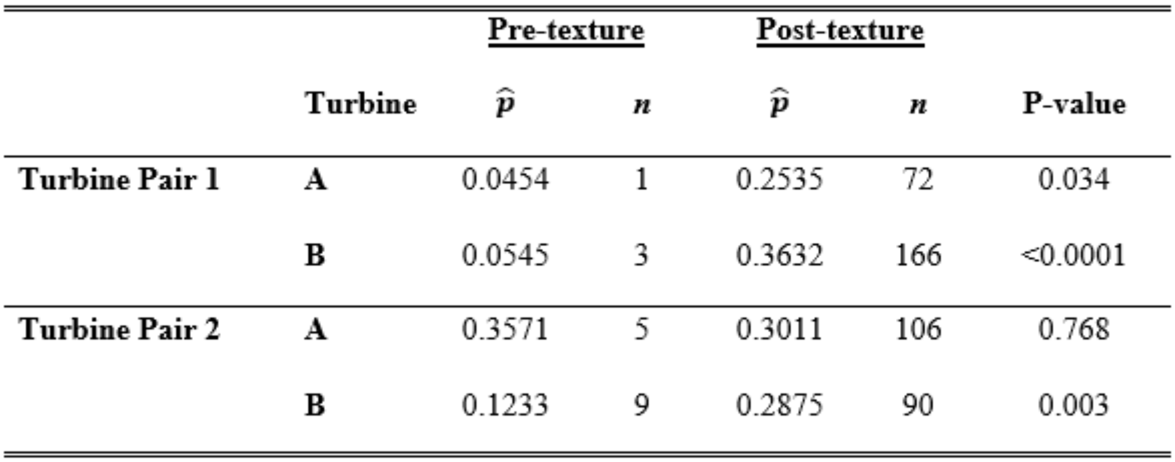
Table 3: Results of a series of Fisher's exact tests comparing the proportions of 'all close' bat observations between turbines in each pair studied at Wolf Ridge. **A** delineates the pre-texture application stage, while **B** represents the post-texture application stage. Turbines a and b indicate the 2 turbines in the pre-textured pairs, and represent to the smooth and textured turbines, respectively, in Pairs 1 and 2.



A	**Turbine a**		**Turbine b**		
	$\widehat{p}$	**n**	$\widehat{p}$	**n**	**P-value**
Turbine Pair 1	0.045	1	0.055	3	1.00
Turbine Pair 2	0.263	5	0.117	9	0.143
Turbine Pair 3	0.214	2	0.048	3	0.070
B	**Smooth**		**Textured**		
	$\widehat{p}$	**n**	$\widehat{p}$	**n**	**P-value**
Turbine Pair 1	0.254	72	0.352	161	0.006
Turbine Pair 2	0.280	104	0.287	90	0.734

To confirm that differences in proximal activity were influenced by the texture application, we compared the proportion of 'all close' observations between pre-texture application and post-texture application stages at each turbine using a series of Fisher's exact tests. The proportion of 'all close' bat observations was significantly greater during the post-texture application stage at both turbines in Turbine Pair 1 and at the textured turbine only in Turbine Pair 2 (Table 4). The proportion of 'all close' passes at the smooth turbine in Turbine Pair 2 was not different between pre- and post-texture stages.

Table 4: The results of Fisher's exact tests comparing the proportion of 'all close' observations between the pre- and post-texture application stages for each turbine studied. **A** delineates the control, or smooth, turbine while **B** represents the experimental, or textured, turbine within each pair.



		Pre-texture		Post-texture		
	Turbine	$\hat{p}$	n	$\hat{p}$	n	**P-value**
Turbine Pair 1	**A**	0.0454	1	0.2535	72	0.034
	B	0.0545	3	0.3632	166	<0.0001
Turbine Pair 2	**A**	0.3571	5	0.3011	106	0.768
	B	0.1233	9	0.2875	90	0.003

Finally, to determine whether variation in proximal activity was potentially driven by specific bat species, we repeated proximal analyses using the subsection of the bat calls obtained from call matching (Fig. 22). Fisher's exact tests revealed a significantly higher proportion of eastern red 'all close' passes at the textured turbine compared with the smooth in Turbine Pair 1, and no other differences in species-specific proximal activity between textured and smooth turbines in either pair (Table 5).

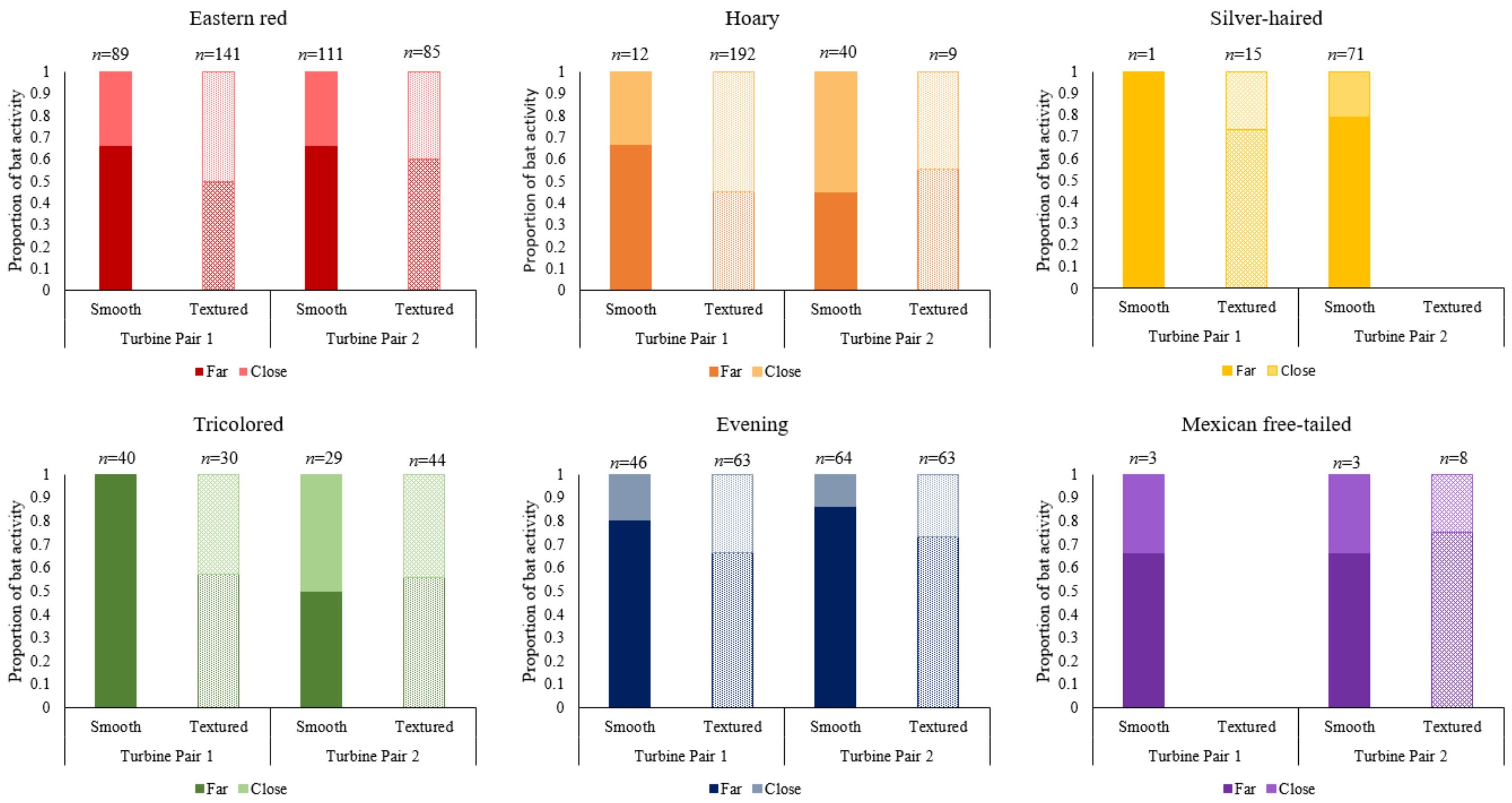


Figure 22: The proximal activity of 6 bat species at Wolf Ridge identified via call matching over 27 survey nights at each turbine pair during the post-texture application stage from 24 June to 22 September 2017. Note that canyon bats were excluded, as they were only detected at one turbine studied. The lighter shade in each bar represents ‘all close’ observations, while the darker shade indicates ‘far’ observations.

Table 5: The results of a series of Fisher's exact tests comparing the species-specific proportion of 'all close' bat activity between smooth and textured turbines over 27 survey nights in each turbine pair during the post-texture application stage from 24 June to 22 September 2017. The '*n*' indicates the number of 'all close' observations that were matched with each species per turbine. Note that bat species were excluded from the analysis if <10 calls at one or both turbines within a pair.

		Smooth		**Textured**		
	Species	$\hat{p}$	n	$\hat{p}$	n	**P-value**
Turbine Pair 1	Eastern red	0.338	30	0.504	141	0.014
	Hoary	0.333	4	0.438	84	0.560
	Evening	0.196	9	0.333	21	0.132
Turbine Pair 2	Eastern red	0.342	38	0.400	34	0.456
	Evening	0.141	9	0.289	18	0.053

Behavioral activity at wind turbine towers

To understand if the texture was associated with changes in bat behavior, we compared the mean number of observed bats per night exhibiting each of the 15 distance-related behaviors identified at the turbines. Most of the bats we observed both close to and far from the turbine tower surfaces exhibited passing or foraging behaviors (Fig. 23). Note that no sweeping or colliding behaviors were observed and were, therefore, excluded from Figure 23.

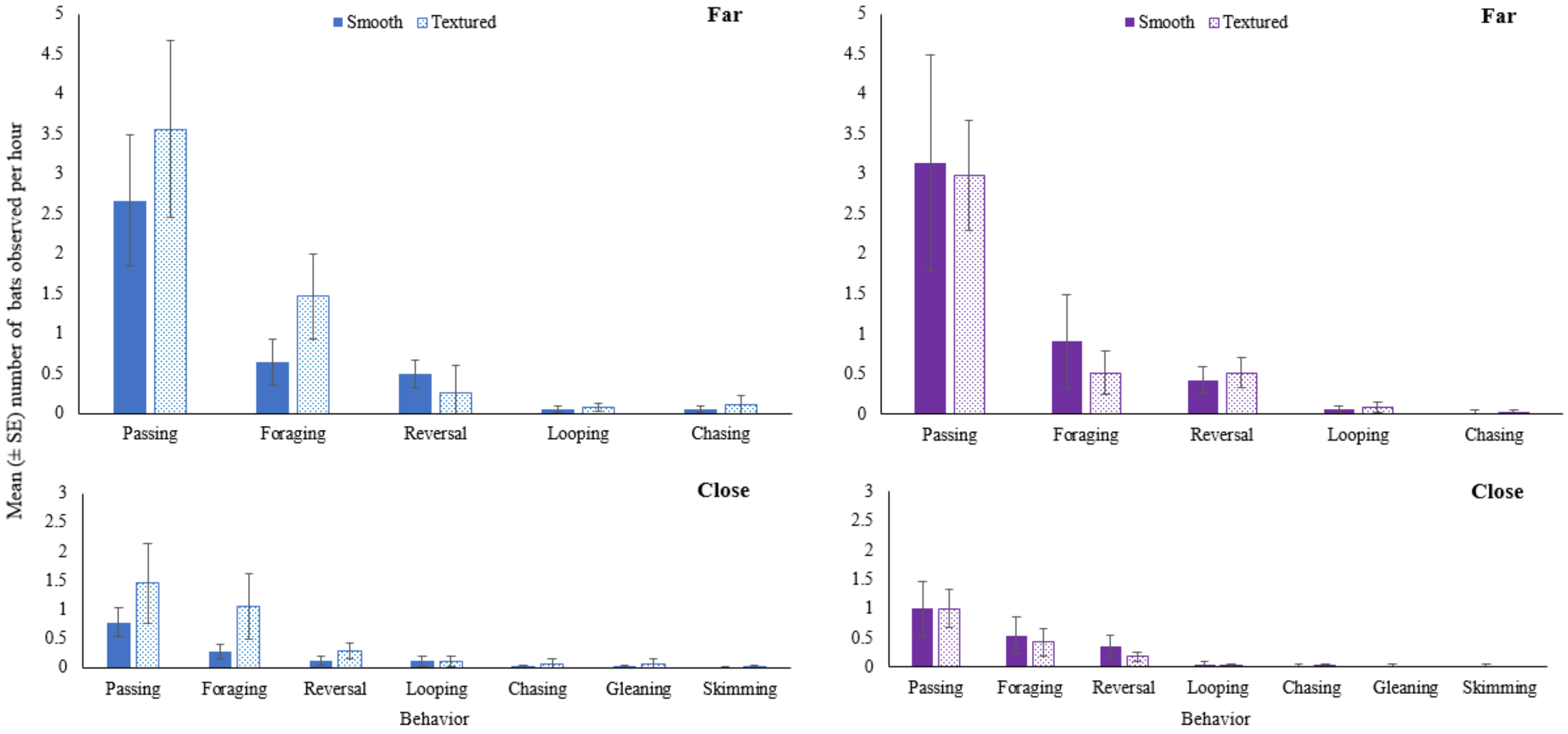
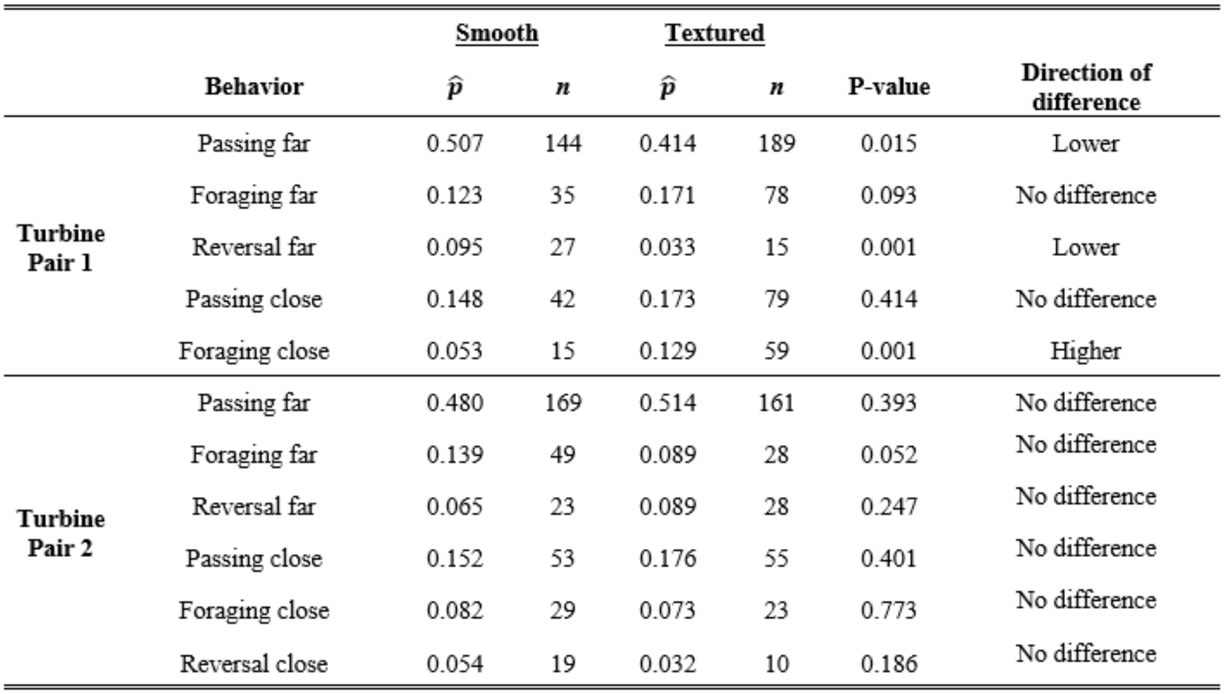


Figure 23: The mean (± SE) number of bats observed per hour exhibiting specific behaviors at Wolf Ridge over 27 survey nights for each turbine pair across the post-texture application stage from 24 June to 22 September 2017. Turbine Pair 1 is shown in blue, while Turbine Pair 2 is shown in purple.

To assess if any behavioral differences between smooth and textured turbines were significant, we conducted a series of Fisher's exact tests comparing the proportion of each behavior exhibited (behaviors with <10 bats observed at either turbine within a pair were excluded from our analyses) between smooth and textured turbines within each pair. These tests revealed significantly fewer bats passing far and reversing far, and more bats foraging close at the textured turbine compared with the smooth in Turbine Pair 1 (Table 6). In contrast, at Turbine Pair 2, we found no significant differences in the proportions of behaviors exhibited between the smooth and textured turbine.

Table 6: The results of a series of Fisher's exact tests comparing the proportion of each bat behavior observed at the smooth and textured turbines surveyed at Wolf Ridge over 27 survey nights in each pair from 24 June to 22 September 2017. Note that behaviors of which *n*<10 bats were excluded from our analyses.



		Smooth		**Textured**			
	Behavior	$\hat{p}$	n	$\hat{p}$	n	**P-value**	**Direction of difference**
Turbine Pair 1	Passing far	0.507	144	0.414	189	0.015	Lower
	Foraging far	0.123	35	0.171	78	0.093	No difference
	Reversal far	0.095	27	0.033	15	0.001	Lower
	Passing close	0.148	42	0.173	79	0.414	No difference
	Foraging close	0.053	15	0.129	59	0.001	Higher
Turbine Pair 2	Passing far	0.480	169	0.514	161	0.393	No difference
	Foraging far	0.139	49	0.089	28	0.052	No difference
	Reversal far	0.065	23	0.089	28	0.247	No difference
	Passing close	0.152	53	0.176	55	0.401	No difference
	Foraging close	0.082	29	0.073	23	0.773	No difference
	Reversal close	0.054	19	0.032	10	0.186	No difference

Next, we examined the proportions of bat behaviors identified using acoustic calls at smooth and textured turbines within each pair (Fig. 24). We then used a series of 4 Fisher's exact tests to reveal if the behavioral differences between smooth and textured turbines were significant (behaviors with <10 bat calls were excluded from our analyses). These tests revealed that the proportion of bats 'foraging' was significantly lower, while the proportion of bats 'searching' was significantly higher at the textured turbine compared with the smooth in both turbine pairs (Table 7).

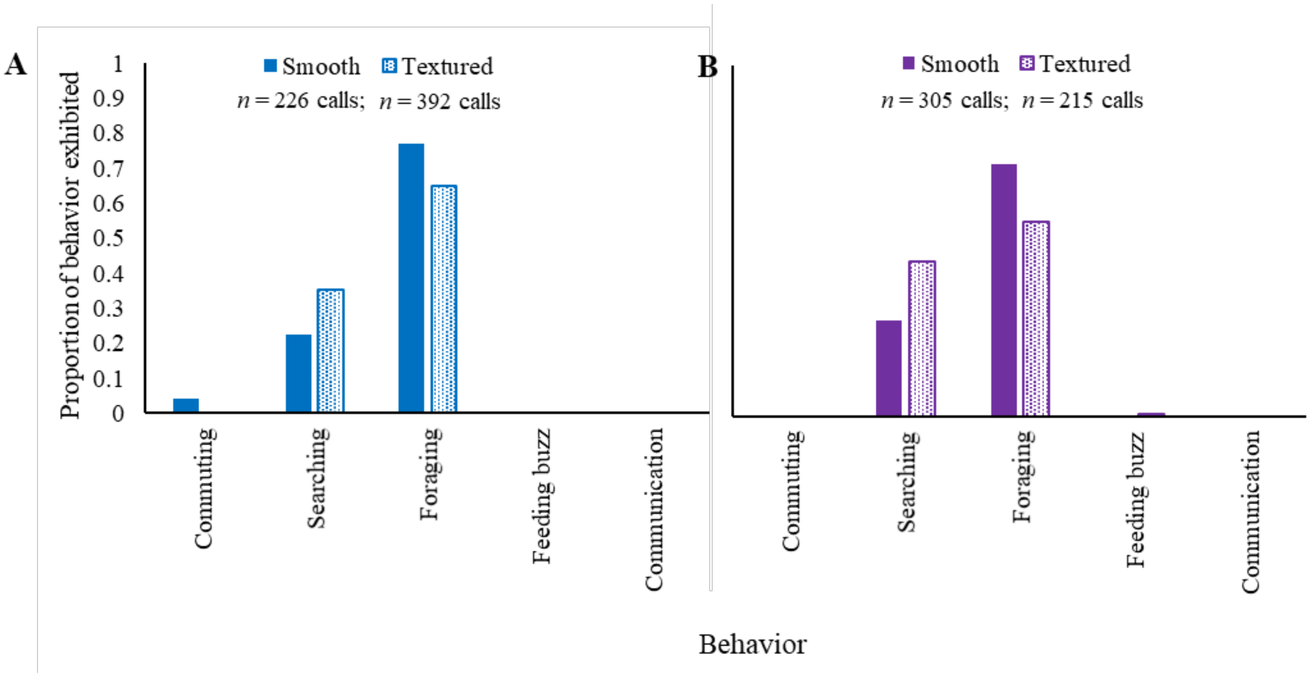
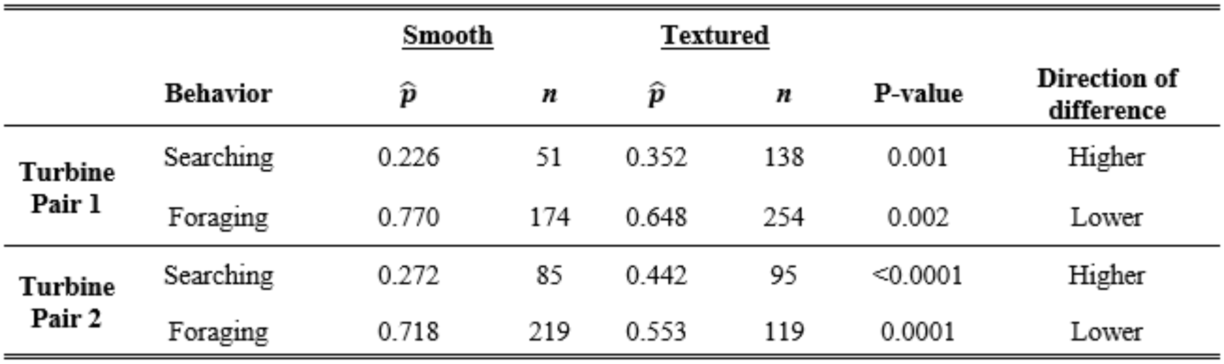


Figure 24: The proportion of bats exhibiting each behavior identified by acoustic calls at turbine pairs surveyed at Wolf Ridge over 27 survey nights at each turbine pair from 24 June to 22 September 2017. **A** delineates Turbine Pair 1, shown in blue, while **B** represents Turbine Pair 2, shown in purple.

Table 7: The results of Fisher's exact tests comparing the proportions of bats exhibiting 'foraging' and 'searching' behaviors in acoustic calls at turbines surveyed at Wolf Ridge over 27 survey nights at each pair from 24 June to 22 September 2017. Note that behaviors were excluded in which *n*<10 bat calls were detected.



		Smooth		Textured			
	Behavior	$\hat{p}$	n	$\hat{p}$	n	**P-value**	**Direction of difference**
Turbine Pair 1	Searching	0.226	51	0.352	138	0.001	Higher
	Foraging	0.770	174	0.648	254	0.002	Lower
Turbine Pair 2	Searching	0.272	85	0.442	95	<0.0001	Higher
	Foraging	0.718	219	0.553	119	0.0001	Lower

To determine if the behavioral differences observed in 'searching' and 'foraging' between smooth and textured turbines were driven by certain species, we compared species-specific acoustic behavior in each turbine pair (Fig. 25). Note that Mexican free-tailed bats were not recorded foraging at either smooth or textured turbine in Turbine Pair 1. A series of Fisher's exact tests comparing the species-specific proportions of behaviors exhibited revealed a significant increase in the proportion of eastern red bat 'searching' and a decrease in 'foraging' at the textured turbine in both turbine pairs. In addition, we found an increase in 'searching' and a decrease in 'foraging' among tricolored and evening bats at the textured turbine in Turbine Pair 2 (Table 8).

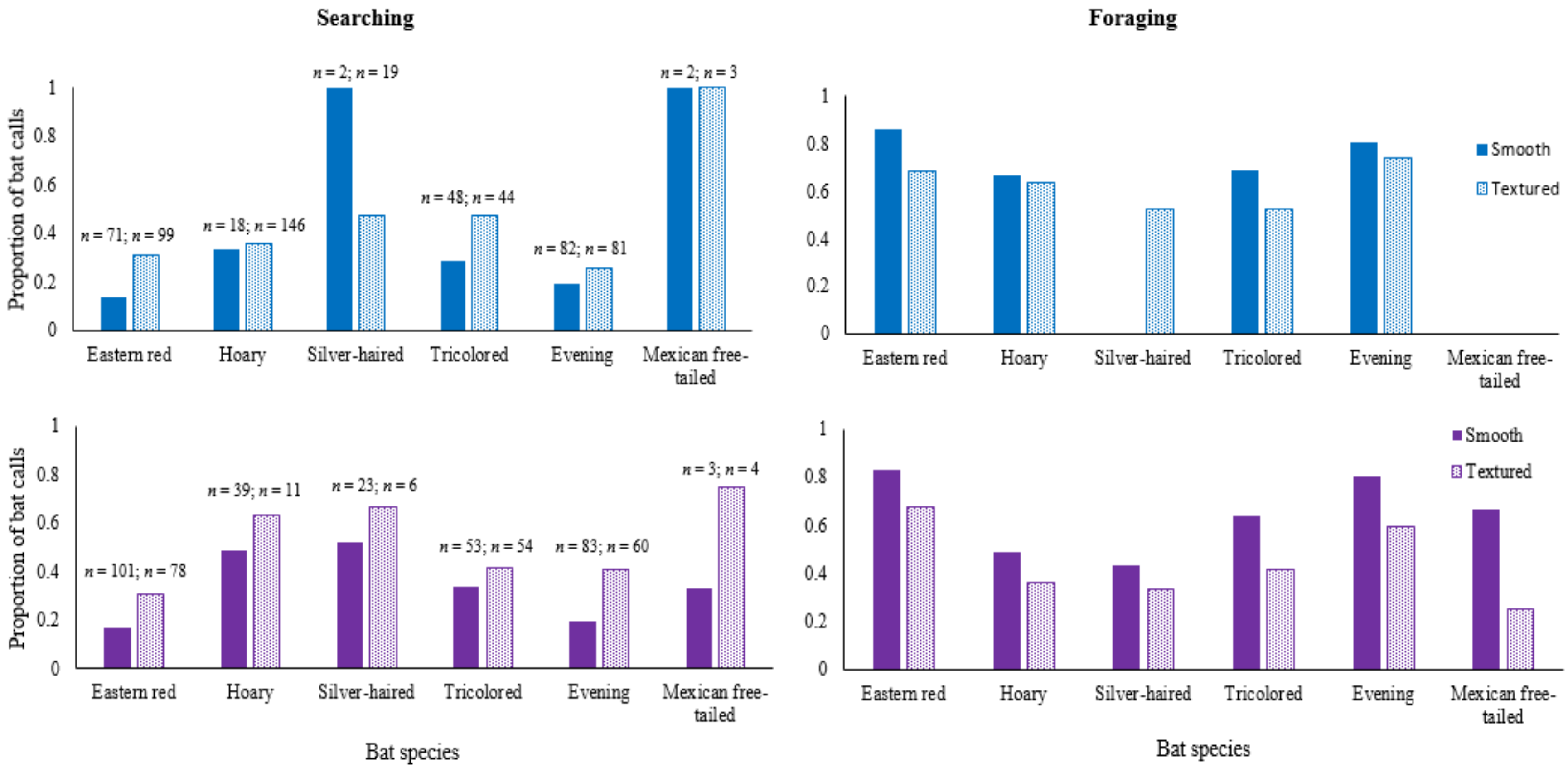
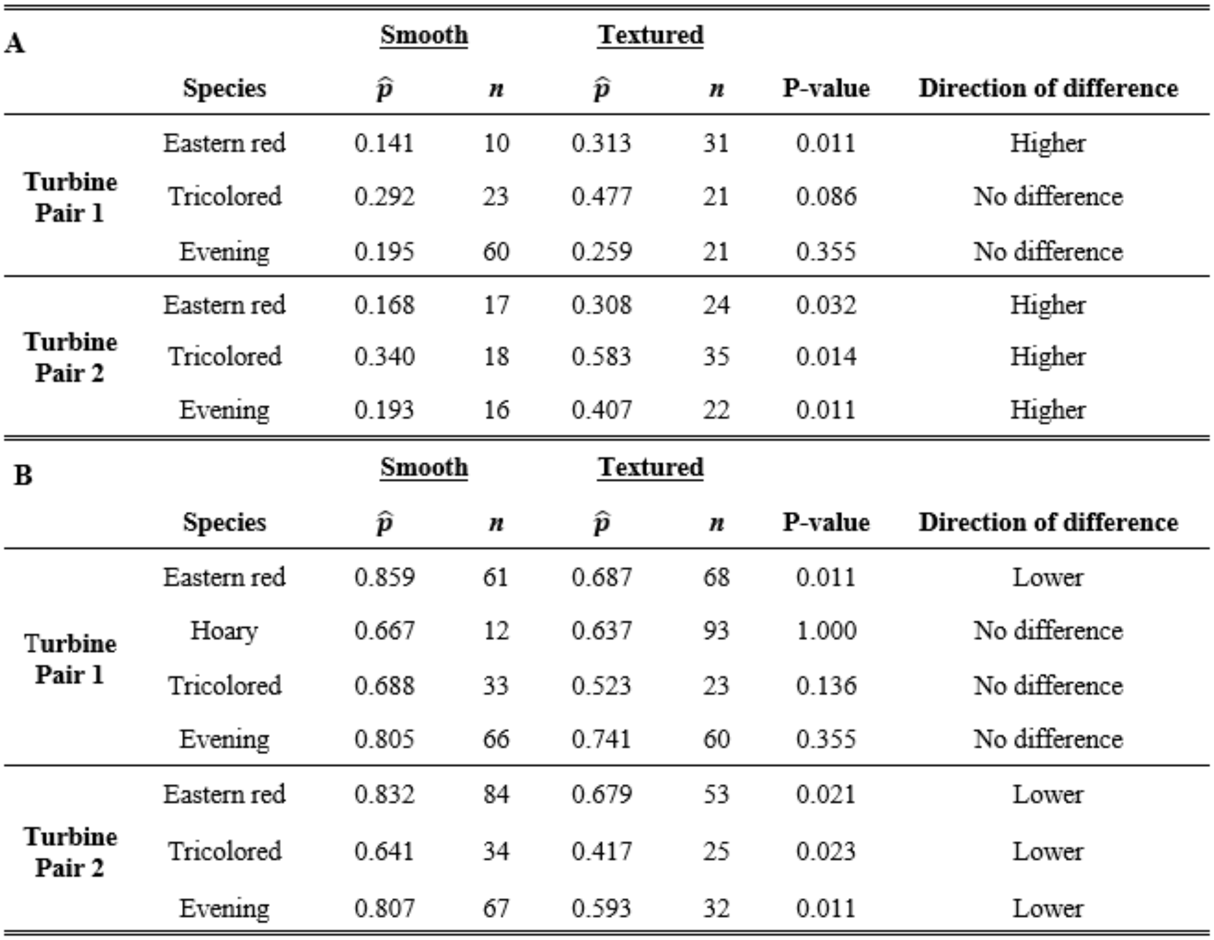


Figure 25: The proportion of bat calls for each species identified as either ‘searching’ or ‘foraging’ for each turbine pair. The *n* indicates the total number of calls recorded for each species at each turbine. Blue indicates Turbine Pair 1, while purple delineates Turbine Pair 2.

Table 8: Fisher's exact tests comparing 'searching' (**A**) and 'foraging' (**B**) behaviors identified in acoustic calls among bat species between smooth and textured turbines in each turbine pair. Note that species were excluded in which *n*<10 calls were recorded.



A		**Smooth**		**Textured**			
	Species	$\hat{p}$	*n*	$\hat{p}$	*n*	**P-value**	**Direction of difference**
Turbine Pair 1	Eastern red	0.141	10	0.313	31	0.011	Higher
	Tricolored	0.292	23	0.477	21	0.086	No difference
	Evening	0.195	60	0.259	21	0.355	No difference
Turbine Pair 2	Eastern red	0.168	17	0.308	24	0.032	Higher
	Tricolored	0.340	18	0.583	35	0.014	Higher
	Evening	0.193	16	0.407	22	0.011	Higher

B		**Smooth**		**Textured**			
	Species	$\hat{p}$	*n*	$\hat{p}$	*n*	**P-value**	**Direction of difference**
Turbine Pair 1	Eastern red	0.859	61	0.687	68	0.011	Lower
	Hoary	0.667	12	0.637	93	1.000	No difference
	Tricolored	0.688	33	0.523	23	0.136	No difference
	Evening	0.805	66	0.741	60	0.355	No difference
Turbine Pair 2	Eastern red	0.832	84	0.679	53	0.021	Lower
	Tricolored	0.641	34	0.417	25	0.023	Lower
	Evening	0.807	67	0.593	32	0.011	Lower

Bat fatalities

From 16 May to 22 September, we recorded 94 bat fatalities over 84 searches among the selected 10 turbines searched (*n* = 52 eastern red; *n* = 35 hoary; *n* = 6 evening; and *n* = 1 Mexican free-tailed). These fatalities were recorded across the survey period and we observed peaks between July and September, coinciding with the fall migration (Fig. 26).

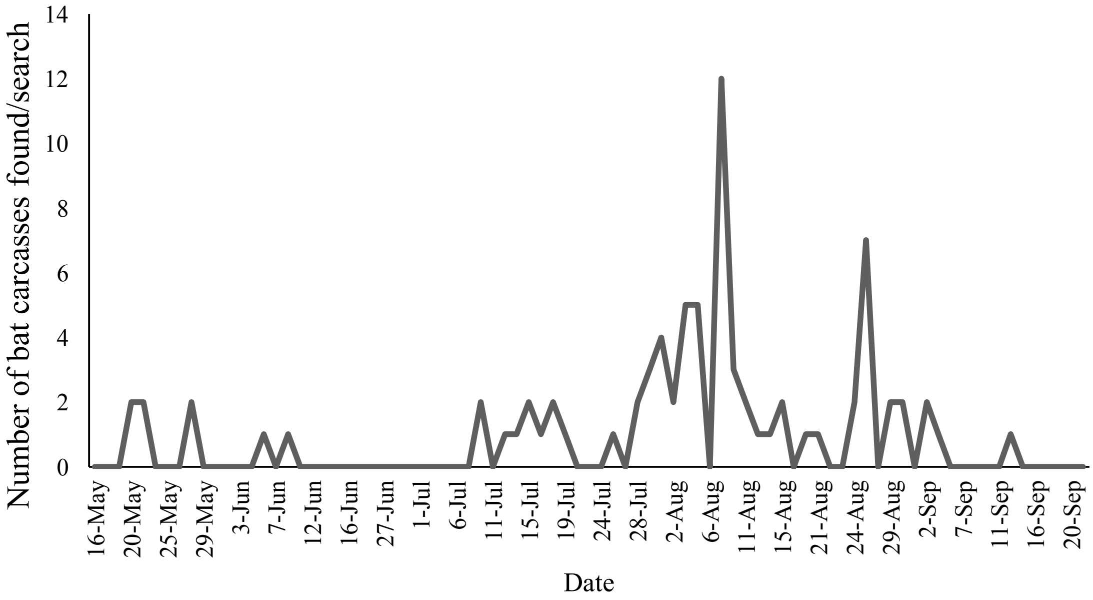


Figure 26: The occurrence of bat fatalities across the selected 10 turbines surveyed over 83 searches at Wolf Ridge over the entire survey season.

Finally, we inspected the patterns of observed and acoustic bat activity with the occurrence of bat fatalities across the entire survey period (Fig. 27). Using a Pearson's correlation, we found a significant positive relationship between bat fatalities and observed bat activity *(r* = 0.542, *P* = 0.02) and acoustic bat activity (*r* = 0.689, *P* = 0.001).

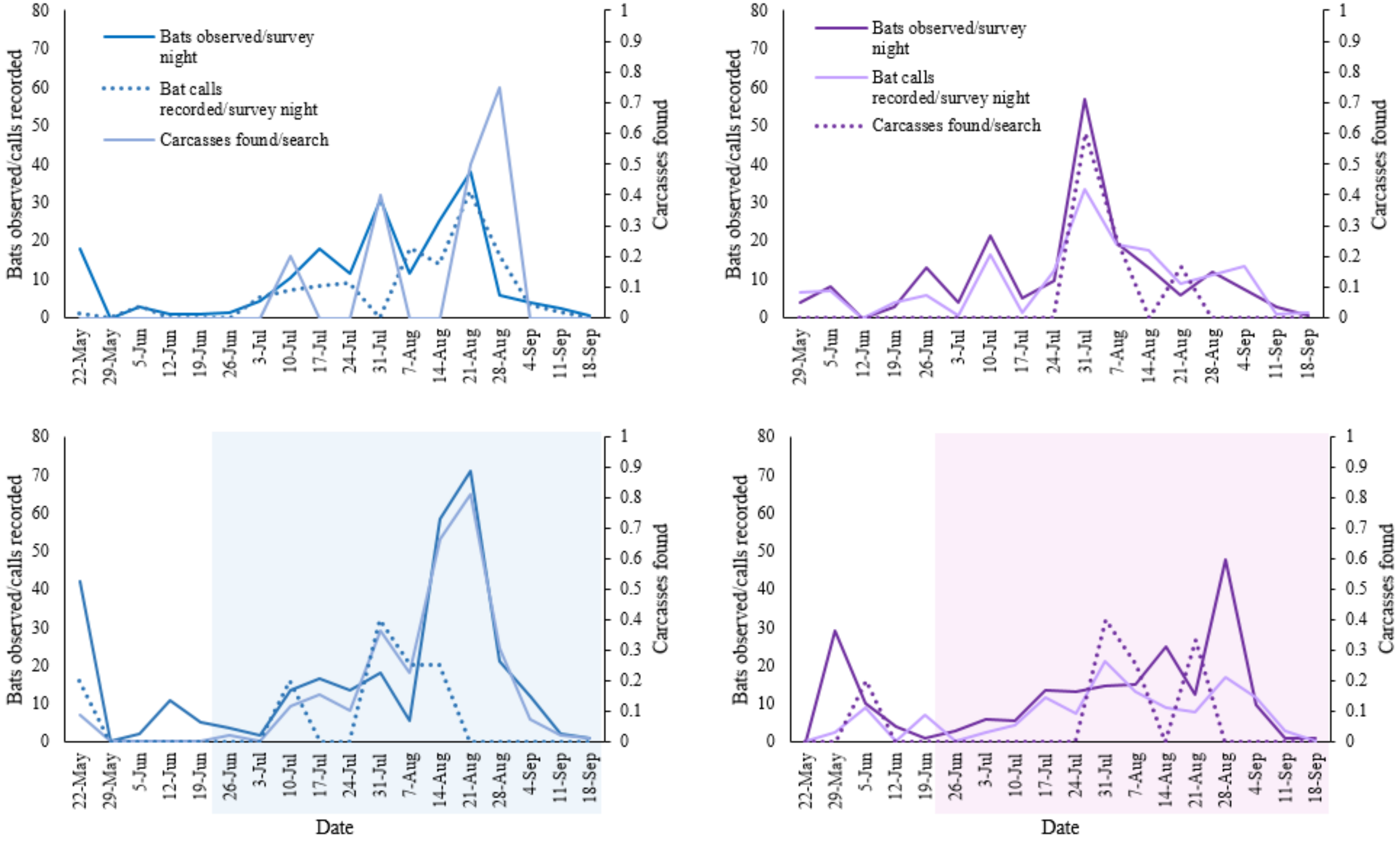


Figure 27: The pattern of bat fatality (measured by number of bat carcasses found per search) and bat activity (in both observed and acoustic calls recorded per survey night) across the entire survey period at Wolf Ridge for each surveyed turbine. Turbine Pair 1 is shown in blue and Turbine Pair 2 is shown in purple. The shading indicates when the texture coating was applied to the 2 textured turbines.

Discussion

While our study did not explicitly demonstrate that a texture application would reduce bat activity at wind turbine towers, we found differences in species-specific activity and behavior in proximity to the towers that indicated that the texture application could have had an influence. For the texture application to be considered an effective mitigation strategy, we would have observed a reduction in bat activity at the textured turbines compared with the smooth in both turbine pairs. However, our results did not show this. In fact, we observed opposing trends in both the observed and acoustic bat activity at the textured turbines between the 2 turbine pairs, This contradicting outcome between turbine pairs could be caused by several factors: 1) differences between the turbines within pairs (i.e., surrounding resource availability or area effects), 2) variations in species-specific responses to the texture, or 3) discrepancies in the texture application itself between the 2 textured turbines.

If this outcome was caused by differences between the turbines within the pairs, we would have consistently observed and recorded a similar activity pattern in the previous years' surveys acoustic surveys, as well as in bat fatalities collected. However, as turbine selection was based on previously consistent fatality and acoustic data, it is not likely that the turbines themselves influenced bat activity during the post-texture application stage.

Similarly, while we did see peaks in species-specific activity, it is unlikely that any one species was driving the variations in activity between the pairs, or across all turbines. While we recorded distinct peaks in hoary bat activity (particularly at the textured turbine in Turbine Pair 1), we also recorded an unprecedented number of hoary bats at each turbine surveyed compared to previous years. Note that hoary bats are one of the three migratory species present at our site that make up the majority of fatalities at wind energy facilities in North America (Arnett &

Baerwald 2013; Zimmerling & Francis 2016; AWWI 2018). As detectors were typically placed on the ground in acoustic surveys and hoary bats predominantly fly at a height beyond the range of our detectors (>40 m), it is rare to record hoary bats on our acoustic detectors (Table 9). Thus, to record a minimum 9-fold increase in hoary bat activity in 2017 indicates that there was a unique peak in activity in the area this year. Furthermore, if there was an influx of a migratory species, we would expect to see 1) an increase in activity across all turbines studied, 2) a peak in activity at the smooth turbines only, or 3) a peak in activity at the textured turbines only. However, while we recorded an increase in hoary bat activity among all turbines studied, this increase was predominantly at one particular turbine, the textured turbine in Turbine Pair 1 (Fig. 28). This result suggests that the potential hoary bat responses to the texture application itself was species-specific, which supports our final theory that the differences in bat activity observed were due to variations in the texture application.

Table 9: Number of hoary bat calls recorded from five years of acoustic monitoring surveys at Wolf Ridge.

Year	Hoary bat calls recorded	Hours surveyed	Nights surveyed	Bat calls recorded per hour
2012	45	252	42	0.179
2013	10	303	101	0.033
2015	0	78	26	0
2016	1	44	21	0.023
2017	214	108	72	1.981

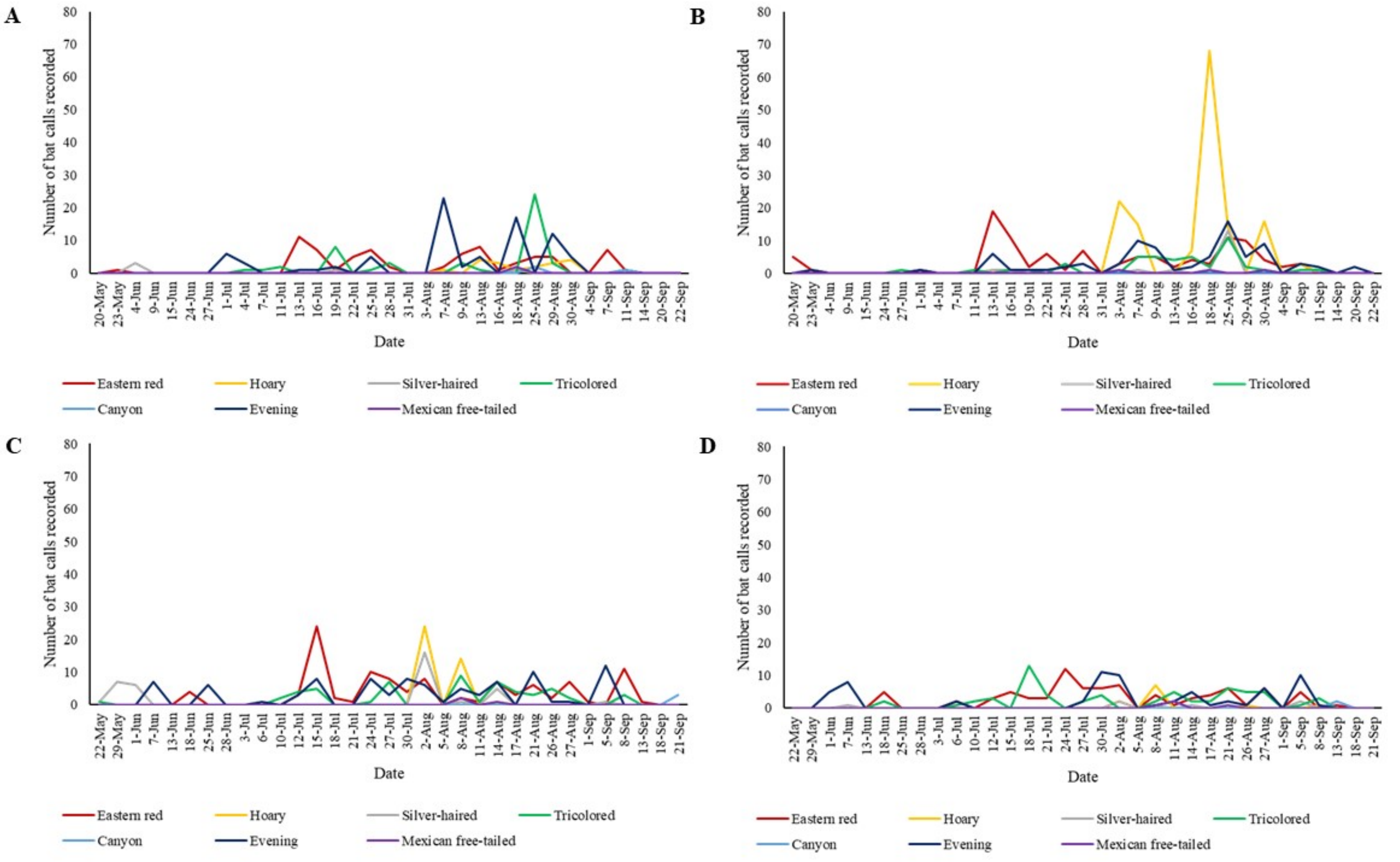


Figure 28: Patterns of species-specific bat activity across the survey season at each turbine study site at Wolf Ridge. **A** represents the smooth turbine in Turbine Pair 1, while **B** represents the textured turbine. **C** shows the smooth turbine in Turbine Pair 2 and **D** shows the textured turbine.

Due to the complexity of the texture coating and the number of materials used, the application process and the appearance of the texture were inconsistent between turbine pairs (see Methods). Such inconsistencies were evident in the turbine in Turbine Pair 1, which was the first turbine coated with the texture. During the application process too much adhesive was applied to the tower, which resulted in the small beads becoming obscured in this layer, leaving only the larger beads exposed (Fig. 29). As the texture was specifically designed to contain a particular distribution of small and large beads, any deviation from this design undoubtedly affected our results. Thus, the opposing trend in bat activity between turbine pairs could potentially be explained by the differences in the texture application.

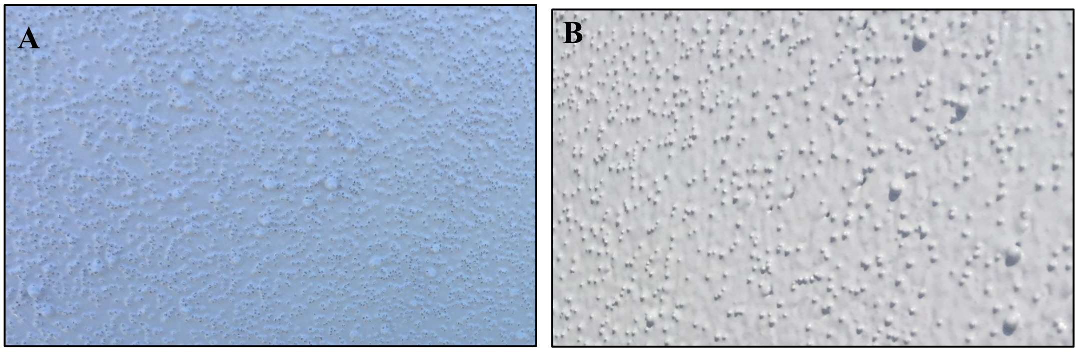


Figure 29: Representative pictures of the texture coating applied to the turbine towers in **A** Turbine Pair 1 and **B** Turbine Pair 2 at Wolf Ridge.

Despite the issues associated with variations in the texture coating, any species-specific results were still informative as the 3 species of migratory tree bats that make up the majority of bat fatalities at wind turbines in North America were present at our study site (eastern red, hoary, and silver-haired bats; Arnett & Baerwald 2013; Zimmerling & Francis 2016; AWWI 2018). As outlined in the Introduction, the 7 bat species at our site could be placed into 2 categories based on their echolocation frequencies: high frequency (eastern red, evening, and tricolored bats), and low frequency (hoary, silver-haired, Mexican free-tailed, and canyon bats). Our results indicate that high frequency bats may have responded more effectively to the texture application than low frequency bats. This response was demonstrated in our acoustic analysis by the observed increase in ‘searching’ and corresponding decrease in ‘foraging’ behaviors among high frequency bats at the textured turbines in both pairs. These results suggest that the presence of the texture on the towers could have made the turbines themselves and the area around the turbines less attractive foraging resources.

As the texture coating was only tested on high frequency bat species (eastern red and evening) in the controlled flight facility, our findings confirm that any texture must be extensively tested to ensure desired responses from all species in a given site. Moreover, our results emphasize that species may respond differently, so the specific design of the texture application is very important and must be applied according to the specifications of the texture tested in the flight facility.

By comparing the proximal bat activity at each turbine between pre- and post-texture application stages, we found an increase in the proportion of ‘all close’ observations at 3 out of the 4 turbines surveyed (refer to Table 3). As the post-texture application stage occurred during the fall migration when species diversity and overall bat abundance was higher, this could account for the increase in the proportion of ‘all close’ passes.

Finally, when we compared bat activity patterns to the occurrences of bat fatalities across the survey season, we observed analogous trends at each turbine studied (refer to Fig. 26). These corresponding trends provide evidence that bat fatalities are associated with bat activity, thus supporting the hypothesis that bat abundance and activity could be used to predict fatality (Weller & Baldwin 2012). Therefore, a mitigation strategy that effectively reduces bat activity in proximity to turbine towers has the potential to reduce bat fatalities at wind turbine towers. We recommend further testing of different textures among multiple species to create a standardized texture application for particular areas or sites. This standardized texture could be applied in the manufacturing process, thereby reducing the potential for variation in the texture application process. Another option would be to design a film of texture that could be wrapped around turbine towers during the manufacturing process and to those already operational. Note that there may not be a texture coating design that would effectively reduce all species-specific bat activity at wind turbines. Based on species-specific variations in bat ecology, behavior, and echolocation (Cryan 2008; Altringham 2011; Bennett & Hale 2014), it is likely that a texture coating will only be effective for a certain number of species. We therefore recommend a combination of different mitigation strategies to significantly reduce bat fatalities. Recent research has found that increasing turbine cut-in speeds and curtailment of turbine blades successfully reduces, but does not eliminate bat fatality (Baerwald *et al.* 2009; Arnett *et al.* 2011). Furthermore, testing of acoustic deterrents has proven promising to help alleviate fatality, but is still in development (Arnett *et al.* 2013). Another study has found potential for the use of UV light deterrents, but is currently undergoing testing as a potential mitigation strategy (Gorressen *et al.* 2015). Our findings indicate that a properly designed and applied texture could also be an effective mitigation strategy if combined with these other methods. Continued research studying bat behaviors at wind turbines is also essential to better inform these mitigation strategies.

Appendix A

Bat Video Identification Key

A. Thermals

1. **Confirmed bat**: A flying object is classified as a confirmed bat when the silhouette of the object resembles that of a bat (i.e., a visible head, body and wings) and only has characteristics associated with a bat (see non-bat characteristics listed below). Also, in very clear images the patagium can been seen stretched over the finger bones and/or the wrist and thumb joints are visible. Note that in the thermals, warm-bodied objects are often seen as being orange, yellow, or white in color, and in clear images the wings may also have bright color on all or part of the wing. Below are some examples of confirmed bats (Image 1a,b,c,d).

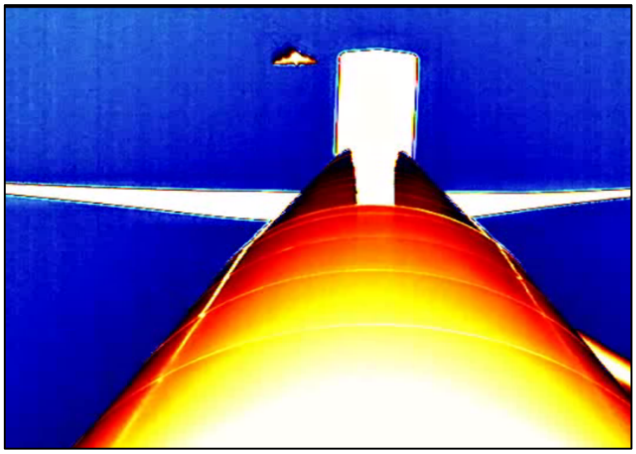


Image 1a: This object was classified as a bat because it has a distinct head, body, and wings. Note that you can see the finger bones in the patagium.

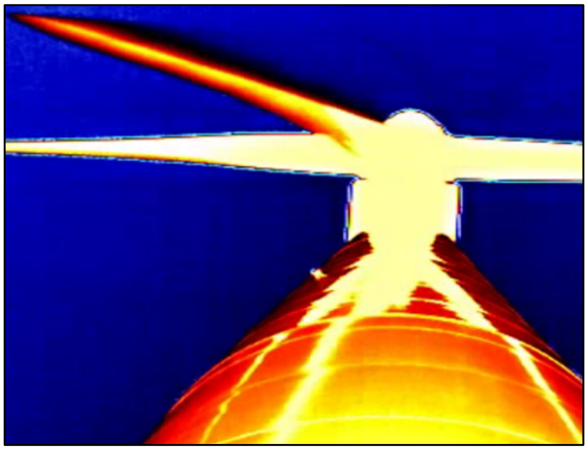


Image 1b: This object was classified as a bat because it has a distinct head, body, and wings.

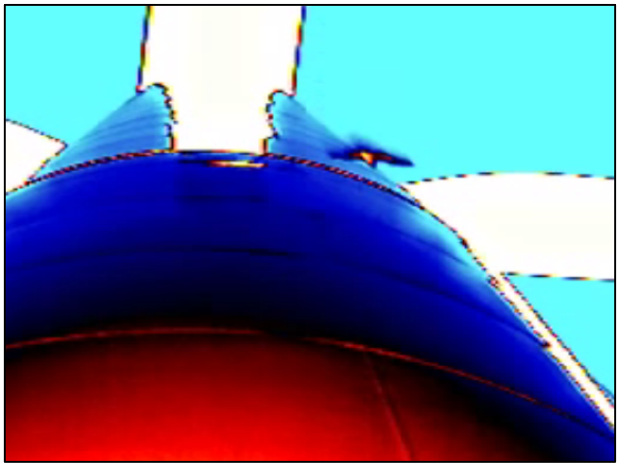


Image 1c: This object was classified to be a bat because it has a distinct head, body, and wings. Note the bat wings are darker than the body.

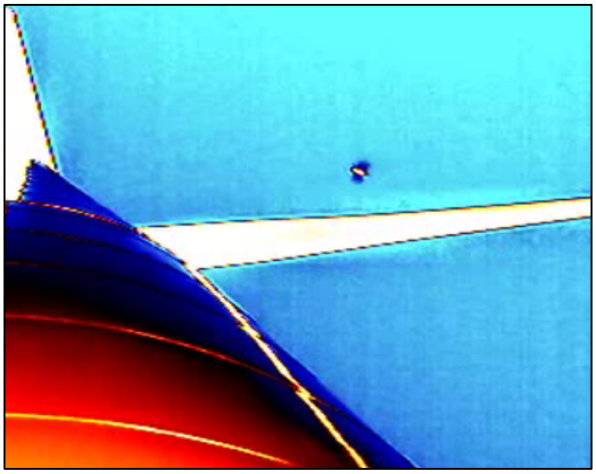


Image 1d: This object was classified to be a bat because it has a distinct body and wings. The bat wings are darker than the body.

2. **Non-bat**: A flying object is classified to be a non-bat when it has characteristics of an insect, bird, plane, or other. For example, common flying insects such as Lepidoptera, Coleoptera, Orthoptera, and Odonata, can be visible on thermal cameras. Features that are characteristic of readily recognizable insects include pairs of wings towards one end of the body, a long thin body, a small body with relatively large wings, or a distinctly large thorax with a long abdomen. Note that insects can appear warm-bodied due to the generation of muscle heat and/or due to proximity to the video camera. In contrast, birds can appear to have characteristics similar to bats (i.e., head, body, and wings); however if a tail is visible, the object is characterized as a bird. In addition, if the image is clear, the wings may be distinctly shaped like a bird (Image 2b). Below are some examples of non-bats (Image 2a-j).

Image 2a: This object was determined to be a bird because it has a distinct body and wings as well as a distinct tail.

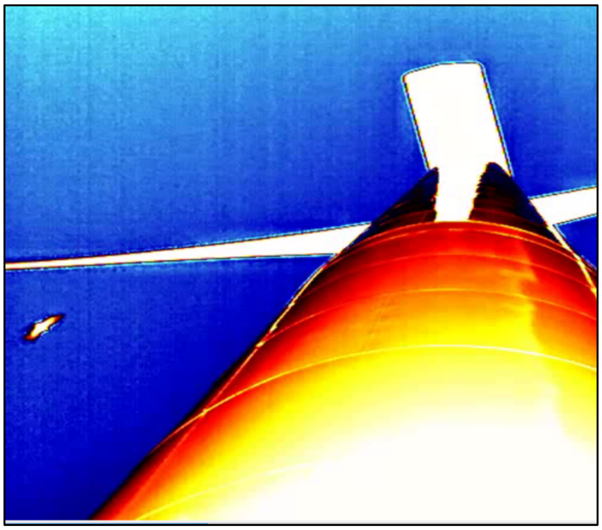


Image 2b: This object was determined to be a bird because it has rectangular wings that are shaped like bird wings but are unlike a bat's wings.

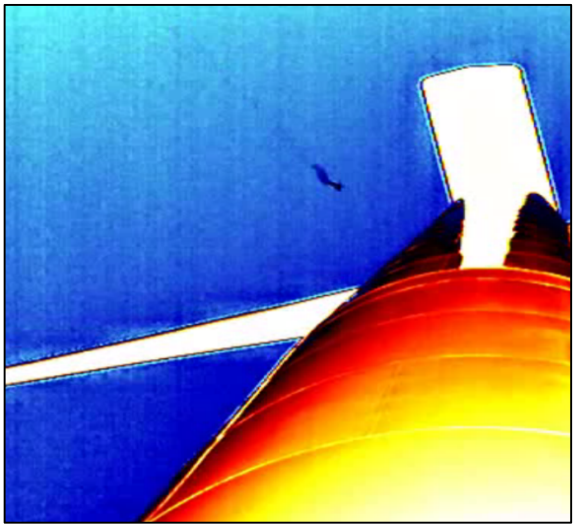


Image 2c: This object was determined to be a moth because it has a tiny body and large wings.

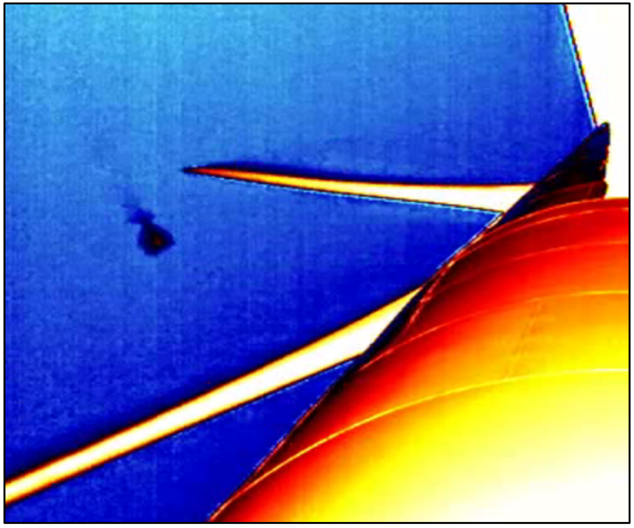


Image 2d: This object was determined to be a moth because it has a tiny body with round wings.

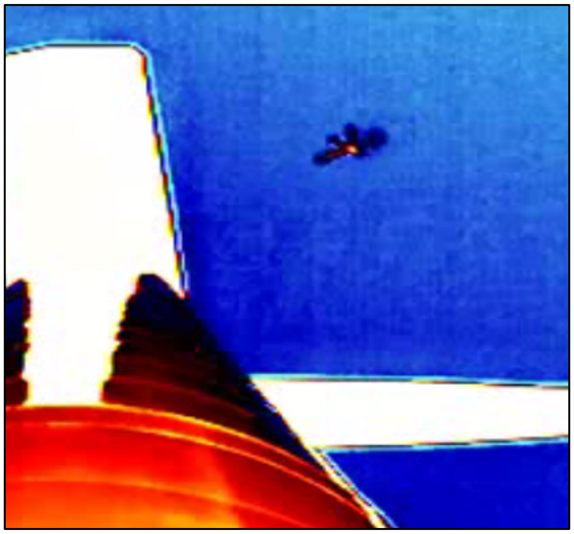


Image 2e: This object was determined to be a dragonfly because it has 2 pairs of wings.

Image 2f: This object was determined to be a dragonfly because it has 2 pairs of wings.

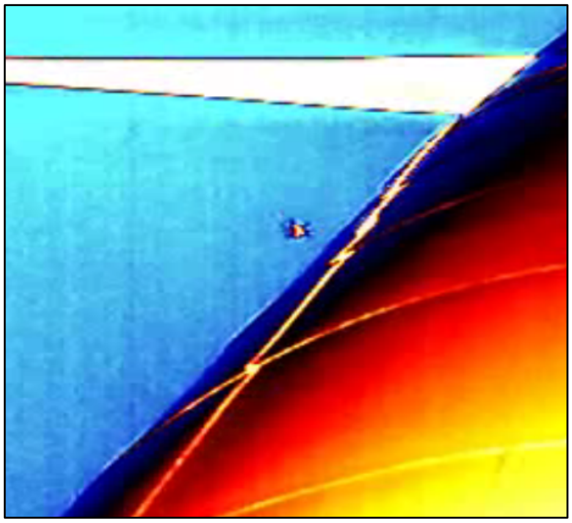


Image 2g: This object was determined to be a dragonfly because it has 2 pairs of wings and a long tail.

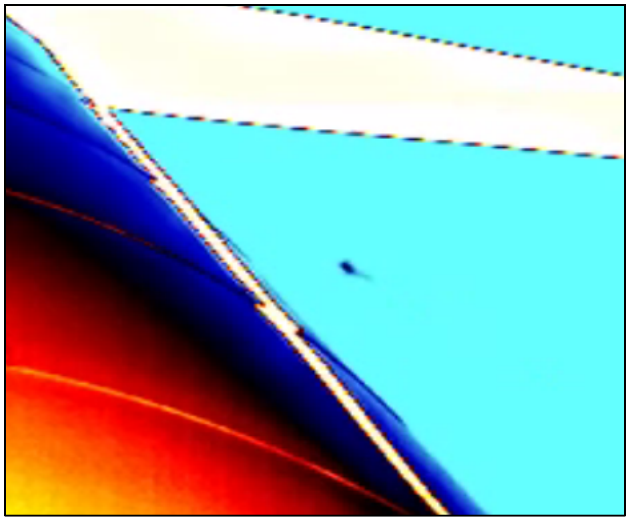


Image 2h: This object was classified to be a dragonfly because it has a long, thin abdomen extending from body.

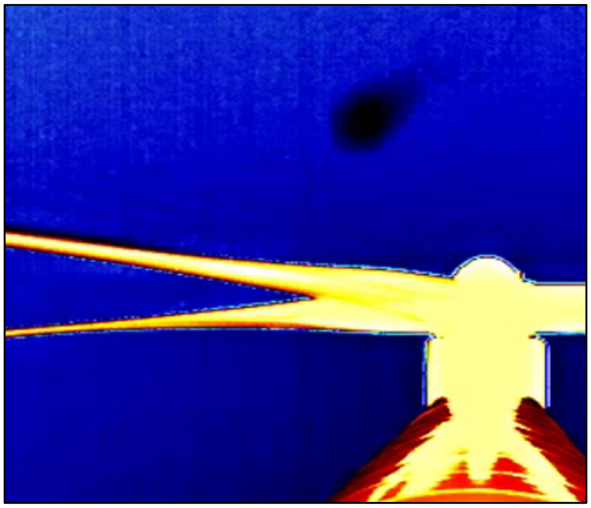


Image 2i: This object was classified to be an insect because it is flying close to the camera and is out of focus. It has no other distinguishing details.

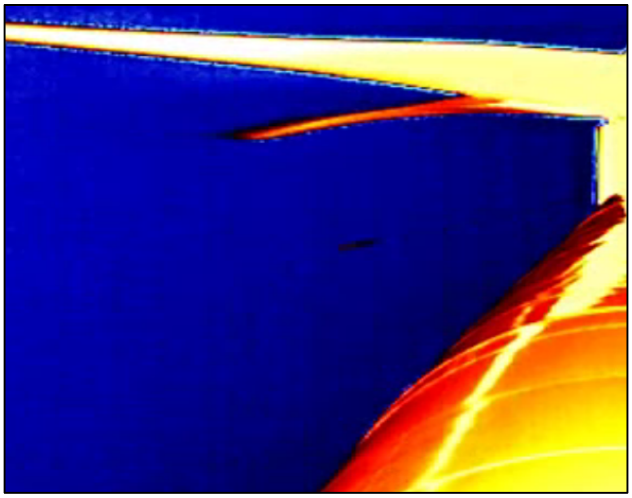


Image 2j: This object was classified to be an insect such as a grasshopper or beetle because it is so fast moving it appears as a black line without any distinguishing features.

3. **Possible Bat**: An object is considered a possible bat when there are: 1) no characteristics observed which suggest the object is a bat (head and distinct wings); 2) no characteristics that suggest the object is a non-bat (i.e., bird-like tail); or 3) characteristics are not sufficiently visible (i.e., indistinct wings). Below are some examples of possible bats (Images 3a-f).

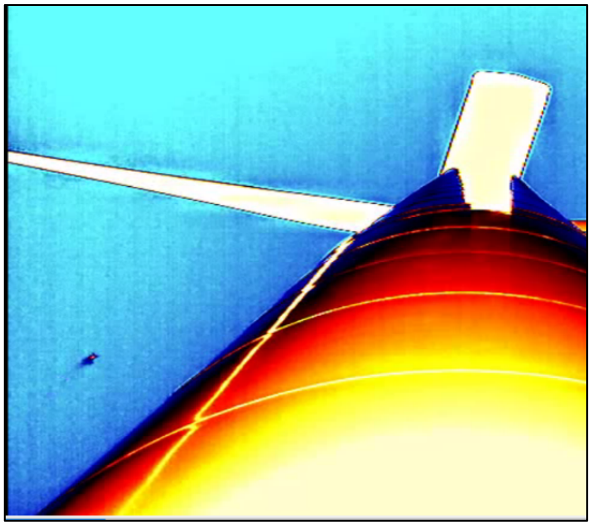


Image 3a: This object was determined to be a possible bat because it has wings that are not visibly distinct and no characteristics to indicate a non-bat.

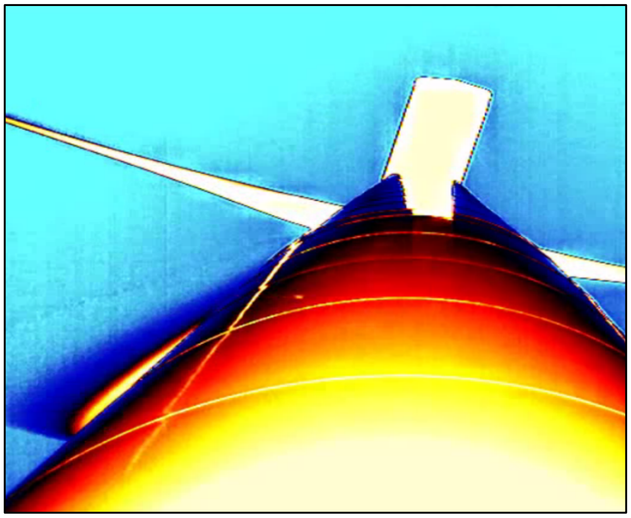


Image 3b: This object was determined to be a possible bat because it has no characteristics to suggest a bat or a non-bat.

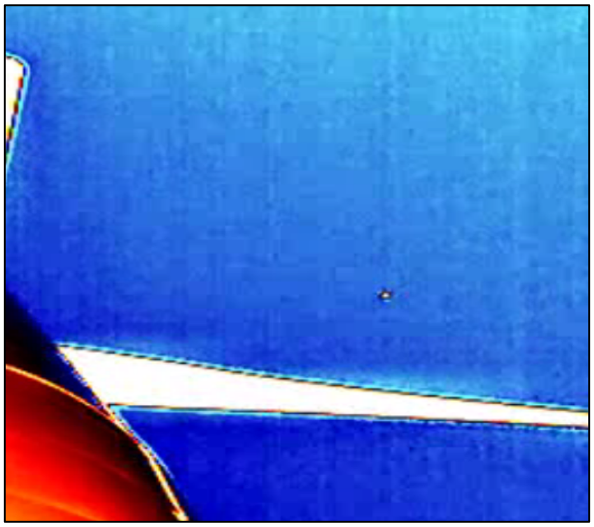


Image 3c: This object was determined to be a possible bat because it has no characteristics to suggest a non-bat and it has indistinct wings.

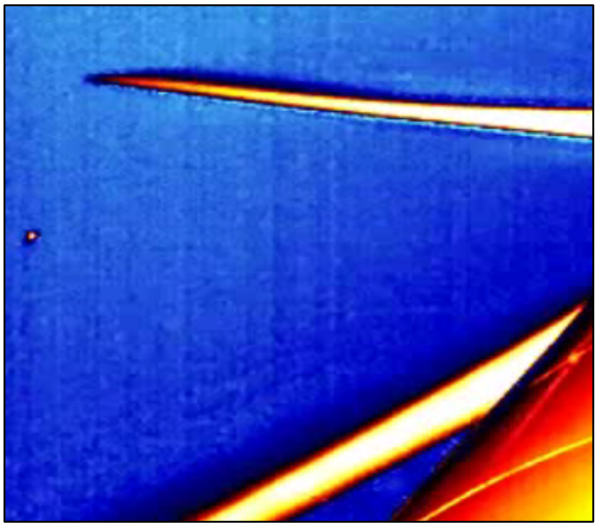


Image 3d: This object was determined to be a possible bat because we cannot ascertain whether the dark patches at the sides of the body are wings or shadows created by the body.

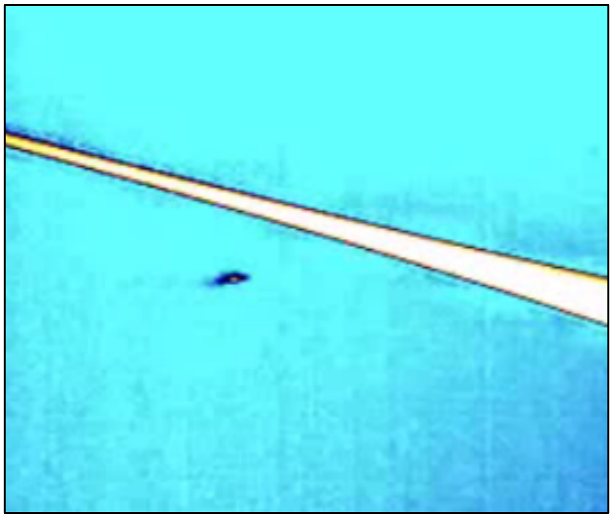


Image 3e: This object is a possible bat because it has no characteristics that suggest a bat or a non-bat.

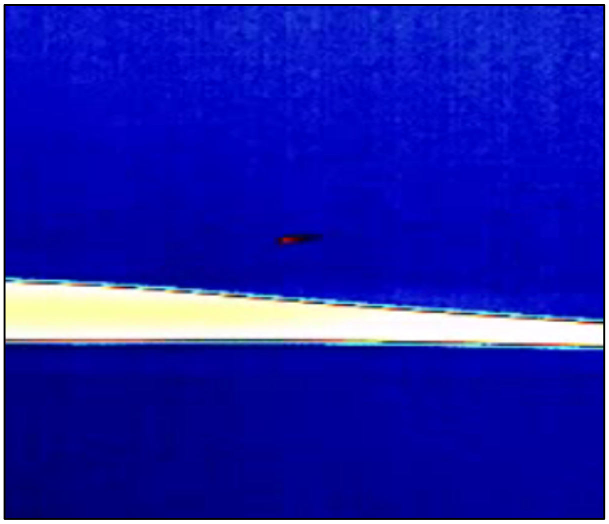


Image 3f: This object is a possible bat because it has no characteristics that suggest a bat or a non-bat.

B. Night vision

In night vision images it may be possible to see an object in more detail than in the thermal images. This detail may be used to help determine whether possible bats are bats or non-bats. In addition, night vision recordings may be used to determine whether possible bats are bats or non-bats by observing the behavior of the flying object. Different types of objects such as birds, bats, and insects, can have distinct flight patterns that can be used to distinguish them.

4. **Bat:** An object is classified as a confirmed bat when the object resembles a bat (i.e., a visible head, body and wings) and only has characteristics associated with a bat. It also may be possible to see more detail in the image, such as hand and finger joints and more a defined wing shape. Below are some examples of bats (Images 4a-f).

   In addition, see section E: Behavioral analysis for the common types of behavior exhibited by bats. One behavior that may be used to determine whether a possible bat is a bat is a foraging flight pattern. Foraging behavior appears as a zig-zag flight in which the bat takes multiple turning angles. This flight pattern is not exhibited by birds or insects.

Image 4a: This object was determined to be a bat because it has a distinct head, body, and wings. The joints of the wing are visible in this image.

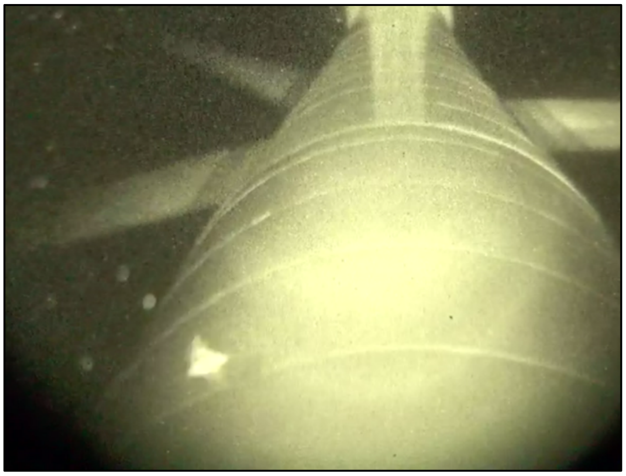


Image 4b: This object was determined to be a bat because it has a distinct head, body, and wings. This bat is flying perpendicular to the camera.

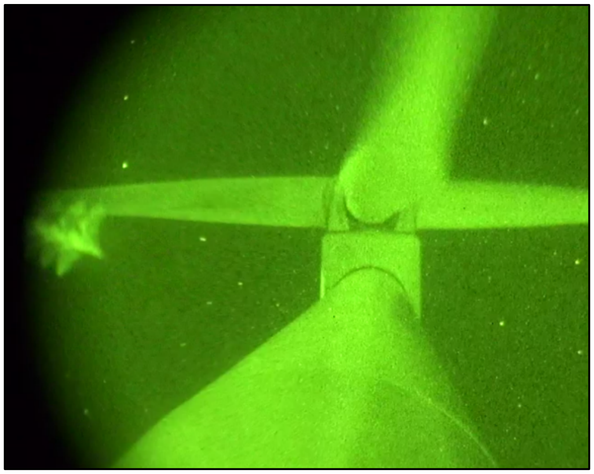


Image 4c: This object was determined to be a bat because it has a distinct head, body, and wings. The joints in the wings can also be seen. This bat is casting multiple images, which can happen on the night vision for fast-moving bats.

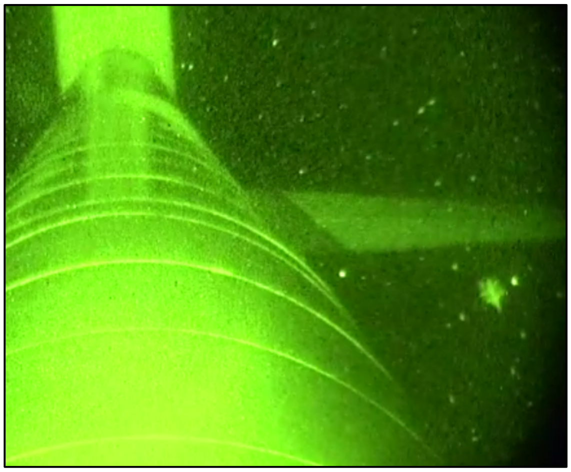


Image 4d: This object was determined to be a bat because it has a distinct body and wings. This bat is casting multiple images, which can happen on the night vision for fast-moving bats.

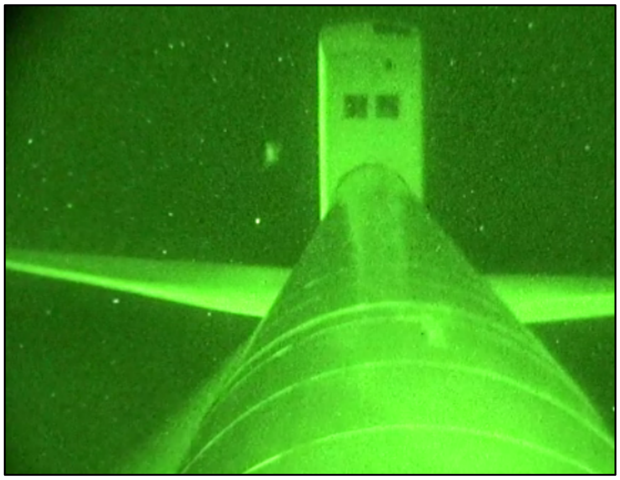


Image 4e: This object was determined to be a bat because it has a distinct body and wings.

Image 4f: This object was determined to be a bat because it has a distinct body and wings. This bat is flying perpendicular to the camera.

5. **Non-bat**: A flying object is classified to be a non-bat when it has characteristics of an insect, bird, plane or other. Below are some examples of non-bats (Images 5a-f).

   Again, flight behavior may be used to confirm that a possible bat is not a bat. For example, many insects, particular moths, have a distinct fluttering flight and/or undulating movement. Grasshoppers often appear to streak across the area of interest with straight flight paths and are seen as a series of dots in a line (Image 2a). Furthermore, birds may display bounding flight.

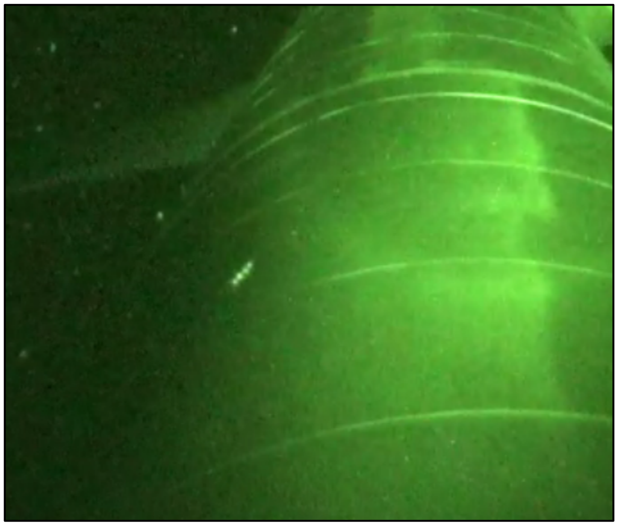


Image 5a: This object was determined to be an insect such as a grasshopper because it is seen as a series of dots in a line with a straight flight path.

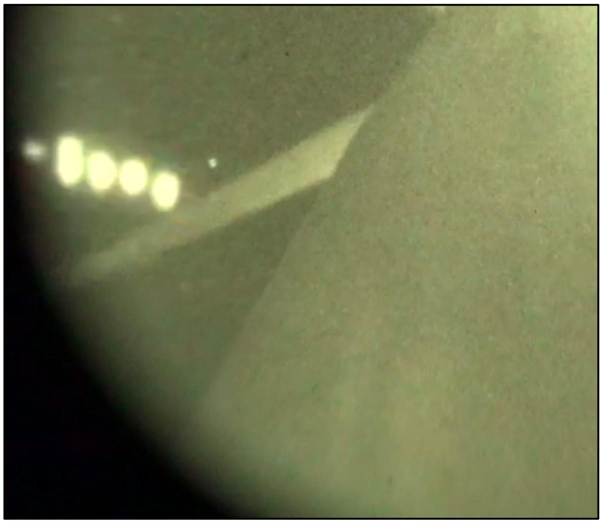


Image 5b: This object was determined to be an insect such as grasshopper because it is seen as a series of dots in a line with a straight flight path. This grasshopper is flying closer to the camera than the in Image 5a and is over-reflecting the IR lights near the camera to appear bright but unfocused.

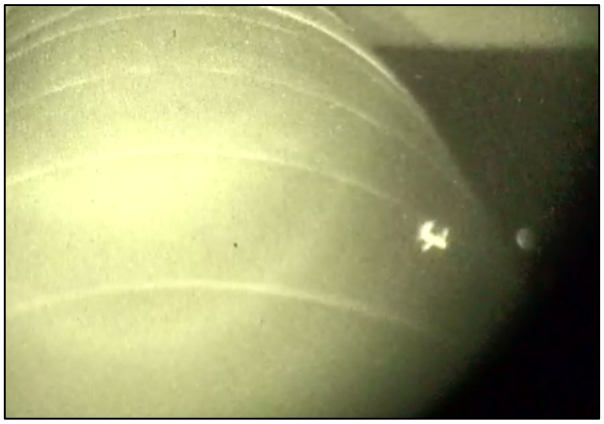


Image 5c: This object was determined to be an insect such as a dragonfly because it has 2 pairs of wings.

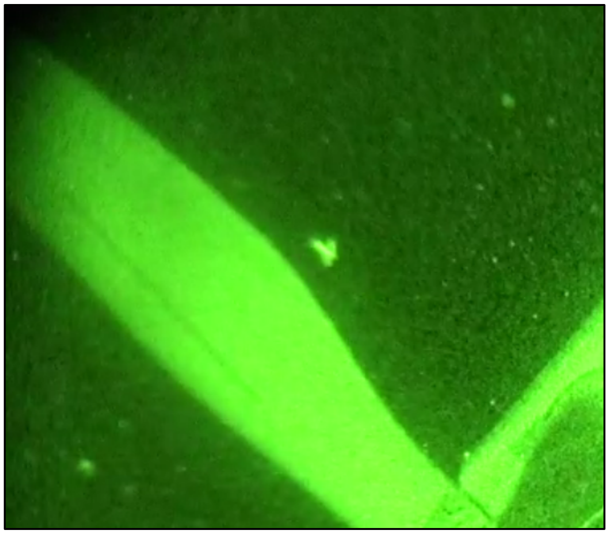


Image 5d: This object was determined to be an insect such as a dragonfly because it has a long body with wings at the abdomen.

Image 5e: This object was determined to be an insect such as a dragonfly because it has 2 pairs of wings.

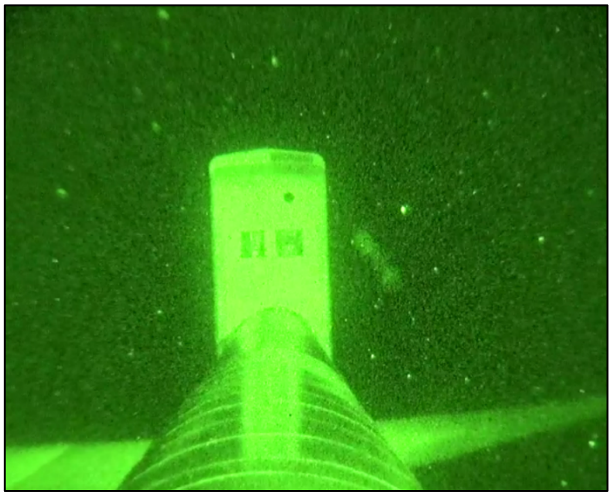


Image 5f: This object was determined to be an insect such as a grasshopper or beetle because it is seen as a series of dots in a line with a straight flight path. This organism is reflecting less light than the objects in Image 5a and 5b.

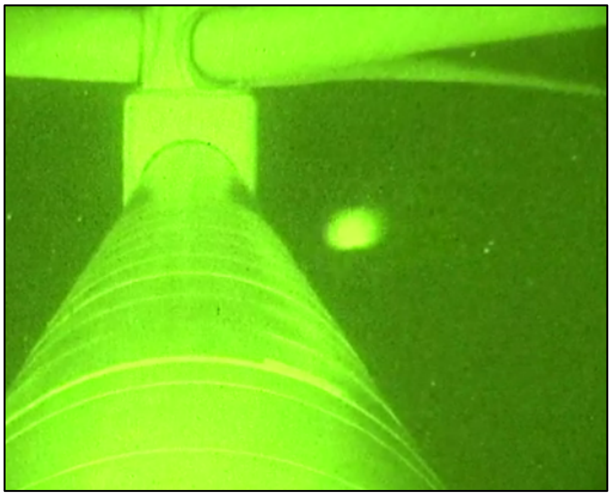


Image 5g: This object was determined to be an insect such as beetle or a moth because it is flying close to the camera and is out of focus. It has either a round body or rounded wings with no other distinguishing details.

6. **Possible Bat:** An object is considered a possible bat when there are: 1) no characteristics observed which suggest the object is a bat (head and distinct wings); 2) no characteristics that suggest the object is a non-bat (i.e., tail); or 3) characteristics are not sufficiently visible (i.e., indistinct wings). Below are some examples of possible bats (Images 6a-f).

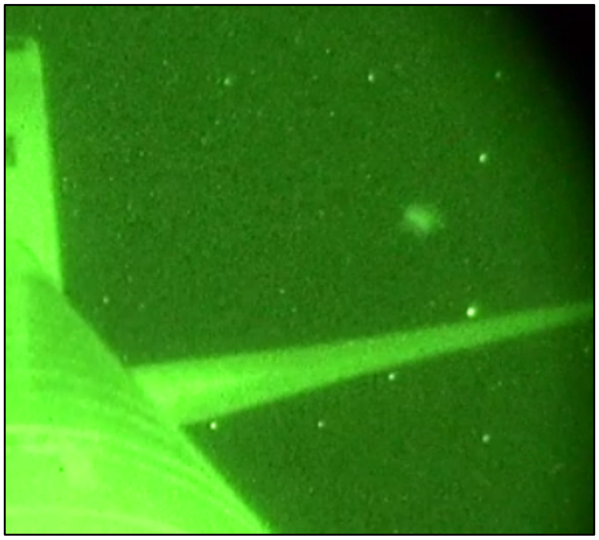


Image 6a: This object was classified to be a possible bat because it does not have distinct wings or any characteristic that suggests it is a bat or a non-bat. Note the object appears out of focus.

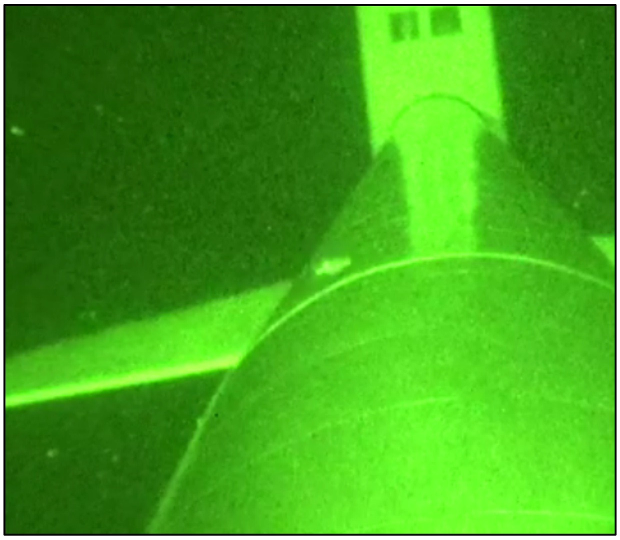


Image 6b: This object was classified to be a possible bat because it does not have distinct wings or any other defining characteristic of a bat or non-bat.

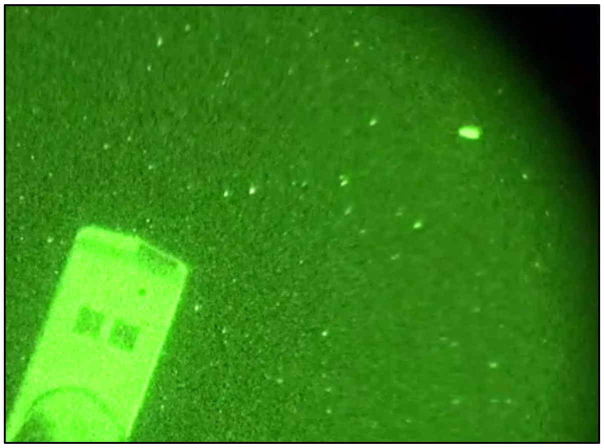


Image 6c: This was classified to be a possible bat because it does not have distinct wings or any other defining characteristic of a bat or non-bat.

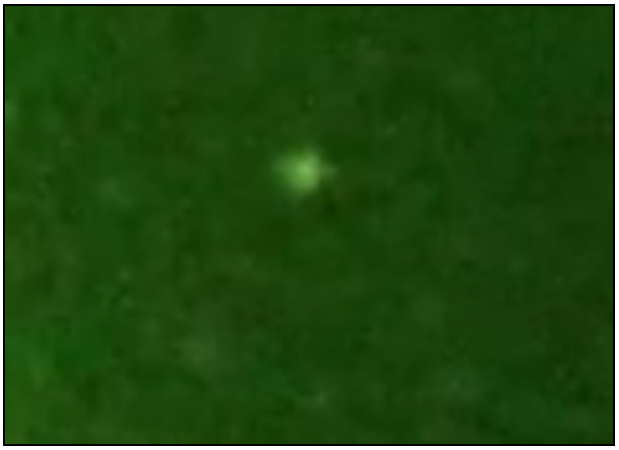


Image 6d: This was classified to be a possible bat because it does not have distinct wings or any other defining characteristic of a bat or non-bat. Note the object appears out of focus.

Appendix B

Table 1: A summary of all observed bat-like objects and their proximity and behaviors at all turbines surveyed at Wolf Ridge in both pre- and post-texture application stages from 20 May to 22 September 2017. In addition, this table has a species-specific summary of calls recorded.

	Turbine Pair	**1**		**2**		**3**		
	Turbine	**A**	**B**	**A**	**B**	**A**	**B**	**Total**
Pre-texture	Confirmed bats	3	4	5	12	4	3	31
	Possible bats	19	51	14	61	7	57	209
	Total	22	55	19	73	11	60	240
	Proximity							
	Far	21	52	14	68	9	60	224
	Close	1	3	4	9	2	3	22
	Contact/Close contact	0	0	1	0	0	0	1
	Behaviors							
	Passing	9	35	12	52	6	38	152
	Foraging	6	11	3	11	3	13	47
	Reversal	3	9	3	13	1	9	38
	Looping	0	0	0	1	1	3	5
	Chasing	0	0	0	0	0	0	0
	Gleaning	0	0	1	0	0	0	1
	Skimming	0	0	0	0	0	0	0
	Species-specific calls recorded							
	Eastern red	1	6	4	5	5	0	21
	Hoary	0	0	0	0	0	0	0
	Silver-haired	3	0	14	1	3	6	27
	Tricolored	0	0	1	2	1	0	4
	Canyon	0	0	0	0	0	0	0
	Evening	0	1	7	13	0	4	25
	Mexican free-tailed	0	0	0	0	0	0	0
	Total calls recorded	4	7	26	21	9	10	77

Post-texture	Confirmed bats	206	347	259	188		1000
	Possible bats	78	110	93	125		406
	Total	284	457	352	313		1406
	Proximity						
	Far	212	291	246	223		972
	Close	71	161	104	90		426
	Contact/Close Contact	1	5	2	0		8
	Behaviors						
	Passing	186	267	222	216		891
	Foraging	50	135	78	51		314
	Reversal	34	30	43	38		145
	Looping	9	10	5	6		30
	Chasing	4	10	2	2		18
	Gleaning	1	4	1	0		6
	Skimming	0	1	1	0		2
	Species-specific calls recorded						
	Eastern red	71	99	101	78		349
	Hoary	18	146	39	11		214
	Silver-haired	2	19	23	6		50
	Tricolored	48	44	53	60		205
	Canyon	3	0	3	2		8
	Evening	82	81	83	54		300
	Mexican free-tailed	2	3	3	4		12
	Total calls recorded	226	392	305	215		1138

Appendix C

We compared the pattern of ‘confirmed’ and ‘possible’ bat activity at the two turbine towers in Turbine Pair 3. These turbines were surveyed between 20 May and 18 June 2017, but were not surveyed following texture application. Furthermore, the pattern of ‘possible bat’ activity mirrors the ‘confirmed bat’ activity, as seen in the other turbines surveyed as well.

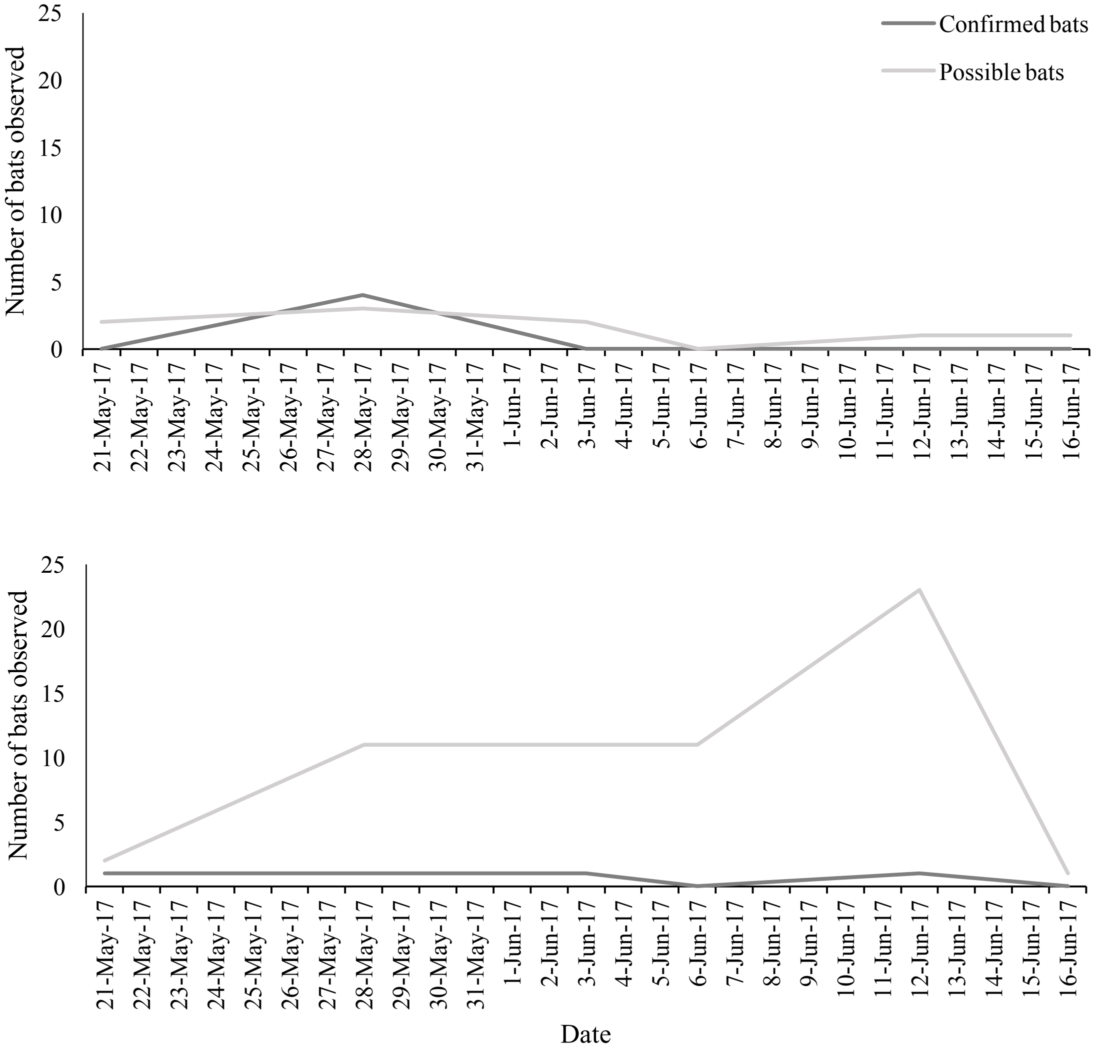


Figure 1: The activity pattern of ‘confirmed’ and ‘possible bats’ at the two turbines in Turbine Pair 3 over 6 survey nights at Wolf Ridge.

References

AWWI (2018) AWWI Technical Report: A Summary of Bat Fatality Data in a Nationwide Database. American Wind Wildlife Institute, Washington, DC.

Altringham, J.D. (2011) *Bats From Evolution to Conservation,* 2nd edn. SPI Publisher Services, Pondicherry, India.

Arnett, E.B. & Baerwald, E.F. (2013) Impacts of wind energy development on bats: Implications for conservation. *Bat Evolution, Ecology, and Conservation* (ed. R.A.A.S.C. Pederson), pp. 435-456. Springer Science+Business Media, New York.

Arnett, E.B., Brown, W.K., Erickson, W.P., Fiedler, J.K., Hamilton, B.L., Henry, T.H., Jain, A., Johnson, G.D., Kerns, J., Koford, R.R., Nicholson, C.P., O'Connell, T.J., Piorkowski, M.D. & Tankersley, R.D. (2008) Patterns of Bat Fatalities at Wind Energy Facilities in North America. *The Journal of Wildlife Management,* **72,** 61-78.

Arnett, E.B., Hein, C.D., Schirmacher, M.R., Huso, M.M.P. & Szewczak, J.M. (2013) Evaluating the Effectiveness of an Ultrasonic Acoustic Deterrent for Reducing Bat Fatalities at Wind Turbines. *PLOS ONE,* **8,** e65794.

Arnett, E.B., Huso, M.M., Schirmacher, M.R. & Hayes, J.P. (2011) Altering turbine speed reduces bat mortality at wind-energy facilities. *Frontiers in Ecology and the Environment,* **9,** 209-214.

Baerwald, E.F. & Barclay, R.M.R. (2011) Patterns of Activity and Fatality of Migratory Bats at a Wind Energy Facility in Alberta, Canada. *Journal of Wildlife Management,* **75,** 1103-1114.

Baerwald, E.F., Edworthy, J., Holder, M. & Barclay, R.M.R. (2009) A Large-Scale Mitigation Experiment to Reduce Bat Fatalities at Wind Energy Facilities. *Journal of Wildlife Management,* **73,** 1077-1081.

Bennett, V. & Hale, A. (2018) Resource Availability May Not Be a Useful Predictor of Migratory Bat Fatalities or Activity at Wind Turbines. *Diversity,* **10,** 44.

Bennett, V.J. & Hale, A.M. (2014) Red aviation lights on wind turbines do not increase bat-turbine collisions. *Animal Conservation,* **17,** 354-358.

Bennett, V.J., Hale, A.M. & Williams, D.A. (2017) When the excrement hits the fan: Fecal surveys reveal species-specific bat activity at wind turbines. *Mammalian Biology,* **87,** 125-129.

Bienz, C. (2016) Surface texture discrimination by bats: Implications for reducing bat mortality at wind turbines. Environmental Science Masters of Science, Texas Christian University.

Blowers, Z., Kloepper, L., Linnenschmidt, M. & Simmons, J. (2015) Population Estimates and Emergence Trends of Mexican Free-tailed Bats Using Image Processing Tools. *Bat Research News,* **56,** 71.

Clare, E.L. & Holderied, M.W. (2015) Acoustic shadows help gleaning bats find prey, but may be defeated by prey acoustic camouflage on rough surfaces. *Elife,* **4**.

Cryan, P.M. (2008) Mating Behavior as a Possible Cause of Bat Fatalities at Wind Turbines. *The Journal of Wildlife Management,* **72,** 845-849.

Cryan, P.M. & Barclay, R.M.R. (2009) Causes of Bat Fatalities at Wind Turbines: Hypotheses and Predictions. *Journal of Mammalogy,* **90,** 1330-1340.

Cryan, P.M., Gorresen, P.M., Hein, C.D., Schirmacher, M.R., Diehl, R.H., Huso, M.M., Hayman, D.T.S., Fricker, P.D., Bonaccorso, F.J., Johnson, D.H., Heist, K. & Dalton, D.C. (2014) Behavior of bats at wind turbines. *Proceedings of the National Academy of Sciences,* **111,** 15126-15131.

Foo, C.F., Bennett, V.J., Hale, A.M., Korstain, J.M., Schildt, A.J. & Williams, D.A. (2017) Increasing evidence that bats actively forage at wind turbines. *Peerj,* **5**.

Frick, W.F., Baerwald, E.F., Pollock, J.F., Barclay, R.M.R., Szymanski, J.A., Weller, T.J., Russell, A.L., Loeb, S.C., Medellin, R.A. & McGuire, L.P. (2017) Fatalities at wind turbines may threaten population viability of a migratory bat. *Biological Conservation,* **209,** 172-177.

Fuller, B., Hammond, S. & Tomasi, T. (2012) Infrared Video Population Counts of Ozark Big-eared Bat Maternity and Limited-Use Sites. *Bat Research News,* **53,** 80.

Geipel, I., Jung, K. & Kalko, E.K.V. (2013) Perception of silent and motionless prey on vegetation by echolocation in the gleaning bat Micronycteris microtis. *Proceedings of the Royal Society Biological Sciences Series B,* **280,** 1-7.

General Electric, G. (2009) 1.5 MW Wind Turbine. (ed. G.E. Energy).

Gorressen, P.M., Cryan, P., Huso, M., Hein, C., Schirmacher, M., Johnson, J., Montoya-Aiona, K., Brinck, K. & Bonaccorso, F. (2015) Behavior of the Hawaiian hoary bat (*Lasiurus cinereous semotus*) and its distribution across the North Ko'Olau Mountains, O'ahu. United States Geological Survey.

Greif, S. & Siemers, B.M. (2010) Innate recognition of water bodies in echolocating bats. **1,** 107.

Greif, S., Zsebok, S., Schmieder, D. & Siemers, B.M. (2017) Acoustic mirrors as sensory traps for bats. *Science,* **357**.

Hayes, J.P. (1997) Temporal variation in activity of bats and the design of echolocation-monitoring studies. *Journal of Mammalogy,* **78,** 514-524.

Hayman, D.T.S., Cryan, P.M., Fricker, P.D. & Dannemiller, N.G. (2017) Long-term video surveillance and automated analyses reveal arousal patterns in groups of hibernating bats. *Methods in Ecology and Evolution,* **8,** 1813-1821.

Horn, J.W., Arnett, E.B. & Kunz, T.H. (2008) Behavioral responses of bats to operating wind turbines. *Journal of Wildlife Management,* **72,** 123-132.

Jameson, J.W. & Willis, C.K.R. (2014) Activity of tree bats at anthropogenic tall structures: implications for mortality of bats at wind turbines. *Animal Behaviour,* **97,** 145-152.

Kunz, T.H., Arnett, E.B., Erickson, W.P., Hoar, A.R., Johnson, G.D., Larkin, R.P., Strickland, M.D., Thresher, R.W. & Tuttle, M.D. (2007) Ecological impacts of wind energy development on bats: questions, research needs, and hypotheses. *Frontiers in Ecology and the Environment,* **5,** 315-324.

Lehnert, L.S., Kramer-Schadt, S., Schönborn, S., Lindecke, O., Niermann, I. & Voigt, C.C. (2014) Wind Farm Facilities in Germany Kill Noctule Bats from Near and Far. *PLOS ONE,* **9,** e103106.

Long, C.V., Flint, J. A., & Lepper, P. A. (2011) Insect attraction to wind turbines: Does colour play a role? *European Journal of Wildlife Research,* **57,** 323-331.

Martin, C.M., Arnett, E.B., Stevens, R.D. & Wallace, M.C. (2017) Reducing bat fatalities at wind facilities while improving the economic efficiency of operational mitigation. *Journal of Mammalogy,* **98,** 378-385.

Matzner, S., Cullinan, V.I. & Duberstein, C.A. (2015) Two-dimensional thermal video analysis of offshore bird and bat flight. *Ecological Informatics,* **30,** 20-28.

McAlexander, A. (2013) Evidence that bats perceive wind turbine surfaces to be water. Biology Masters of Science, Texas Christian University.

Piorkowski, M.D. & O'Connell, T.J. (2010) Spatial Pattern of Summer Bat Mortality from Collisions with Wind Turbines in Mixed-grass Prairie. *The American Midland Naturalist,* **164,** 260-269.

Ren21 (2017) Renewables 2017 Global Status Report. Paris: Ren21 Secretariat.

Roscioni, F., Rebelo, H., Russo, D., Carranza, M.L., Di Febbraro, M. & Loy, A. (2014) A modelling approach to infer the effects of wind farms on landscape connectivity for bats. *Landscape Ecology,* **29,** 891-903.

Russo, D., Cistrone, L. & Jones, G. (2012) Sensory Ecology of Water Detection by Bats: A Field Experiment. *PLOS ONE,* **7,** e48144.

Scanlon, A.T. & Petit, S. (2008) Effects of site, time, weather and light on urban bat activity and richness: considerations for survey effort. *Wildlife Research,* **35,** 821-834.

Valdez, E.W. & Cryan, P.M. (2013) Insect prey eaten by hoary bats (*Lasiurus cinereus*) prior to fatal collisions with wind turbines. *Western North American Naturalist,* **73,** 516-524.

Warren, J.H., Sherwin, R.E., Ross, C., Williams, J. & Skalak, S.L. (2006) Applicability and reliability of external survey techniques when monitoring for Townsend's big-eared bat (*Corynorhinus townsendii*) in Pershing County, Nevada. *Bat Research News,* **47,** 157-158.

Weller, T.J. & Baldwin, J.A. (2012) Using echolocation monitoring to model bat occupancy and inform mitigations at wind energy facilities. *The Journal of Wildlife Management,* **76,** 619-631.

Weller, T.J., Castle, K.T., Liechti, F., Hein, C.D., Schirmacher, M.R. & Cryan, P.M. (2016) First Direct Evidence of Long-distance Seasonal Movements and Hibernation in a Migratory Bat. *Scientific Reports,* **6**.

Wiser, R. & Bolinger, M. (2017) 2016 Wind Energies Market Report. United States Department of Energy.

Yuen, B. (2015) Surface texture differentiation using synthetic bat echolocation calls: Implications for reducing bat fatalities at wind turbines. Environmetal Science Masters of Science, Texas Christian University.

Zimmerling, J.R. & Francis, C.M. (2016) Bat mortality due to wind turbines in Canada. *The Journal of Wildlife Management,* **80,** 1360-1369.

VITA

Personal Background

Brynn Huzzen
Gainesville, Florida
Daughter of John and Heather Huzzen

Education

2011	Diploma, Buchholz High School, Gainesville, FL
2014	Associate's of Arts, Jounralism, Santa Fe College, Gainesville, FL
2016	Bachelor's of Science, Natural Resource Conservation, Gainesville, FL

Experience

2018-present	Head Teaching Assistant, Texas Christian Univerisity
2018-present	Research Assistant, Texas Christian University
2017-2018 (Aug-May)	Teaching Assistant, Texas Christian University
2018(March-Sep)	Research Technician, Texas Christian University
2017 (May-Sep)	Research Coordinator, Texas Christian University
2017 (Jan-May)	Biological Intern, US Fish and Wildlife Service
2016 (May-Aug)	Wildlife Intern, Deseret Ranch

Reports, Presentations, and Posters

Texas Christian University, 2019. *Texturizing wind turbine towers to reduce bat fatality*. Technical Report for DOE EERE-Wind & Water Power Program. Report # DE-EE0007033

Huzzen BE, Bennett VJ, Hale AM. 2018. *Does a textured coating alter bat activity and behavior in proximity to wind turbine towers?* 98th Annual Meeting for the Society of Mammalogists. Manhattan, KS, USA. (Poster)

Huzzen BE, Bennett VJ, Hale AM. 2018. *Does a textured coating alter bat activity and behavior in proximity to wind turbine towers?* Student Research Symposium, Texas Christian University. Fort Worth, TX, USA. (Poster)

Hale AM, Bennet VJ, Bienz CR, Brenton CC, Huzzen BE, McAlexander AM. 2018. *Could the smooth surface of tower monopoles be a contributing factor to bat fatalieis at wind turbines?* 12th NWCC Wind Wildlife Research Meeting. St. Paul, MN, USA. (Presentation).

Grants and Awards

2018	TCU 3 Minute Thesis First Place Winner
2018	American Society of Mammalogists Travel Award
2018	Adkins Fellowship Research Grant
2018	TCU Graduate Student Travel Grant
2018	Best Environmental Science Poster at Student Research Symposium

ABSTRACT

DOES A TEXTURED COATING ALTER BAT ACTIVITY AND BEHAVIOR IN PROXIMITY TO WIND TURBINE TOWERS?

By Brynn Huzzen, M.S., 2019
Department of Environmental Sciences
Texas Christian University

Thesis Advisors: Dr. Victoria J. Bennett, Assistant Professor of Environmental Science

Dr. Amanda M. Hale, Associate Professor of Biology

Committee Member: Dr. John D. Horner, Professor of Biology

Wind turbines kill large numbers of migratory bats. There is therefore a need to alleviate bat-wind turbine collisions. Research has shown that bats approach and interact with the smooth tower surfaces as if they provide resources (i.e., water and food). We hypothesized that a textured coating would disrupt the smooth surface and potentially result in decreased bat activity in proximity to towers, thereby reducing collision risk. We conducted a paired behavioral survey using thermal, night vision, and ultrasonic acoustic technologies to assess bat activity at 2 pairs of wind turbines (containing a textured and control turbine) in north-central Texas. We found no difference in overall bat activity between smooth and textured turbines, however, we did find some responses to the texture that were species-specific. Our results demonstrate the importance of texture design and suggest that multple mitigation strategies should be used to account for species-specific variation in activity and behavior.