Patterns of pre-construction bat acoustic activity at the proposed Resolute Wind Energy Project, Wyoming, 2009–2010

Final Project Report

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EXECUTIVE SUMMARY

We initiated a multi-year, pre-construction study in mid-summer 2009 to investigate patterns of bat activity and evaluate the use of acoustic monitoring to predict mortality of bats at the proposed Resolute Wind Energy Project (RWEP) in east-central Wyoming. The primary objectives of this study were to: 1) determine levels and patterns of activity for three phonic groups of bats (high-frequency emitting bats, low-frequency emitting bats, and hoary bats) using the proposed wind facility prior to construction of turbines; 2) determine if bat activity can be predicted based on weather patterns; correlate bat activity with weather variables; and 3) combine results from this study with those from similar efforts to determine if indices of pre-construction bat activity can be used to predict post-construction bat fatalities at proposed wind facilities. We report results from two years of pre-construction data collection.

We recorded echolocation calls of bats with Anabat II zero-crossing ultrasonic detectors, programmed to record calls beginning ½-hour prior to sunset and ending ½-hour after sunrise each day of the study from 3 August–18 October 2009, and 2 June–30 September 2010. We assigned each bat pass to one of two phonic groups based on minimum frequency of the echolocation sequence; high frequency bats (≥33 kHz average minimum frequency; e.g., *Myotis* spp.) or low frequency bats (<33 kHz average minimum frequency; e.g., big brown, silver-haired, hoary bats). We also identified a third phonic group, hoary bats, a subset of the low frequency phonic group, because this species is vulnerable to wind-energy development and its echolocation sequences are relatively easy to distinguish among other low-frequency emitting bats. We used 5 meteorological (met) towers to position detector microphones at ~1.5 m and ~44 m above ground level (agl) to acoustically sample bat activity during this study.

In 2009, we recorded a total of 976 bat passes. We recorded 454 high frequency passes and 522 low frequency passes. Hoary bats comprised 22% (n = 114) of low frequency passes. In 2010, we recorded a total of 1,111 bat passes. We recorded 410 and 701 high frequency and low frequency passes, respectively. Hoary bats comprised 30% (n = 208) of low frequency passes.

Bat activity varied, by phonic groups, within and among nights. High frequency bats were most active 1–2 hours past sunset. Low frequency bat activity peaked during the middle of the night and hoary bats were most active within the first hour past sunset. Bat activity typically was highest between August and mid-September for all phonic groups. However, the timing and intensity of peak activity for each group differed between years.

Bat activity varied among phonic groups by height and among towers. We detected high frequency bats more often at 1.5 m agl with greatest activity recorded at tower 5042 in both 2009 and 2010. Low frequency bat activity was relatively consistent between heights and among towers for both years. We detected hoary bats more often at 44 m agl and recorded the greatest activity at towers 5032 and 5042 in 2009 and at tower 5032 in 2010. We recorded the fewest calls by any phonic group at tower 5034.

We modeled bat activity (passes/detector-night) in relation to tower location, temperature, and several measures of wind speed with 1) the probability of activity and 2) the estimated number of calls given that activity occurred. Tower location and temperature were consistently the most important factors in our models, accounting for ~5–29% of the variation in activity. However, location alone explained ~3–9.5% of the variation in activity. In general, we found the highest probability of activity and highest counts for each phonic group at towers on the western edge of the project. Both the probability of activity and estimated number of calls from each phonic group increased with increasing temperature. While some measure of wind was often important, it never explained more than an additional ~9% of the variation in activity. When included in the models, the effect of average wind speed on the probability of bat activity and estimated number of bat passes was always negative.

This study was conducted at a single proposed wind energy facility located on shrubland habitat in east-central Wyoming, and statistical inferences are limited to this site. However, we believe that our findings reflect patterns of bat activity on similar landscapes with comparable vegetation composition and topography in this region. Despite equipment malfunctions, we were able to quantify the spatial (vertical and horizontal) and temporal (seasonal and yearly) activity patterns of bats. These data may provide useful information for predicting when, where, and which bats may be most at risk of interactions with wind turbines at the RWEP. Moreover, specific timings and locations of peak activity may further refine the use of curtailment as a mitigation option.

INTRODUCTION

As energy demands increase worldwide, many countries are seeking ways to reduce fossil fuel consumption and generate alternate forms of energy. Wind is one of the fastest growing forms of renewable energy and has been produced commercially in North America for nearly 4 decades (Pasqualetti et al. 2004, National Research Council 2007). In recent years, the United States has been a world leader in wind generating capacity, including 5,115 Megawatts (MW) of new capacity in 2010 (AWEA 2011). Currently, Wyoming ranks 10th in the U.S. for installed capacity at 1,412 MW. Although wind-generated energy reduces carbon and other greenhouse gas emissions associated with climate change, it is not environmentally neutral because wildlife and habitats can be directly or indirectly impacted by development.

Bat fatalities have been reported at wind facilities since the early 1970‟s (Hall and Richards 1972, Dürr and Bach 2004, Johnson 2005, Kunz et al. 2007a, Arnett et al. 2008), but have received little attention until 2003 when an estimated 1,400–4,000 fatalities were reported at the Mountaineer Wind Energy Center, West Virginia (Kerns and Kerlinger 2004). High fatality rates also have been documented at other facilities along forest ridges across the eastern United States, including Meyersdale, PA (Kerns et al. 2005), Buffalo Mountain, Tennessee (Fielder 2004 and Fiedler et al. 2007), and Cassleman, PA (Arnett et al. 2009). However, data from the Midwestern US and Canada suggest high fatality events occur across a variety of landscapes, including agricultural fields, grassland prairies, and deciduous or coniferous forests (Jain 2011, Barclay et al. 2007, Kunz et al. 2007a, Arnett et al. 2008). Concerns regarding potential cumulative negative impacts of wind energy development on bat populations persist, particularly when many species of bats, especially tree-roosting species, are known or suspected to be in decline (Pierson 1998, Racey and Entwistle 2003, Winhold and Kurta 2006, Jones et al. 2009, Frick et al. 2010). Because bats provide numerous ecosystem services (e.g., insect suppression, or pollination and seed dispersal), adverse impacts of wind development on local bat populations could disrupt the ecological health and stability of a region (see Kunz et al. 2011).

Twelve species of bats occur in Wyoming and all are listed as Species of Special Concern and protected from take in Section 11 Chapter 52 in the Wyoming Game and Fish Commission Regulations (Hester and Greiner 2005). These species include western long-eared bat (*Myotis evotis*), small-footed bat (*M. ciliolabrum*), little brown bat (*M. lucifugus*), northern bat(*M. septentrionalis*), fringed bat (*M. thysanodes*), long-legged bat (*M. volans*), spotted bat (*Euderma maculatum)*, Townsend‟s big-eared bat (*Corynorhinus townsendii*), pallid bat (*Antrozous pallidus*), big brown bat (*Eptesicus fuscus*), silver-haired bat (*Lasionycteris noctivagans*), and hoary bat (*Lasiurus cinereus)*. Of these species, the silver-haired bat and hoary bat are both of increasing concern in the region, particularly with respect to wind development, because high fatalities have been reported for these migratory tree-bats at wind-energy facilities across North America (Arnett et al. 2008). At the Foot Creek Rim Wind Energy Project in Wyoming, Gruver (2002) summarized carcasses collected from 1999–2001 and showed 92% of bats found during carcass searches were migratory tree bats (108 hoary and 5 silver-haired bats of the 123 carcasses found). Similarly, of the 337 bat fatalities collected at existing wind-energy facilites in the Columbia Plateau Ecoregion of Oregon and Washington, hoary and silver-haired bats comprised 93.5% (n=315) of the total (Johnson and Erickson 2008).

Although several attraction hypotheses (e.g., roost, landscape, acoustic, or visual) have been proposed, interactions between bats and wind turbines are poorly understood (Arnett 2005, Barclay et al. 2007, Cryan and Brown 2007, Kunz et al. 2007a). Resolution of these different hypotheses requires additional data on the flight behavior of bats. However, the combination of nocturnal habits, volancy, small size, and variation in resource dependence (i.e., species vary in roost, water, and food requirements; Findley 1993; Kunz and Fenton 2003), makes even a rudimentary understanding of how bats interface with their environment difficult to establish (Gannon et al. 2003). Available post-construction monitoring data from a few wind energy facilities have provided a baseline for bat behaviors and reported fatalities at these installations (Arnett et al. 2008, Horn et al. 2008). Our current understanding of bat fatalities at wind energy facilities allows for some conjecture regarding risk factors for certain species, but further information on nightly and seasonal activity patterns encompassing a facility or region is still necessary to place bat fatalities in an appropriate context (Fiedler 2004). Pre-construction bat activity surveys at wind-energy facilities commonly employ mist nets and acoustic detectors to assess local bat species presence and activity, but using this information to predict bat fatality and to quantify risk is unproven. Moreover, the ability to generate reliable risk assessments during early planning phases (i.e., prior to site selection and construction) often is hampered by lack of baseline data on distributions, densities, migratory patterns, and behavior of bats (O‟Shea et al. 2003, Larkin 2006, Reynolds 2006, Cryan and Brown 2007) throughout much of North America. Thus, extensive planning (e.g., study design, survey intensity) for future wind developments is essential (EIA 2007, Kunz et al. 2007a, 2007b).

Acoustic monitoring allows researchers to detect and record various calls of echolocating bats as a means of investigating relative activity and identifying species or species groups (Kunz et al. 2007b). Understanding bat activity patterns prior to construction of wind facilities may assist in identifying landscape features which pose high risk of fatality and aid with decision-making, such as specific placement of turbines (Fiedler 2004, Reynolds 2006). Acoustic monitoring also provides insight into nightly and seasonal activity patterns, which presumably will help refine the timing and extent of potential mitigation strategies (e.g., curtailment). However, acoustic detectors often are used in the field without a thorough understanding of underlying assumptions and limitations or standardized protocols (Hayes 2000, Gannon et al. 2003; Parsons and Szewczak 2009). In addition, a lack of information and agreement among stakeholders and scientists exists regarding what constitutes acceptable levels of risk in relation to bat activity and potential fatality of bats at wind facilities. Collectively, several studies have shown a positive correlation (r = 0.79) between total number of bat calls/night and estimated fatalities/turbine/year (see Kunz et al. 2007b), yet confounding factors associated with these studies limit our ability to make inferences and develop a fundamental link necessary for understanding potential risk of wind facilities to bats.

OBJECTIVES

Clipper Wind Power Development (Clipper) proposes to develop the Resolute Wind Energy Project (RWEP) in east-central Wyoming. In 2009, we initiated a multi-year, pre-construction acoustic monitoring study to assess the patterns of bat activity and evaluate the use of acoustic monitoring to predict fatality of bats following methods and objectives of similar studies (e.g., Arnett et al. 2006, 2007; Kunz et al. 2007b). The goal of Phase I of this study was to collect data on echolocation passes and develop indices of temporal and spatial activity patterns. The second phase, which will occur after turbines are installed and the site is operational, will involve post-construction fatality monitoring. Our objectives for this report were to: 1) report baseline information on activity levels for different phonic groups using the RWEP, 2) examine temporal and spatial patterns of bat activity with acoustic detectors positioned at five meteorological (met) towers at 2 heights, and 3) combine our results with those of similar studies to evaluate if indices of pre-construction bat activity can be used to predict relative risk of post-construction bat fatality at a site. This report focuses on objectives 1 and 2; results from this study will be combined with several similar ongoing efforts in the region to address Objective 3.

STUDY AREA

The RWEP is a proposed 300 MW wind energy facility located in Converse County, near Casper in east-central Wyoming (Fig. 1). The habitat is mostly sagebrush shrublands (Wyoming Game and Fish Department [WGFD] 2010), with some trees in the foothills on the western edge of the project. We sampled 5 meteorological („met") towers (5032, 5034, 5041, 5042, and 5043), which allowed us to characterize variation in bat activity across the RWEP. The RWEP is currently in the planning stage and the total number of turbines and their locations are not yet finalized.

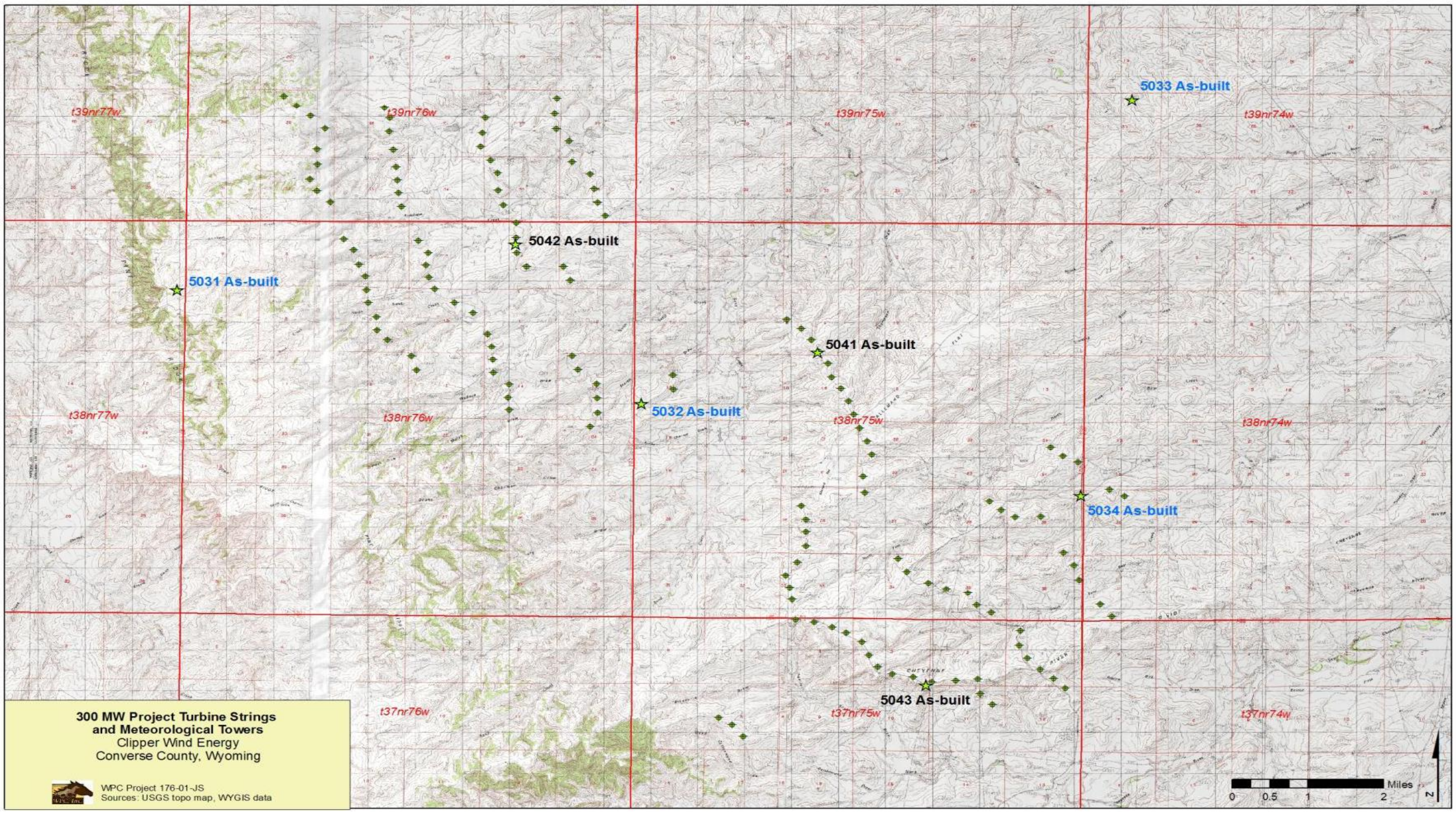
METHODS

We followed recommendations for conducting wildlife studies at wind energy facilities described by Kunz et al. (2007b). We defined a bat pass as an echolocation sequence of ≥2 echolocation calls with a minimum duration of 10 ms (Thomas 1988, Hayes 2000, Sherwin et al. 2000, Gannon et al. 2003; Parsons and Szewczak 2009). We recognized that echolocation passes are reliably distinguished from other nocturnal sounds (e.g., birds, arthropods, wind, rain, mechanical noises), but the ability to differentiate species of bats is challenging and varies with 1) detectability (distance of bat to microphone), call intensity (loud vs. quiet species), 2) species call rates, 3) migratory vs. foraging call rates, 4) weather, 5) surrounding habitat, and 6) equipment used (Barclay 1999, Hayes 2000, Kunz et al. 2007b). We considered each pass a discrete event and each detector an independent observational unit repeatedly measured each night throughout the sampling period. We assumed that; 1) echolocation calls were consistent within a species, 2) species consistently called at either high or low frequencies, 3) 33 kHz (average minimum call frequency) represented an appropriate threshold to separate species into these two phonic groups, 4) simultaneous sampling at 5 sites/night would adequately account for spatial and temporal variation at the RWEP, and 5) the number of bat passes recorded indicated relative use by bats and did not reflect abundance (e.g., 100 bat passes may be a single bat recorded 100 different times or 100 different bats each recording a single pass; Kunz et al. 2007b).

Equipment

We used Anabat II broadband acoustic detectors coupled with CF-ZCAIM storage units (Titley Electronics, Ballina, New South Wales, Australia) with an approximate detection range of 20 m (actual range is dependent on temperature, humidity, and frequency and intensity of echolocation sequences) to record bat echolocation sequences or passes. We positioned detector microphones at 2 heights (1.5 m and 44 m above ground level [agl]) on 5 met towers from 3 August to 18 October 2009 and 2 June to 30 September 2010 (Fig. 2). This spatial arrangement allowed us to sample bat activity at ground level and within the lower portion of the Rotor-Swept Area (RSA), across the proposed RWEP. Prior to sampling, we calibrated each Anabat unit (sensitivity set at approximately 6) to minimize variability among detectors (Larson and Hayes 2000). Additionally, each week we rotated detectors at each tower between the 2 heights to ensure no particular detector was consistently used at any one height. We housed microphones in waterproof "bat-hats" (EME Systems, Berkley, California, USA) attached to electrical cables extending to ground level, where detectors were placed in waterproof boxes (Figs. 3, 4). We used rechargeable batteries to provide power to all detector units.

Figure 1. Location of seven meteorological towers and proposed turbine locations at the Resolute Wind Project. Towers used for acoustic sampling include numbers 5032, 5034, 5041, 5042, and 5043. Towers 5031 and 5033 were not used in the study for either year.



ANALYSIS

We visited each tower approximately every week to exchange CF cards and batteries. We downloaded and analyzed data using Anabat CFC Read (version 4.2a) and Analook (version 4.9j) software, respectively. Prior to analysis, we removed extraneous noise from our data using customized filters derived from Britzke and Murray (2000).

Phonic group identification

We assigned each bat pass to one of 2 phonic groups based on minimum frequency of the echolocation sequence, in part because bats using these frequencies may differ in their use of habitat and in their response to environmental factors. To accomplish this, we constructed 2 filters to classify bat passes as being produced by either high frequency bats (≥33 kHz average minimum frequency; e.g., *Myotis* spp.) or low frequency bats (<33 kHz average minimum frequency; e.g., big brown, silver-haired, hoary bats). Both filters were derived from those developed by Britzke and Murray (2000), with a Smoothness = 15 and a Bodyover = 80. We adjusted frequency parameters to separate high and low echolocation sequences. For the low frequency phonic group filter, we set the maximum frequency at 33 kHz, and for the high frequency phonic group filter, we set the minimum frequency at 33 kHz. We visually scanned all files not assigned by the filters and placed them into the appropriate high or low group. We also identified a third phonic group, hoary bats, a subset of the low phonic group, using a customized filter, with a Soothness = 12, Bodyover = 110, MinFmin = 14, MaxFmin = 21, and CallNum = 1. We chose to identify the hoary bat to species because it is vulnerable to wind-energy development and its echolocation sequences are relatively easy to distinguish among other low-frequency emitting bats.

Temperature and wind speed

We used civil sunrise and sunset data from the US Naval Observatory Astronomical Applications Department (http://aa.usno.navy.mil/data/docs/RS_OneYear.php) to define our crepuscular and nocturnal sampling period or “night”. We monitored bat activity each night between ½ hr before sunset to ½ hr after sunrise. This sampling schedule provided coverage during times when bats are most active (Hayes 1997). We adjusted met tower dates to “effective date” such that all morning hours within each night were assigned the previous calendar date value. We summarized data for each “effective date” and checked for missing observations or anomalous or unreasonable values. Mean ambient temperature and wind speed were recorded at 10-minute intervals on each met tower. Wind speed was measured at 50 m agl and 10 m agl on each tower and ambient temperature was measured at 2 m agl. We averaged wind speed data collected from two directions. At each met tower, we calculated 5 summary statistics for each night: mean temperature (T) = mean over all 10 minute averages, mean wind speed (WS) = mean over all 10 minute averages, proportion of 10-minute intervals during which average wind speed was greater than 3.5 m/s (PctG3.5), >5 m/s (PctG5), >6.5 m/s (PctG6.5), and <6.5 m/s (PctL6.5). We merged the total number of calls recorded by each phonic group with weather data for each location, height and night. Because of acoustic or meteorological equipment malfunctions, complete data on all sample nights were not available for analysis. We chose dates for each analysis to maximize coincident data recordings among the met towers.

We designed our analysis to examine the relationship of bat activity within three phonic groups to various measures of temperature and wind speed. Because our response variable, counts (i.e., number of bat passes/night) from each location and height, contained numerous zeros (i.e., nights with no bat activity recorded) our data naturally conformed to the sequential questions: 1) which variables relate to the probability of activity occurring on any given night/height/ location; and 2) given that activity occurs, which variables are associated with level of activity? To examine these two questions simultaneously, we used hurdle models (Zuur et al. 2009) which divide the response into two parts, the zero counts and the non-zero counts. In the first part, the probability of activity is modeled as a binomial (binary) response and can be related to explanatory covariates such as temperature or wind speed. In the second part (the count part), the activity rate can be modeled as a truncated Poisson or negative binomial response and also can be related to explanatory covariates. We modeled activity as a truncated negative binomial response to accommodate variation in bat passes/night that exceeded variation assumed from a Poisson distribution. We included location and mean ambient temperature in all models to account for the correlation of observations within these factors while including temperature as a surrogate for changing seasonal effects.

To explore how temperature and wind might affect the probability of activity and the activity rate of bats in the 3 phonic groups, we established 2 sets of candidate models (Appendices 1 and 2). The first set compared the activity of high and low frequency bats at 1.5 m, and consisted of 128 candidate models, including one null (no explanatory variables), three baseline models, and 124 plausible wind velocity models (Appendix 1). The null model included no covariates for either the binomial part (probability of activity) or the count part (activity rate) of the hurdle model. The three baseline models differed in the factors included in each part of the hurdle model (i.e., location, and temperature), excluding wind speed. The first baseline model (location model) included only location effects in both parts, whereas the second included location and mean ambient temperature. The third baseline model included location and the interaction between temperature and phonic group in both parts. The second set of models compared activity by low frequency or hoary bats at 44 m, and consisted of 40 candidate models including 1 null, a location model, a location and temperature model, and 37 wind models. Wind models built upon the third baseline model (full design model) and included covariates of nightly wind speed. To construct the suite of candidate wind models, we first incorporated WS both separately and simultaneously in the binomial and count parts of the hurdle model. Next, we maintained WS in the binomial part, and considered each wind speed measurement (i.e., PctG6.5, PctG5, or PctG3.5), and interactions between wind speed and temperature for the count part of the hurdle model. We repeated this process, but maintained WS in the count part and varied wind speed measurements and interactions in the binomial part. The same process was used for PctG3.5, PctG5 and PctG6.5, thus we considered wind speed for both parts of the hurdle model simultaneously. This method of candidate model construction allowed us to first relate higher wind speed thresholds to the probability of bat activity, and then given that activity occurred, examine relationships between the amount of activity and wind speed measurements up to and including the higher threshold.

We performed three separate AIC model selection analyses (Burnham and Anderson 2002), one for each of the three phonic groups (i.e., high frequency, low frequency, and hoary bats) to evaluate and select the most-parsimonious model given the data and set of candidate models. We established a confidence set of models (i.e., highly competing models) by including only those models within two AIC units of the best approximating model. We calculated Nagelkerke‟s pseudo-R^2 (Rp^2) as a rough indicator of model strength. We compared Rp^2 values of the location model and the full design model with the null model. We also compared additional Rp^2 values of the best approximating model with the full design model. We report results for all base models and all models within 4 AIC units of the best approximating model. If clear evidence indicated a specific wind model was better than the full design model, we interpreted the most parsimonious, highly competing wind model.

We examined the effects of changing ambient temperature and wind speed on the probability of bat activity and the amount of activity at different heights. We calculated parameter estimates, standard errors, and effects for coefficients of the best model for each phonic group and year. We evaluated the ecological importance of each variable by computing 95% confidence intervals for each coefficient and interpreted the values within these intervals (Gerard et al. 1998). Only factors whose 95% confidence intervals of odds ratios did not include 1 were interpreted as being related to bat activity.

RESULTS

In 2009, we conducted bat acoustic monitoring for 77 nights from 3 August to 18 October from 2 heights at 5 towers for a total of 762 potential detector-nights (# detectors * # towers * # nights). All detectors were installed on 3 August 2009, with the exception of the 1.5 m detector on tower 5042; this detector became operational on 11 August. In addition, because of acoustic and meteorological equipment malfunctions, we only were able to use coincident data (i.e., nights when all detectors and weather equipment were operational for a specific height) for 506 (1.5 m = 229; 44 m = 277) detector-nights.

In 2010, we monitored bat activity for 121 nights from 2 June to 30 September from 2 heights at 5 towers for 1,089 potential detector-nights. All detectors were installed on 2 June, except for the 44 m detector at tower 5034, which was not in operation during the 2010 study period. Additionally, equipment malfunctions limited our coincident dataset to 591 (1.5 m = 341; 44 m = 250) detector-nights.

General Bat Activity

In 2009, we recorded a total of 976 bat passes. At 1.5 m, we identified 447 and 203 passes as high frequency and low frequency bats, respectively. Of the low frequency recordings, we identified 17 as hoary bat passes. At 44 m, we identified 7 and 319 passes as high frequency and low frequency, respectively. Of the low frequency recording, we identified 97 as hoary bat passes. In 2010, we recorded a total of 1,111 bat passes. At 1.5

m, we identified 392 and 311 passes as high frequency and low frequency bats, respectively. Of the low frequency recordings, we identified 37 as hoary bat passes. At 44 m, we identified 18 and 390 passes as high frequency and low frequency bats, respectively. Of the low frequency recordings, we identified 171 as hoary bat passes.

Temporal Variation in Bat Activity

We observed temporal variations in bat activity among phonic groups. High frequency bat activity peaked 1–2 hours past sunset and steadily decreased throughout the night in both years (Fig. 2). In contrast, low-frequency bat activity peaked later in the evening in 2009 and remained relatively high from sunset to two hours pre-sunrise. Hoary bat activity peaked within the hour past sunset in both years. Activity by hoary bats remained relatively low for the remaining hours of the night in 2009, but relatively high until one hour pre-sunrise in 2010.

Bat activity varied among nights, with the majority of activity occurring in August for both years (Fig. 3). In 2009, high frequency activity peaked in early August, but was more evenly distributed in 2010. Mean number of low frequency passes increased multiple times from mid-August to mid-September in 2009. In 2010, we observed a peak in low frequency bat activity in early August with smaller peaks in late August and early September. Hoary bat activity was low and relatively constant for both years, however we observed a peak in activity in early August 2010.

Spatial Variation in Bat Activity

Bat activity varied among phonic groups by height and among towers (Fig. 4). We detected high frequency bats most often at 1.5 m in 2009 and 2010, and recorded the greatest activity at tower 5042 in both years. Low frequency bat activity was relatively uniform between heights and among towers for both years. We detected hoary bats most often at 44 m and recorded the greatest activity at towers 5032 and 5042 in 2009 and at tower 5032 in 2010. We recorded the fewest calls by any phonic group at tower 5034.

In 2009, the range of mean activity among towers at 1.5 m for high frequency, low frequency and hoary bats was between 0.16–4.21, 0.37–1.02, and 0.02–0.11 passes/night, respectively (Table 1). Among towers at 44 m, the range of mean activity for high frequency, low frequency, and hoary bats was between 0.00–0.07, 0.78–0.93, and 0.20–0.61 passes/night, respectively. On nights when bat passes were recorded at a station (i.e., excluding nights with zero activity), the range of mean activity among towers at 1.5 m was 2.5–6.0 times the average for high frequency bats, 2.3–5 times for low frequency bats, and 12–55 times for hoary bats. The range of mean activity among towers at 44 m was 16–46 times the average for high frequency bats, 1.8–3.0 times for low frequency bats, and 3.2–6 times for hoary bats. Although we recorded zero bat passes on the majority of nights, we detected at least one high frequency bat pass on 39% and 3% of detector-nights, one low frequency bat pass on 40% and 48% and 1 hoary bat pass on 6% and 24% of detector-nights at 1.5 m and 44 m, respectively (Table 2).

In 2010, the range of mean activity among towers at 1.5 m for high frequency, low frequency, and hoary bats was between 0.18–2.75, 0.42–1.44, and 0–0.27 passes/night, respectively (Table 3). Among towers at 44 m, the range of mean activity for high frequency, low frequency, and hoary bats was between 0–0.13, 1.13–2.09, and 0.20–0.61 passes/night, respectively. On nights when bat passes were recorded at a station (excluding nights with zero activity), the range of mean activity among towers at 1.5 m was 1.6–5.9 times the average for high frequency bats, 2.1–3.5 times for low frequency bats, and 7.3–32 times for hoary bats. The range of mean activity among towers at 44 m for nights when at least one pass was recorded was 11–32 times the average for high frequency bats, two times for low frequency bats, and 3–4 times for hoary bats. Although we recorded zero bat passes on the majority of nights, we detected at least one high frequency bat pass on 40% and 4% of detector-nights, one low frequency bat pass on 36% and 49% of detector-nights and one hoary bat pass on 7% and 34% of detector-nights at 1.5 m and 44 m, respectively (Table 4).

Bat Activity in Relation to Weather Variables

In 2009, both high and low frequency bat activity at 1.5 m was negatively related to wind speed, and positively related to ambient temperature (Fig. 5). There was too little hoary bat activity at this height to statistically investigate relationships with either wind or ambient temperature. At 44 m, there was too little high frequency bat activity to determine whether any relationship existed with either wind or ambient temperature. Low frequency and hoary bat activity were positively related to temperature and negatively related to wind speed.

In 2010, high frequency bat activity was positively related to temperature and negatively related to wind speed at 1.5 m (Fig. 6). Low frequency bat activity was positively related to temperature, but showed little relation to wind speed. There was insufficient hoary bat activity at 1.5 m to determine the relationship between activity and either wind or temperature. At 44 m, there was insufficient high frequency bat activity to explore relationships between activity and either wind or temperature. Low frequency and hoary bat activity was positively related to temperature but appeared relatively insensitive to wind speed.

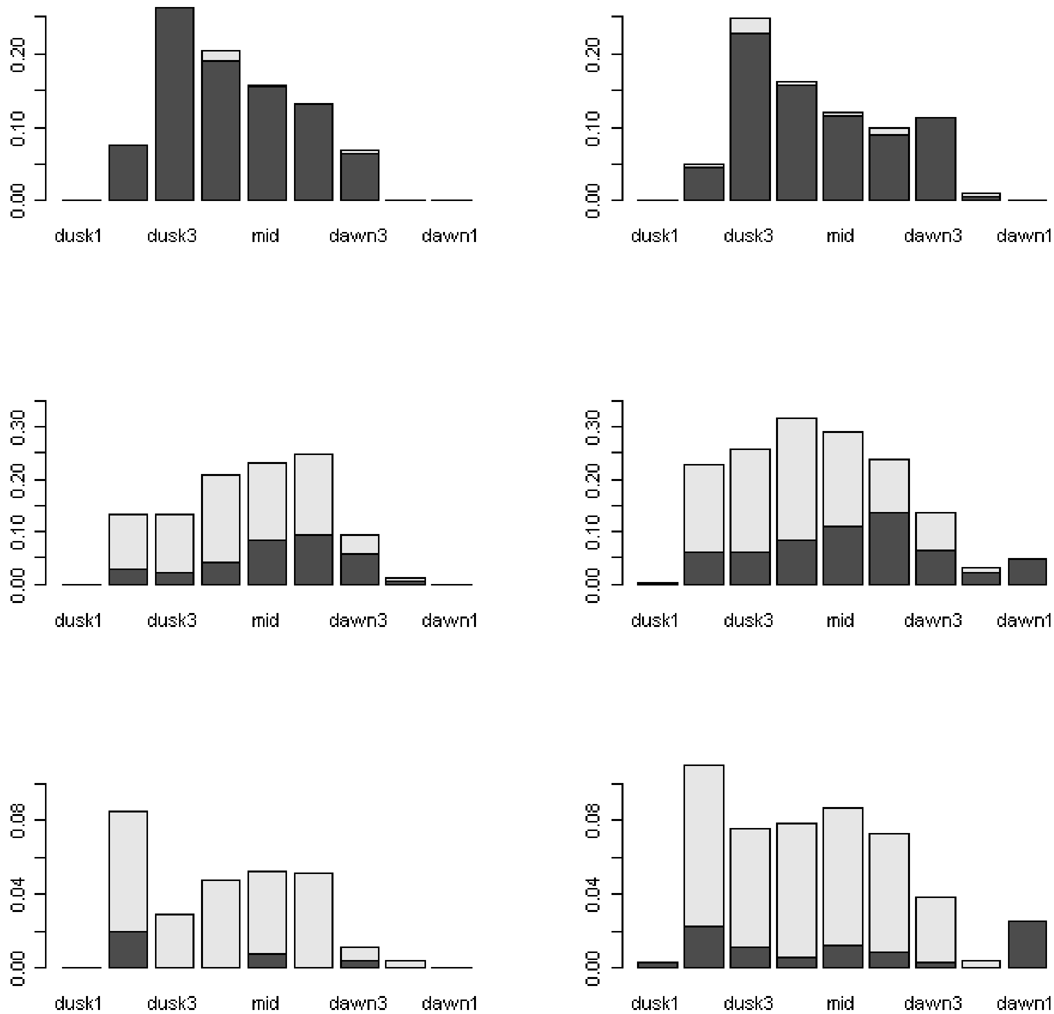


Figure 2. Mean number of passes/hour/tower at each height during the night for (top to bottom) high- (≥33kHz), low- (<33kHz) frequency bats and hoary bats at the proposed RWEP, 2009 (left) and 2010 (right). Dark and light shading represents activity at 1.5 m and 44 m, respectively.

Dusk1 = 1 hr pre-sunset – sunset
Dusk2 = sunset – 1 hr post-sunset
Dusk3 = 1 hr post sunset – 2hrs post-sunset
Dusk4 = 2 hrs post sunset – 3 hrs post-sunset
Mid = 3 hrs post sunset – 3 hrs pre-sunrise
Dawn4 = 3 hrs pre sunrise – 2 hrs pre-sunrise
Dawn3 = 2 hrs pre sunrise – 1 hrs pre-sunrise
Dawn2 = 1 hs pre sunrise – sunrise
Dawn1 = sunrise – 1 hr post-sunrise

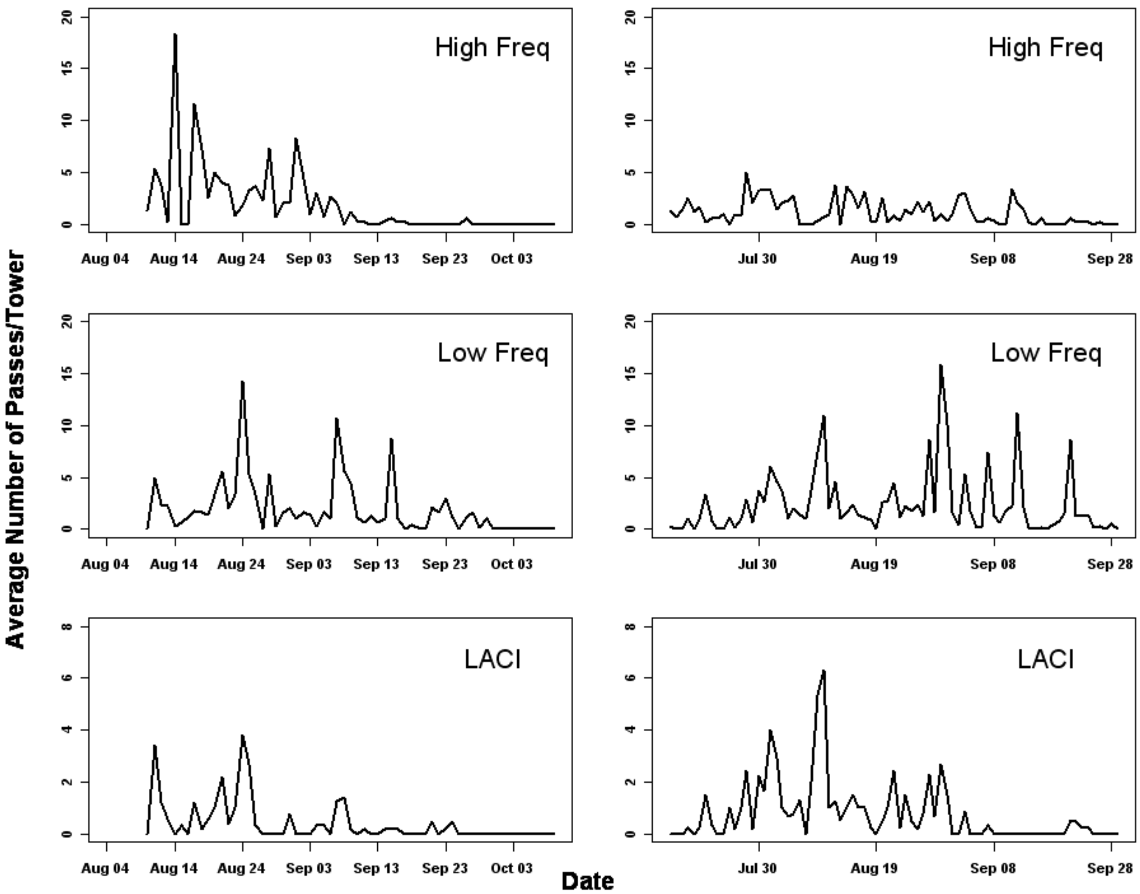


Figure 3. Mean passes/tower for each phonic group at the proposed RWEP, 2009 (left) and 2010 (right). High freq, low freq, and LACI represent high frequency, low frequency, and hoary bats, respectively.

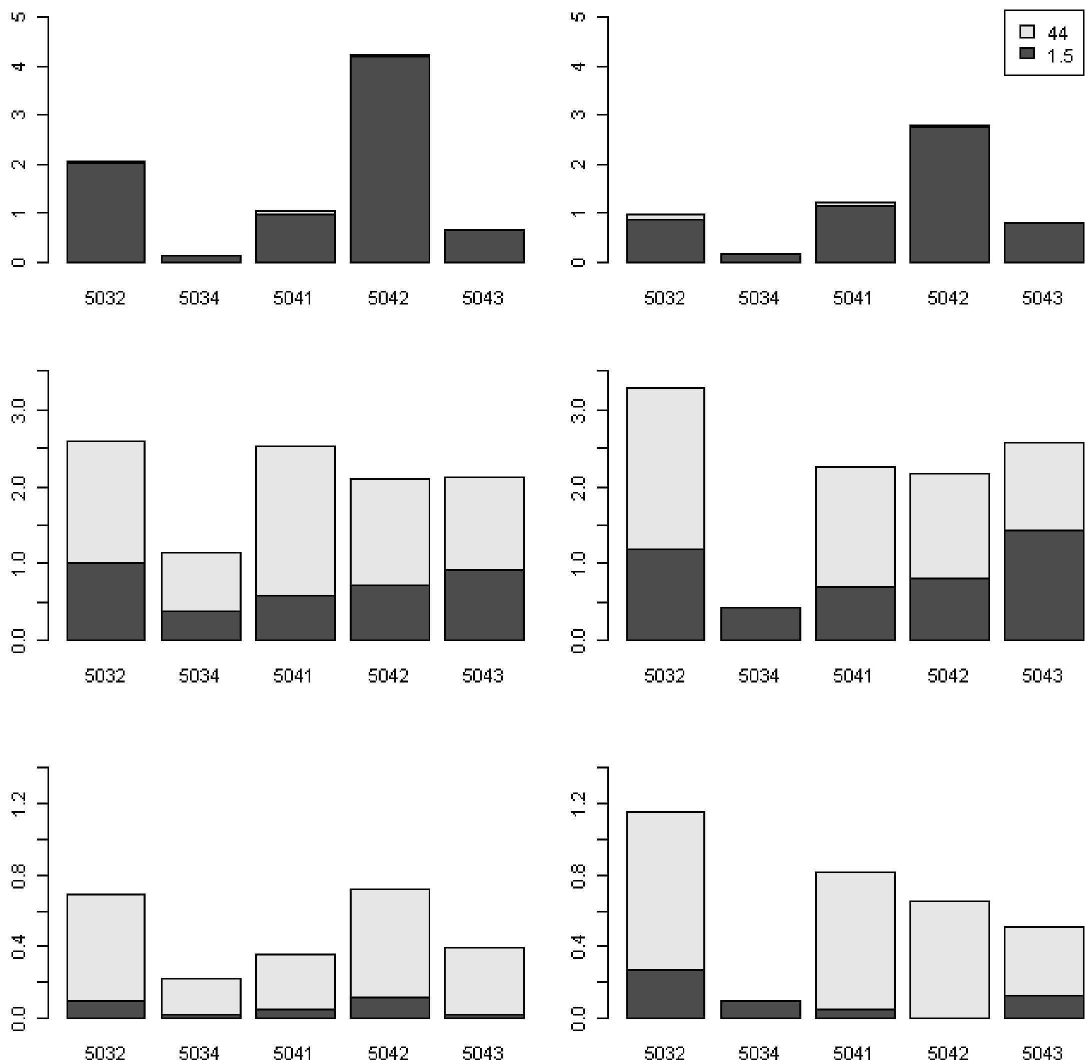


Figure 4. Mean passes/night at each tower and height for (top to bottom) high- (≥33kHz) and low- (<33kHz) frequency bats, and hoary bats at the proposed RWEP, 2009 (left) and 2010 (right). Dark and light shading represent activity at 1.5 m and 44 m, respectively.

Table 1. Summary of bat activity, by phonic group, recorded from 5 towers and 2 heights at the RWEP, Wyoming, 2009.

Height	Tower/ Phonic group	Mean passes/night	Mean passes/night (given activity)[a]	Maximum number of passes	Perecent nights with zero bat passes
1.5 m	5032				
	High	2.02	5.21	22	0.61
	Low	1.02	2.42	15	0.58
	LACI	0.10	1.20	2	0.92
	Overall	3.03	5.53	28	0.45
	5034				
	High	0.16	1.00	1	0.84
	Low	0.37	1.73	4	0.78
	LACI	0.02	1.00	1	0.98
	Overall	0.53	1.69	4	0.69
	5041				
	High	0.98	2.39	7	0.59
	Low	0.59	1.74	8	0.66
	LACI	0.05	1.50	2	0.96
	Overall	1.57	3.03	10	0.48
	5042				
	High	4.21	10.14	57	0.58
	Low	0.72	2.38	12	0.70
	LACI	0.11	1.50	3	0.92
	Overall	4.92	10.04	57	0.51
	5043				
	High	0.65	2.77	9	0.76
	Low	0.91	2.63	15	0.65
	LACI	0.02	1.00	1	0.98
	Overall	1.56	3.58	16	0.56
44 m	5032				
	High	0.06	1.00	1	0.94
	Low	1.57	2.85	9	0.45
	LACI	0.59	1.93	4	0.69
	Overall	1.63	2.96	9	0.45
	5034				
	High	0.00	NA	0	1.00
	Low	0.78	2.38	5	0.68
	LACI	0.20	1.33	2	0.85
	Overall	0.78	2.38	5	0.68
	5041				
	High	0.07	1.50	2	0.96
	Low	1.93	3.56	22	0.46
	LACI	0.30	1.75	5	0.83
	Overall	2.00	3.68	22	0.46
	5042				
	High	0.02	1.00	1	0.98
	Low	1.39	2.67	11	0.48
	LACI	0.61	2.00	7	0.70
	Overall	1.41	2.71	11	0.48

Table 1. Continued.

Height	Tower/ Phonic group	Mean passes/night	Mean passes/night (given activity)[a]	Maximum number of passes	Percent nights with zero bat passes
44 m	5043				
	High	0.00	NA	0	1.00
	Low	1.21	2.76	8	0.56
	LACI	0.38	1.64	4	0.77
	Overall	1.21	2.76	8	0.56

[a]Mean bat activity for nights in which at least 1 bat call was recorded.

Table 2. Number of detector-nights in which high frequency, low frequency, and hoary bats were detected/not detected at the listed rate at each of two heights for all towers combined at the RWEP, Wyoming, 2009.

Year / Height	Number of Passes/Night	Phonic group: High	Low	Hoary
2009				
1.5 m	0	187	186	264
	1	32	49	10
	2	13	24	2
	3	11	9	1
	4	6	3	0
	>4	28	6	0
	Non-zero[a]	90	91	13
	Missing[b]	33	33	33
44 m	0	223	119	175
	1	5	43	32
	2	1	24	11
	3	0	16	5
	4	0	9	4
	>4	0	18	2
	Non-zero[a]	6	110	54
	Missing[b]	16	16	16

[a]Refers to the number of detector-nights with at least one bat pass recorded.
[b]Refers to the number of detector-nights during which data were not collected because of equipment malfunctions.

Table 3. Summary of bat activity, by phonic group, recorded from five towers and two heights at the RWEP, Wyoming, 2010.

Height	Tower/Species Group	Mean passes/night	Mean passes/night (given activity)[a]	Maximum number of passes	Percent nights with zero bat passes
1.5 m	5032				
	High	0.86	2.11	5	0.59
	Low	1.20	2.93	18	0.59
	LACI	0.27	2.00	4	0.86
	Overall	2.06	3.49	23	0.41
	5034				
	High	0.18	1.08	2	0.83
	Low	0.42	1.43	4	0.70
	LACI	0.10	1.17	2	0.92
	Overall	0.61	1.65	4	0.63
	5041				
	High	1.16	3.70	9	0.69
	Low	0.69	2.44	8	0.72
	LACI	0.05	1.50	2	0.97
	Overall	1.84	3.93	14	0.53
	5042				
	High	2.75	4.52	17	0.39
	Low	0.81	2.43	16	0.67
	LACI	0.00	NA	0	1.00
	Overall	3.57	5.47	19	0.35
	5043				
	High	0.82	1.71	4	0.52
	Low	1.44	3.00	20	0.52
	LACI	0.13	1.13	2	0.89
	Overall	2.25	3.08	20	0.27
44 m	5032				
	High	0.13	1.50	4	0.91
	Low	2.09	4.30	19	0.51
	LACI	0.88	2.73	11	0.68
	Overall	2.22	4.31	19	0.49
	5041				
	High	0.08	1.67	2	0.95
	Low	1.56	2.86	11	0.45
	LACI	0.77	2.04	6	0.63
	Overall	1.64	2.92	13	0.44
	5042				
	High	0.06	2.00	3	0.97
	Low	1.37	2.69	15	0.49
	LACI	0.65	1.71	7	0.62
	Overall	1.43	2.81	18	0.49
	5043				
	High	0.00	NA	0	1.00
	Low	1.13	2.70	15	0.58
	LACI	0.38	1.50	4	0.75
	Overall	1.13	2.70	15	0.58

[a]Mean bat activity for nights in which at least one bat call was recorded.

Table 4. Number of detector-nights in which high frequency, low frequency, and hoary bats were detected/not detected at the listed rate at each of two heights for all towers combined at the RWEP, Wyoming, 2010.

Year / Height	Number of Passes/Night	Phonic group: High	Low	Hoary
2010				
1.5 m	0	206	218	316
	1	60	67	18
	2	22	21	4
	3	20	14	1
	4	9	4	2
	>4	24	17	0
	Non-zero[a]	135	123	25
	Missing[b]	14	14	14
44 m	0	239	127	166
	1	7	47	43
	2	2	30	25
	3	1	16	5
	4	1	10	5
	>4	0	20	6
	Non-zero[a]	11	123	84
	Missing[b]	34	34	34

[a]Refers to the number of detector-nights with at least one bat pass recorded.
[b]Refers to the number of detector-nights during which data were not collected because of equipment malfunctions.

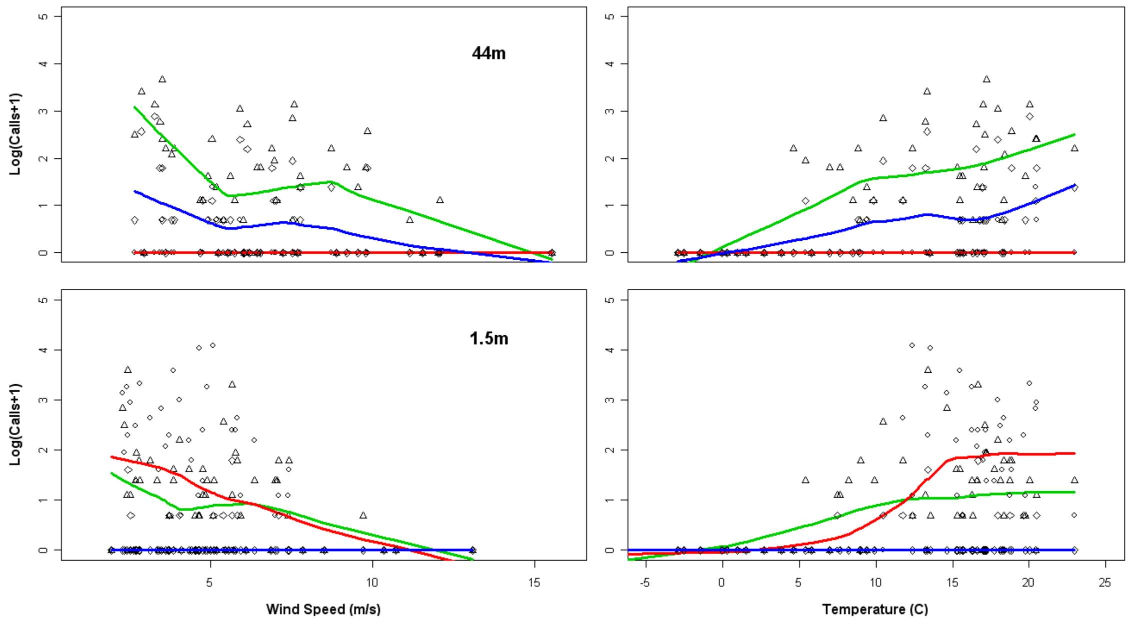


Figure 5. $\mathrm{Log_e}$ (number of calls) of high frequency (○), low frequency (◊) and hoary (Δ) bats at each height at the proposed RWEP, 2009, related to wind speed (left column) and temperature (right column). Red, green and blue lines are the loess fits for high-, low-frequency and hoary bats, respectively.

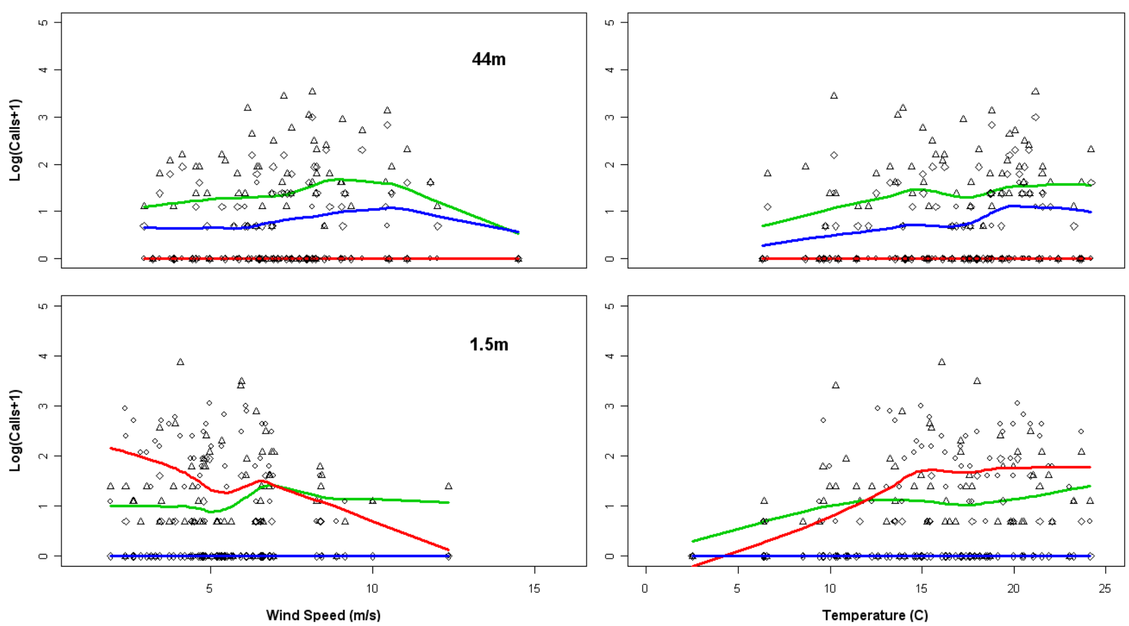


Figure 6. $\mathrm{Log_e}$ (number of calls) of high frequency (○), low frequency (◊) and hoary (Δ) bats at each height at the proposed RWEP, 2010, related to wind speed (left column) and temperature (right column). Red, green and blue lines are the loess fits for high-, low-frequency and hoary bats, respectively.

MODEL ANALYSIS

We were unable to model high frequency bat activity at 44 m because we only recorded seven and 18 passes in 2009 and 2010, respectively. Similarly, we were unable to model hoary bats at 1.5 m because we only recorded 17 and 37 passes in 2009 and 2010, respectively. We were able to compare high and low frequency bat activity at 1.5 m for both years.

2009

In 2009 at 1.5 m, mean wind speed and ambient temperature were 5.16 m/s (range = 1.18–14.15 m/s) and 11.97° C (range = -12.27–23.74° C), respectively (Table 5). At 44 m, mean wind speed and temperature were 6.76 m/s (range = 0.39–16.76 m/s) and 11.69° C (range = -3.30–23.74° C), respectively. On average at 1.5m, the proportion of the night during which wind speed ≥3.5 m/s (PctG3.5) was 67% and ranged from near 50% to 100%. The PctG5 and PctG6.5 averaged 48% (range = ~0–100%) and 30% (range = ~0–100%), respectively. At 44 m, the proportion of the night during which wind speed ≥3.5 m/s (PctG3.5) was 78% and ranged from near 0% to 100%. The PctG5 and PctG6.5 averaged 65% (range = ~0–100%) and 51% (range = ~0–100%), respectively.

High and Low Frequency Bats at 1.5m

The best approximating model comparing high and low frequency bat activity at 1.5 m, with a 21.2% probability, was based on the full design model and incorporated the interaction of temperature, frequency, and wind speed in the probability part and contained wind speed in the count part of the hurdle model (Appendix 3). This model was 1.6 times more likely than the next best approximating model which contained the same parameters minus the interaction of ambient temperature in the probability part of the hurdle model. The confidence set (within 2 AIC Units of the best model) of models included the top six models with a sum of Akaike weights of 0.719, indicating a 71.9% chance that one of these models was the best approximating model given the data and set of candidate models. The location model was 34 AIC units better than the null model, accounting for approximately 9.5% of variation in activity at the site, while the full design model was 142 AIC units better than the null model, accounting for approximately 28.7% of variation. The full design model was not included in the confidence set of models, and was 40.46 AIC units away from the best approximating model, and only accounted for an additional 7.0% of the variation in activity.

On a night with average wind speed and temperature, the probability of activity at 1.5 m ranged from 8–24% over the locations (Table 6). For every 1° C increase in temperature, the odds of bat activity increased by 22–45% and 8–19% for high and low frequency bats, respectively. The probability of bat activity was positively related to decreasing wind speed, with odds of activity increasing by 40–105% and by 4–37% for every 1 m/s decrease in wind speed, for high and low frequency bats respectively. Given activity, the expected number of high frequency passes at 1.5 m on nights with mean temperature and wind speed, ranged from 0.36 to 3.09 across the locations. Low frequency passes were estimated to be 20–90% less than high frequency bat passes. We found no strong evidence of a relationship between activity and ambient temperature for either frequency group.

Low Frequency Bats at 44m

The best approximating model for low frequency bat activity, with a probability of 30.5%, was based on the full design model and incorporated average wind speed in the probability and count parts of the hurdle model (Appendix 3). This model was 1.6 times more likely than the next best approximating model, which incorporated PctL6.5 in both parts of the hurdle model. The confidence set of models included the top 3 models with a sum of Akaike weights of 0.611. Location alone accounted for approximately 3.7% of variation in activity at the site, while the full design model was 39 AIC units better than the null model, accounting for approximately 23.6% of variation. The best fitting model was roughly 23 AIC units better than the full design model, accounting for an additional 8.9% of the variation in activity beyond the full design model.

On a night with average wind speed and ambient temperature, the probability of low frequency activity at 44 m ranged from 28–58% across locations (Table 6). For every 1°C increase in temperature, the odds of low frequency bat activity increased 11–23%. The probability of activity was positively related to decreasing wind speed, with odds of activity increasing by 13–45% for every 1 m/s decrease in wind speed. Given activity, the expected number of low frequency passes at 44 m on nights with mean temperature and wind speed ranged from 0.7–1.7 across locations (Table 6). For every 1° C increase in temperature, the expected number of passes increased 0.1–14%. Expected number of passes/night decreased 6–25% for every 1m/s increase in wind speed.

Hoary bats at 44 m

The best approximating model for hoary bat activity, with a probability of 13.7%, was based on the full design model and incorporated wind speed in both parts of the hurdle model (Appendix 3). This model was 1.4 times more likely than the next best approximating model which contained the same parameters minus wind speed in the count part of the model. The confidence set of models included the top 8 models with a sum of Akaike weights of 0.64. The location model only accounted for approximately 3.8% of variation in activity at the site, while the full design model was 16 AIC units better than the null model, accounting for approximately 18% of variation. The best fitting model was roughly 10 AIC units better than the full design model, accounting for an additional 6.3% of the variation in activity beyond the full design model.

On a night with average wind speed and temperature, the probability of hoary bat activity at 44 m ranged from 11 to 25% across locations (Table 6). For every 1° C increase in temperature, the odds of hoary bat activity increased 8–23%. The probability of bat activity was positively related to decreasing wind speed, with odds of hoary bat activity increasing 8–31% for every 1 m/s decrease in wind speed.

Given the observed bat activity, the expected number of passes, on nights with mean temperature and wind speed, ranged from 0.16 to 0.46 across the locations (Table

6). We found little evidence of change in mean passes/night with temperature or wind speed.

Table 5. Mean, standard deviation (SD), minimum and maximum for temperature (°C), wind speed (m/s), and proportion of night with wind speed >3.5 m/s (PctG3.5), >5 m/s (PctG5), and >6.5 m/s (PctG6.5) from each of 5 meteorological towers at the RWEP, Wyoming, 2009.

Height/Tower	Variable	Mean	SD	Minimum	Maximum
1.5 m					
5032	Temperature	12.92	7.50	-11.98	23.74
	Wind Speed	5.12	2.49	1.50	14.15
	PctG3.5	0.66	0.29	0.07	1.00
	PctG5	0.49	0.31	0.00	1.00
	PctG6.5	0.30	0.29	0.00	0.97
5034	Temperature	11.95	6.85	-3.01	22.92
	Wind Speed	5.54	2.58	2.19	13.82
	PctG3.5	0.71	0.27	0.20	1.00
	PctG5	0.53	0.32	0.03	1.00
	PctG6.5	0.33	0.32	0.00	1.00
5041	Temperature	11.45	7.41	-12.27	22.51
	Wind Speed	5.30	2.23	1.94	12.53
	PctG3.5	0.69	0.28	0.07	1.00
	PctG5	0.47	0.30	0.00	1.00
	PctG6.5	0.31	0.27	0.00	0.98
5042	Temperature	10.84	6.55	-3.30	22.18
	Wind Speed	4.53	2.26	1.18	12.39
	PctG3.5	0.60	0.31	0.05	1.00
	PctG5	0.40	0.30	0.00	0.98
	PctG6.5	0.23	0.26	0.00	0.90
5043	Temperature	12.52	7.78	-12.02	23.47
	Wind Speed	5.29	2.33	1.69	12.48
	PctG3.5	0.68	0.25	0.07	1.00
	PctG5	0.50	0.29	0.00	1.00
	PctG6.5	0.31	0.28	0.00	0.98
All Towers	Temperature	11.97	7.26	-12.27	23.74
	Wind Speed	5.16	2.40	1.18	14.15
	PctG3.5	0.67	0.28	0.05	1.00
	PctG5	0.48	0.31	0.00	1.00
	PctG6.5	0.30	0.29	0.00	1.00
44 m					
5032	Temperature	12.50	7.22	-2.56	23.74
	Wind Speed	6.59	2.93	2.31	16.56
	PctG3.5	0.76	0.25	0.22	1.00
	PctG5	0.64	0.30	0.09	1.00
	PctG6.5	0.50	0.31	0.00	1.00

Table 5. Continued.

Height/Tower	Variable	Mean	SD	Minimum	Maximum
44 m					
5034	Temperature	11.79	7.47	-3.01	22.92
	Wind Speed	7.48	3.13	3.00	16.76
	PctG3.5	0.83	0.19	0.38	1.00
	PctG5	0.70	0.29	0.00	1.00
	PctG6.5	0.58	0.32	0.00	1.00
5041	Temperature	11.12	6.96	-3.04	22.51
	Wind Speed	6.87	2.95	0.39	14.37
	PctG3.5	0.78	0.26	0.00	1.00
	PctG5	0.65	0.31	0.00	1.00
	PctG6.5	0.52	0.32	0.00	1.00
5042	Temperature	10.72	6.93	-3.30	22.18
	Wind Speed	6.19	2.86	2.13	15.22
	PctG3.5	0.74	0.26	0.19	1.00
	PctG5	0.61	0.31	0.05	1.00
	PctG6.5	0.44	0.31	0.00	1.00
5043	Temperature	12.27	7.21	-2.71	23.47
	Wind Speed	6.80	2.76	1.46	14.67
	PctG3.5	0.80	0.23	0.18	1.00
	PctG5	0.66	0.28	0.00	1.00
	PctG6.5	0.50	0.31	0.00	1.00
5043	Temperature	12.52	7.78	-12.02	23.47
	Wind Speed	5.29	2.33	1.69	12.48
	PctG3.5	0.68	0.25	0.07	1.00
	PctG5	0.50	0.29	0.00	1.00
	PctG6.5	0.31	0.28	0.00	0.98
All Towers	Temperature	11.69	7.15	-3.30	23.74
	Wind Speed	6.76	2.94	0.39	16.76
	PctG3.5	0.78	0.24	0.00	1.00
	PctG5	0.65	0.30	0.00	1.00
	PctG6.5	0.51	0.32	0.00	1.00

Table 6. Model parameter estimates, standard error (SE), parameter effects, and 95% confidence limits for probability and count models of bat activity at the RWEP, Wyoming, 2009. Tower effects estimate the probability of activity (Probability) or estimated number of calls (Count) on a night with mean temperature and wind speed. Additional parameter effects are interpreted as odds ratios.

Height/Phonic Group/ Model	Coefficient	Estimate	SE	Effect	Lower 95% CL	Upper 95% CL
1.5 m/Low and High						
Probability[a]	Loc 5032	-1.338	0.306	0.208	0.126	0.323
	Loc 5034	-2.460	0.366	0.079	0.040	0.149
	Loc 5041	-1.144	0.304	0.242	0.149	0.366
	Loc 5042	-1.334	0.312	0.209	0.125	0.327
	Loc 5043	-1.970	0.339	0.122	0.067	0.213
	Freq Low	0.679	0.285	1.973	1.127	3.452
	Temp (High Freq)	0.284	0.043	1.328	1.219	1.446
	Temp (Low Freq)	0.127	0.026	1.135	1.079	1.193
	WS (High Freq)	-0.527	0.100	0.591	0.486	0.718
	WS (Low Freq)	-0.174	0.071	0.840	0.731	0.965
Count[b]	Loc 5032	0.749	1.065	2.114	0.262	17.046
	Loc 5034	-1.021	1.190	0.360	0.035	3.711
	Loc 5041	-0.294	1.091	0.746	0.088	6.324
	Loc 5042	1.129	0.980	3.094	0.453	21.125
	Loc 5043	0.454	1.106	1.574	0.180	13.754
	Freq Low	-1.287	0.550	0.276	0.094	0.812
	Temp (High Freq)	-0.097	0.076	0.908	0.781	1.054
	Temp (Low Freq)	-0.026	0.072	0.974	0.847	1.122
44 m/Low						
Probability[a]	Loc 5032	0.023	0.339	0.506	0.345	0.665
	Loc 5034	-0.946	0.394	0.280	0.152	0.457
	Loc 5041	0.300	0.342	0.575	0.409	0.725
	Loc 5042	0.048	0.345	0.512	0.348	0.673
	Loc 5043	-0.534	0.346	0.369	0.229	0.536
	Temp	0.158	0.027	1.171	1.111	1.234
	WS	-0.248	0.063	0.780	0.690	0.883
Count[b]	Loc 5032	-0.101	0.431	0.904	0.388	2.106
	Loc 5034	-0.399	0.529	0.671	0.238	1.892
	Loc 5041	0.507	0.377	1.661	0.793	3.481
	Loc 5042	-0.133	0.432	0.876	0.375	2.042
	Loc 5043	-0.076	0.445	0.927	0.388	2.216
	Temp	0.065	0.032	1.067	1.001	1.137
	WS	-0.174	0.058	0.841	0.750	0.942
44 m/Hoary						
Probability[a]	Loc 5032	-1.265	0.368	0.220	0.121	0.367
	Loc 5034	-2.107	0.497	0.108	0.044	0.244
	Loc 5041	-1.826	0.431	0.139	0.065	0.273
	Loc 5042	-1.089	0.367	0.252	0.141	0.408
	Loc 5043	-1.685	0.403	0.156	0.078	0.290
	Temp	0.144	0.033	1.154	1.082	1.232
	WS	-0.227	0.072	0.797	0.692	0.917

Table 6. Continued.

Height/Phonic Group/ Model	Coefficient	Estimate	SE	Effect	Lower 95% CL	Upper 95% CL
44 m/Hoary						
Count[b]	Loc 5032	-0.767	0.793	0.464	0.098	2.194
	Loc 5034	-1.851	1.175	0.157	0.016	1.570
	Loc 5041	-0.799	0.949	0.450	0.070	2.889
	Loc 5042	-0.493	0.675	0.611	0.163	2.290
	Loc 5043	-1.328	0.980	0.265	0.039	1.808
	Temp	0.093	0.062	1.098	0.973	1.239
	WS	-0.163	0.099	0.849	0.699	1.032

[a]Zero Hurdle Model: Binomial with Logit Link.
[b]Count Model: Truncated Negative Binomial with Log Link.
[c]Theta estimates the extra variation of the count distribution.
[d]Theta does not apply as the count date were modeled as a Poisson distributed random variable.

2010

In 2010 at 1.5 m, mean wind speed and temperature were 5.48 m/s (range = 1.28–12.85 m/s) and 15.7° C (range = -2.13°–25.2° C), respectively (Table 7). At 44 m, mean wind speed and temperature were 7.30 m/s (range = 2.36–14.73 m/s) and 16.70 °C (range = 5.35°–25.16° C), respectively. On average at 1.5 m, the proportion of the night during which wind speed ≥3.5 m/s was 72% (range = ~7–100%). The PctG5 and PctG6.5 averaged 52% (range = ~0–100%) and 34% (range = ~0–100%), respectively. At 44 m, the proportion of the night during which wind speed ≥3.5 m/s was 84% (range = ~16–100%). The PctG5 and PctG6.5 averaged 71% (range = ~8–100%) and 56% (range = ~0–100%), respectively.

High and Low Frequency Bats at 1.5m

The best approximating models comparing high- and low frequency bat activity at 1.5m, with an 11.8% probability, was based on the full design model and incorporated the interaction of frequency with PctG5 in the probability model and contained an additional interaction of temperature with PctG5 in the count part of the hurdle model (Appendix 3). This model was only 1.02 times more likely than the next best approximating model which contained the same parameters minus the interaction of temperature with PctG5 in the count part of the hurdle model. The confidence set of models included the top 9 models with a sum of Akaike weights of 0.700. The location model was 41 AIC units better than the null model, accounting for approximately 8.7% of variation in activity at the site, while the full design model was 49 AIC units better than the null model, accounting for approximately 11.5% of variation. Although the full design model was not included in the confidence set of models, it was 19 AIC units away from the best approximating model, and only accounted for an additional 4.3% of the variation in activity.

On a night with average wind speed and temperature, the probability of activity at 1.5 m ranged from 25–50%. For every 1° C increase in temperature, the odds of high frequency bat activity increased 8–21% and the odds of low frequency bat activity increased 1.3–13%. The odds of high frequency bat activity was negatively related to PctG5, with odds decreasing by 10–25% with every 10 percent increase in the proportion of night with wind speeds >5 m/s.

Given the observed bat activity, the expected number of high frequency passes at 1.5 m on nights with mean temperature and wind speed ranged from 0.35 to 0.77 (Table 8). The expected number of passes of high frequency bats was negatively related to PctG5, with 6–29% decrease in mean passes/night with every 10% increase in the proportion of night with wind speeds >5 m/s. We found no strong evidence of a relationship of activity with PctG5 for low frequency bats or with ambient temperature for either frequency group.

Low Frequency Bats at 44m

The best approximating model for low frequency bat activity at 44 m, with a 40.9% probability, was based on the full design model and incorporated the interaction of ambient temperature and wind speed in the count part of the model (Appendix 3). This model was 2.5 times more likely than the next best approximating model that incorporated the interaction between ambient temperature and wind speed in both parts of the model. The confidence set of models included the top 3 models with a sum of Akaike weights of 0.725. The location model accounted for approximately 2.7% of variation in activity at the site, while the full design model was only 4.7 AIC units lower than the null model, accounting for approximately 4.6% of variation in activity. The best fitting model was roughly 8.7 AIC units better than the full design model, accounting for an additional 4.9% of the variation in activity beyond the full design model.

On a night with average wind speed and temperature, the probability of low frequency bat activity at 44 m ranged from 42–55% (Table 8). We found no strong evidence that the odds of low frequency bat activity was related to ambient temperature.

Given the observed bat activity, the expected number of passes on nights with mean ambient temperature and wind speed at 44 m ranged from 0.8–3.3 across locations (Table 8). The odds of low frequency bat activity were negatively related to wind speed, but this relationship varied with ambient temperature. At cool temperatures (8° C) there was little change in activity with wind speed. At 16° C, the expected number of passes decreased by 5–73%and at 24 °C, the expected number of passes decreased by 19–88% with every 1 m/s increase in wind speed.

Hoary bats at 44m

The best approximating model for hoary bat activity, with a 17.4% probability, incorporated the full design model and an interaction between temperature and wind speed in the count parts of the model (Appendix 3). This model was 1.6 times more likely than the next best approximating model that was similar, but contained PctL6.5 in the count part of the model. The confidence set of models included the top two models with a sum of Akaike weights of 0.283. The location model accounted for approximately 4% of variation in activity at the site, while the full design model was only two AIC units better than the null model, accounting for approximately 7.7% of variation in activity. The best fitting model was roughly 4 AIC units better than the full design model, accounting for an additional 3.3% of the variation in activity beyond the full design model.

On a night with mean wind speed and ambient temperature, the probability of hoary bat activity at 44 m ranged from 25–40 % (Table 8). We found a 2.6–17% increase in odds of hoary bat activity with every 1° C increase in temperature.

Given the observed bat activity, the expected number of hoary bat passes at 44 m, on nights with mean temperature and wind speed ranged from 0.4–1.9 (Table 8). We found no strong evidence of a relationship of expected number of hoary bat passes/night with wind speed at any temperature.

Table 7. Mean, standard deviation (SD), minimum and maximum for temperature (° C), wind speed (m/s), and proportion of night with wind speed >3.5 m/s (PctG3.5), >5 m/s (PctG5), and >6.5 m/s (PctG6.5) from each of five meteorological towers at the RWEP, Wyoming, 2010. No data collected from tower 5034, 44 m.

Height/Tower	Variable	Mean	SD	Minimum	Maximum
1.5 m					
5032	Temperature	16.38	4.82	2.53	25.16
	Wind Speed	5.63	2.24	1.51	12.63
	PctG3.5	0.70	0.27	0.07	1.00
	PctG5	0.55	0.30	0.00	1.00
	PctG6.5	0.38	0.27	0.00	1.00
5034	Temperature	15.60	4.66	2.42	23.96
	Wind Speed	5.61	1.92	2.15	11.89
	PctG3.5	0.75	0.23	0.24	1.00
	PctG5	0.55	0.27	0.04	1.00
	PctG6.5	0.36	0.27	0.00	0.97
5041	Temperature	15.11	4.62	2.56	23.72
	Wind Speed	5.55	1.93	2.23	12.85
	PctG3.5	0.74	0.22	0.22	1.00
	PctG5	0.52	0.27	0.00	1.00
	PctG6.5	0.33	0.26	0.00	0.97
5042	Temperature	15.04	4.73	2.13	23.92
	Wind Speed	4.99	2.09	1.28	11.70
	PctG3.5	0.66	0.27	0.07	1.00
	PctG5	0.47	0.28	0.01	1.00
	PctG6.5	0.29	0.26	0.00	0.97
5043	Temperature	16.29	4.69	2.86	24.53
	Wind Speed	5.64	1.94	2.34	12.57
	PctG3.5	0.75	0.20	0.10	1.00
	PctG5	0.53	0.26	0.00	1.00
	PctG6.5	0.34	0.27	0.00	0.99
All Towers	Temperature	15.69	4.72	2.13	25.16
	Wind Speed	5.48	2.03	1.28	12.85
	PctG3.5	0.72	0.24	0.07	1.00
	PctG5	0.52	0.28	0.00	1.00
	PctG6.5	0.34	0.27	0.00	1.00
44 m					
5032	Temperature	17.57	4.34	6.72	25.16
	Wind Speed	7.34	2.60	2.61	14.70
	PctG3.5	0.82	0.21	0.20	1.00
	PctG5	0.70	0.25	0.12	1.00
	PctG6.5	0.56	0.30	0.00	1.00
5041	Temperature	16.68	3.90	6.59	23.72
	Wind Speed	7.42	2.23	3.16	14.54
	PctG3.5	0.85	0.17	0.35	1.00
	PctG5	0.74	0.22	0.22	1.00
	PctG6.5	0.58	0.26	0.05	1.00

Table 7. Continued.

Height/Tower	Variable	Mean	SD	Minimum	Maximum
44 m					
5042	Temperature	15.71	4.46	5.35	23.92
	Wind Speed	7.02	2.53	2.36	13.98
	PctG3.5	0.79	0.22	0.16	1.00
	PctG5	0.67	0.25	0.14	1.00
	PctG6.5	0.54	0.29	0.01	1.00
5043	Temperature	16.78	4.43	6.71	24.53
	Wind Speed	7.45	2.20	3.62	14.73
	PctG3.5	0.89	0.14	0.38	1.00
	PctG5	0.75	0.21	0.08	1.00
	PctG6.5	0.57	0.26	0.00	1.00
All Towers	Temperature	16.70	4.32	5.35	25.16
	Wind Speed	7.30	2.40	2.36	14.73
	PctG3.5	0.84	0.19	0.16	1.00
	PctG5	0.71	0.24	0.08	1.00
	PctG6.5	0.56	0.28	0.00	1.00

Table 8. Model parameter estimates, standard error (SE), parameter effects, and 95% confidence limits for probability and count models of bat activity at the RWEP, Wyoming, 2010. Tower effects estimate the probability of activity (Probability) or estimated number of calls (Count) on a night with mean ambient temperature and wind speed. Additional parameter effects are interpreted as odds ratios. No data collected at tower 5034, 44 m.

Height/Phonic Group/ Model	Coefficient	Estimate	SE	Effect	Lower 95% CL	Upper 95% CL
1.5m/Low and High						
Probability[a]	Loc 5032	-0.324	0.203	0.420	0.327	0.518
	Loc 5034	-1.119	0.220	0.246	0.175	0.334
	Loc 5041	-0.747	0.215	0.321	0.237	0.419
	Loc 5042	-0.010	0.196	0.497	0.403	0.592
	Loc 5043	-0.040	0.195	0.490	0.396	0.585
	Freq Low	-0.164	0.167	0.849	0.612	1.178
	Temp (High Freq)	0.132	0.030	1.141	1.076	1.209
	Temp (Low Freq)	0.066	0.027	1.068	1.013	1.126
	PctG5 (High Freq)	-0.201	0.047	0.818	0.745	0.897
	PctG5 (Low Freq)	-0.014	0.044	0.986	0.904	1.075
Count[b]	Loc 5032	-0.919	0.826	0.399	0.079	2.014
	Loc 5034	-2.719	0.966	0.066	0.010	0.438
	Loc 5041	-0.434	0.788	0.648	0.138	3.036
	Loc 5042	-0.266	0.770	0.766	0.169	3.466
	Loc 5043	-1.059	0.833	0.347	0.068	1.774
	Freq Low	0.437	0.272	1.548	0.908	2.638
	Temp (High Freq)	0.076	0.050	1.079	0.980	1.189
	Temp (Low Freq)	-0.003	0.050	0.997	0.904	1.100
	PctG5 (High Freq)	-0.203	0.074	0.816	0.706	0.943
	PctG5 (Low Freq)	0.000	0.076	1.000	0.861	1.161
44m/Low						
Probability[a]	Loc 5032	-0.107	0.246	0.473	0.357	0.593
	Loc 5034					
	Loc 5041	0.191	0.253	0.548	0.425	0.665
	Loc 5042	0.086	0.256	0.521	0.398	0.643
	Loc 5043	-0.340	0.275	0.416	0.293	0.550
	Temp	0.054	0.030	1.056	0.995	1.120
Count[b]	Loc 5032	1.182	0.444	3.259	1.366	7.777
	Loc 5034					
	Loc 5041	0.517	0.457	1.677	0.685	4.110
	Loc 5042	0.100	0.506	1.106	0.410	2.983
	Loc 5043	-0.168	0.550	0.845	0.288	2.482
	WS|Temp=8	-0.195	0.159	0.822	0.602	1.124
	WS|Temp=16	-0.683	0.319	0.505	0.270	0.944
44m/Hoary						
Probability[a]	Loc 5032	-0.846	0.268	0.300	0.202	0.420
	Loc 5034					
	Loc 5041	-0.526	0.262	0.371	0.261	0.497
	Loc 5042	-0.416	0.265	0.398	0.282	0.526
	Loc 5043	-1.122	0.316	0.246	0.149	0.377
	Temp	0.092	0.034	1.096	1.026	1.172

Table 8. Continued.

Height/Phonic Group/ Model	Coefficient	Estimate	SE	Effect	Lower 95% CL	Upper 95% CL
44 m/Hoary						
Count[b]	Loc 5032	1.182	0.444	3.259	1.366	7.777
	Loc 5034					
	Loc 5041	0.517	0.457	1.677	0.685	4.110
	Loc 5042	0.100	0.506	1.106	0.410	2.983
	Loc 5043	-0.168	0.550	0.845	0.288	2.482
	WS|Temp=8	-0.195	0.159	0.822	0.602	1.124
	WS|Temp=16	-0.683	0.319	0.505	0.270	0.944

[a]Zero Hurdle Model: Binomial with Logit Link.
[b]Count Model: Truncated Negative Binomial with Log Link.
[c]Theta estimates the extra variation of the count distribution.
[d]Theta does not apply as the count date were modeled as a Poisson distributed random variable.

DISCUSSION

We found that bat activity generally was highest in August with little activity past late September, consistent with other pre-construction monitoring studies. Another study in Converse County, Wyoming recorded relatively fewer bats in August, with activity peaking in September; however, malfunctioning equipment may have accounted for low activity rates recorded in August (Johnson et al. 2008). Johnson et al. (2009) found high activity from mid-July through mid-September with a few peaks in August at another wind energy site in Wyoming. Temporal patterns of acoustic activity observed at the RWEP are similar to those reported with fatalities from post-construction fatality studies in Wyoming. Gruver (2002) summarized carcasses collected from 1999–2001 and showed 92% of bats found during carcass searches were migratory tree bats (108 hoary bats and 5 silver-haired bats) with 96% and 100% of hoary bat and silver-haired bat carcasses, respectively, found during a 2 month period from 15 July to 15 September. Association between timing of bat activity and overall incidence of bat fatality previously reported (Arnett et al. 2008) suggests that temporal patterns of activity may prove useful for predicting the timing of fatalities. Fall migration by bats varies spatially (Baerwald and Barclay 2009), temporally (Cryan 2003), and by species (Baerwald 2011). Among-night variation in activity, as well as turbine-related fatality, during late summer and fall may be attributed to changes in insect abundance and availability, weather, timing of migration, migratory routes (Baerwald and Barclay 2009), life history traits of certain bat species (e.g., preparations for hibernation or migration, and reproductive condition; Horn et al. 2008), or mating behaviors (Cryan 2008). In addition, if bats are attracted to wind turbines during migration, wind energy facilities may act as population „sinks" when and where large proportions of affected populations concentrate in space and time (Cryan 2011).

We recorded greater activity by high frequency bats at 1.5 m and greater activity by hoary bats at 44 m. Numerous studies have documented the importance of sampling at higher altitudes to adequately describe bat activity in an area (Jung et al. 1999, Kalcounis et al. 1999, Hayes and Gruver 2000, Menzel et al. 2005, Lacki et al. 2007, Collins and

Jones 2009). Moreover, acoustic monitoring studies at proposed or existing wind facilities also have reported similar findings (Arnett et al. 2006, 2007, Redell et al. 2006, Reynolds 2006, Baerwald and Barclay 2009, Baerwald 2011). The airspace in which certain species of bats occur generally can be predicted by their echomorphology (e.g., body size, wing shape, call frequency; Aldridge and Rautenbach 1987). Larger, less maneuverable bats with lower call frequencies typically fly higher and in more open habitats, whereas smaller, more maneuverable bats with higher call frequencies fly lower to the ground and in more cluttered (e.g., higher vegetation, increased tree density) habitats. The majority of available acoustic studies in Wyoming only sampled at ground level (Gruver 2002, Johnson et al. 2008, Johnson et al. 2009), thus it remains unknown whether vertical acoustic sampling increases predictability of fatality events, particularly in areas with open habitat. Because bat fatalities found at wind sites are predominately comprised of low frequency species (e.g., hoary bats; Johnson 2005, Kunz et al. 2007a, Arnett et al. 2008), and because low frequency bats generally fly at higher altitudes (i.e., in and around the rotor-swept area), it is important to account for altitudinal variation during acoustic surveys (Baerwald and Barclay 2009, Collins and Jones 2009). Our findings support this concern and we suggest that pre-construction acoustic surveys must include detectors placed as high as possible above ground to sample the airspace within the rotor-swept area.

Location and ambient temperature were consistently the most important factors in predicting bat activity, with the full design model explaining ~9–29% of the variation in activity. However, location alone explained ~3–9.5% of the variation in activity. In general, we found the highest probability of activity and highest counts for each phonic group at towers on the western edge of the project. Although it is not surprising to see spatial variation in bat activity across a project site (Arnett et al. 2006, Reynolds et al. 2006, Mabee and Schwab 2008, Hein et al. 2009), specific reasons for variability among towers remain unknown, but may be attributed to differences in landscape features (e.g., proximity to water, forest edge, canyons, cliff faces, or foothills) among towers, which may attract foraging or roosting bats. Baerwald and Barclay (2009) demonstrated increasing fatalities, at turbines of similar size with increasing proximity to the foothills of the Rocky Mountains in Alberta, Canada. Piorkowski and O‟Connell (2010) observed higher fatalities at individual turbines closer to ravine edges. Although more data are needed, we recorded lower activity levels at towers surrounded by flat topography on the eastern end, and higher activity levels on more rugged terrain near the western end of the RWEP. If bat activity and fatalities are related to landscape features, altering turbine placement away from these features may reduce fatalities.

Bat activity was positively related to ambient temperature. Arnett et al. (2006) and Redell et al. (2006) reported a similar relationship in Pennsylvania and Wisconsin, respectively. Low frequency bats were more active at cooler temperatures, but overall we recorded little activity below 10^{o} C. Reynolds (2006) also found little activity of bats at a proposed wind facility in New York when ambient temperatures were below 10.5^{o} C. Erickson and West (2002) reported that regional patterns of climatic conditions as well as local weather events can be used to predict bat activity. Relationships between bat activity and temperature could be explained by the availability of insect prey. Insect flight occurrence decreases with ambient temperature and little or no flight activity may occur below 10^{o} C (Taylor 1963, Anthony et al. 1981). Insect migrations are known to be positively related to temperature (e.g., Sparks et al. 2005, Fleming and Eby 2003, McCracken et al. 2007). High frequency bats, which were more active at low altitudes, were more responsive to temperature than low frequency bats, whereas low frequency bats were more responsive to temperature changes at higher altitudes. This may be related to differences in body size and energetic relationships. Body temperature and body size have profound impacts on how animals function, and even small changes in body temperature can have significant effects on small mammals such as bats (Speakman and Thomas 2003). Larger animals are better equipped physiologically to deal with lower ambient temperatures than are smaller ones because they have a relatively lower surface area to volume ratio through which heat is lost (Speakman and Thomas 2003). Thus, it is plausible that smaller bodied, high frequency bats are more sensitive to lower ambient temperature and consequently more active during warmer nights relative to larger, low frequency bats. Another possibility is that low frequency bats are more likely to be migrating through the area (Cryan 2003, Cryan and Brown 2007) and these bats may be less responsive to temperature than local, foraging species of high frequency bats because they are occupying the site for different reasons.

While some measure of wind speed was often important in predicting activity, it never explained more than an additional 9% of the variation. However, when parameter estimates included mean wind speed, the effect on odds of bat activity and estimated number of bat passes was typically negative. Strong winds influence insect abundance and activity, which in turn influence bat activity; bats are known to suppress their activity during periods of rain, low ambient temperatures, and strong winds (Anthony et al. 1981, Erkert 1982, Erickson and West 2002, Lacki et al. 2007). Wind speed and direction affected habitat use by hoary bats and silver-haired bats in Canada, with higher activity detected on the lee side of a ridge (Barclay 1985). In the Netherlands, Verboom and Spoelstra (1999) reported that foraging and commuting activity of pipistrelle bats was concentrated closer to the leeward sides of trees as wind speed increased. Patterns of bat activity and wind speed also generally corroborate recent studies of bat fatality and the relationships with wind. At Buffalo Mountain in Tennessee, Fiedler (2004) found a negative relationship between bat fatality and wind speed. Kerns et al. (2005) reported that the majority of bats killed at the Meyersdale, Pennsylvania and Mountaineer, West Virginia facilities occurred on low wind nights, and fatalities tended to increase just before and after the passage of storm fronts. Capitalizing on the negative relationship between bat activity and wind speed, Baerwald et al. (2009) and Arnett et al. (2011) demonstrated how increasing turbine cut-in speeds (i.e., the speed at which turbines begin generating electricity) to 5.5 m/s, and 5.0 m/s and 6.5 m/s can reduce bat fatalities up to 60% and 93%, respectively. Using the same cut-in treatments as Arnett et al. (2011), Good et al. (2011) reported a 50% and 78% reduction in bat fatalities compared to fully operational turbines. Young et al. (2010) showed that feathering turbine blades so that they revolve less than once per minute prior to normal operational cut-in speed (4.0 m/s) can reduce bat fatality significantly.

SCOPE, LIMITATIONS, and NEXT STEPS

Although numerous acoustic monitoring surveys at wind-energy facilities in North America have been conducted, most of these studies are from the northeastern United States. Similar acoustic studies are rare for Wyoming and adjacent states. Because a paucity of information concerning the spatial and temporal activity of bats in this region exists, predicting impacts of wind power development on resident and migratory species can be problematic and thus strengthens the rationale for additional studies in western states. Furthermore, differences in species assemblages and identification, landscape characteristics (e.g., habitat, elevation, and climate), sampling effort (e.g., number of detectors or towers, sampling dates, altitude of detectors, detector position), and analytical methods can make comparing bat activity among studies difficult. To minimize variability associated with sampling design and analysis, recent publications have presented recommendations for acoustic monitoring surveys (Hayes 2000, Gannon et al. 2003, Kunz et al. 2007b). Our pre-construction study follows these recommendations and in doing so, we were able to provide comparative baseline information on both spatial and temporal patterns of bat activity, particularly for migratory tree-roosting bats.

Several factors, including microphone position, orientation, and weatherproofing, influence the quality and quantity of recorded bat calls. Britzke et al. (2010) reported that the weatherproofing approach we used for our microphones, commonly referred to as "bat-hats," led to recording significantly fewer call sequences, pulses per file, and species per site, and resulted in generally lower quality calls compared with other weatherproofing options (e.g., using a curved PVC tube) and non-weatherproofed microphones. However, a similar study contradicted these findings and determined that microphones equipped with bat-hats recorded more calls than other weatherproofing systems (Gruver et al. 2009). Britzke et al. (2010) suggested that possible detrimental effects of weatherproofing microphones likely vary with local site conditions. Moreover, where the goal is to determine relative activity levels among sites, as is the case for the broad assessment of activity in relation to fatality, any weatherproofing or orientation may be acceptable as long as deployment is similar among sampling locations (Britzke et al. 2010). Because there is no reason to believe that the bias associated with our weatherproofing system differed among our sampling points, we believe we were able to adequately sample the relative bat activity at the RWEP.

This study was conducted at a single proposed wind energy facility located on shrubland habitat in east-central Wyoming, and statistical inferences are limited to this site. Additional studies in the region will determine whether our findings reflect patterns of bat activity on similar sites with comparable vegetation composition and topography in this region. Despite equipment malfunctions, we were able to quantify the spatial (vertical and horizontal) and temporal (seasonal and yearly) activity patterns of bats in the vicinity of a proposed wind-energy facility. These data may provide useful information for predicting when, where, and which bats may be most at risk of interactions with wind turbines at the RWEP. Combining acoustic data from this site and with data from other facilities in the region, and correlating activity to the corresponding fatality data will help determine if risk can be predicted with reasonable certainty. In addition, understanding the specific timings and locations of peak activity may assist with refining the use of raising turbine cut-in speeds to reduce bat fatalities (Arnett et al. 2011).

Our analyses are exploratory, in part because so little data exist upon which to develop *a priori*, confirmatory hypotheses and associated candidate models. We performed our analysis using weather data gathered only from met towers located on site; future modeling may incorporate additional weather data gathered from local weather stations to model broad-scale weather events and bat activity. The current analysis only estimates activity rates and differences in activity patterns of three phonic groups (high and low frequency bats and hoary bats), at two heights from five towers. High variation in levels of activity has consequences with respect to sampling design and level of effort required to obtain accurate estimates of activity; as fewer nights are sampled, there is an increased probability of obtaining mean estimates of activity that differ greatly from those calculated from large datasets (Hayes 1997). Low-intensity sampling could result in under- or over-estimates of activity and the most precise and accurate estimates will likely come from intensive sampling efforts (Hayes 1997, M. Huso, Oregon State University, unpublished data). Future analyses should evaluate the trade-offs among various sampling efforts regarding accuracy and precision of estimates of bat activity, with the ultimate goal of optimizing sampling designs and data requirements for employing acoustic monitoring to predict bat fatality at wind facilities.

There is a paucity of information relating pre-construction activity with post-construction fatality of bats. Although several studies, collectively, have shown a positive correlation ($r = 0.79$) between total number of bat calls/night and estimated fatalities/turbine/year, confounding factors limit our ability to make inferences from these reports (see Kunz et al. 2007b). The lack of information regarding such relationships further supports the necessity for additional acoustic studies. Because bat acoustic monitoring can provide spatial and temporal activity patterns of bats, studies such as the one at the RWEP are useful in resolving potential negative impacts of wind development on bat populations. After turbines are constructed at the RWEP, we intend to gather post-construction activity and fatality data. Data from this report in combination with similar data from other studies will be used to determine if relationships exist between pre-construction acoustic monitoring and post-construction fatality.

LITERATURE CITED

Aldridge, H. D. J. N., and I. L. Rautenbach. 1987. Morphology, echolocation and resource partitioning in insectivorous bats. Journal of Animal Ecology 56:763–778.

American Wind Energy Association (AWEA). 2011. AWEA US wind industry annual market report year ending 2010. http://www.awea.org/la_pubs_reports.cfm. Accessed February 2011.

Anthony, E. L. P., M. H. Stack, and T. H. Kunz. 1981. Night roosting and the nocturnal time budgets of the little brown bat, *Myotis lucifugus*; effects of reproductive status, prey density, and environmental conditions. Oecologia 51:151–156.

Arnett, E. B., technical editor. 2005. Relationships between bats and wind turbines in Pennsylvania and West Virginia: an assessment of bat fatality search protocols, patterns of fatality, and behavioral interactions with wind turbines. A final report submitted to the Bats and Wind Energy Cooperative. Bat Conservation International. Austin, Texas, USA.

Arnett, E. B., J. P. Hayes, and M. M. P. Huso. 2006. Patterns of pre-construction bat activity at a proposed wind facility in south-central Pennsylvania. An annual report submitted to the Bats and Wind Energy Cooperative. Bat Conservation International. Austin, Texas, USA.

Arnett, E. B., M. M. P. Huso, D. S. Reynolds, and M. Schirmacher. 2007. Patterns of pre-construction bat activity at a proposed wind facility in northwest Massachusetts. An annual report submitted to the Bats and Wind Energy Cooperative. Bat Conservation International. Austin, Texas, USA.

Arnett, E. B., K. Brown, W. P. Erickson, J. Fiedler, T. H. Henry, G. D. Johnson, J. Kerns, R. R. Kolford, C. P. Nicholson, T. O‟Connell, M. Piorkowski, and R. Tankersley, Jr. 2008. Patterns of fatality of bats at wind energy facilities in North America. Journal of Wildlife Management 72:61–78.

Arnett, E. B., M. R. Schirmacher, M. M. P. Huso, and J. P. Hayes. 2009. Patterns of bat fatality at the Casselman Wind Project in south-central Pennsylvania. An annual report submitted to the Bats and Wind Energy Cooperative and the Pennsylvania Game Commission. Bat Conservation International. Austin, Texas, USA.

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

Baerwald, E. F. and R. M. R. Barclay. 2009. Geographic variation in activity and fatality in migratory bats at wind energy facilities. Journal of Mammalogy 90:1341–1349.

Baerwald, E. F., J. Edworthy, M. Holder, and R. M. R. Barclay. 2009. A large-scale mitigation experiment to reduce bat fatalities at wind energy facilities. Journal of Wildlife Management 73:1077–1081.

Baerwald, E. F. 2011. Patterns of activity and fatality of migratory bats at a wind energy facility in Alberta, Canada. Journal of Wildlife Management DOI: 10.1002/jwmg.147.

Barclay, R. M. R. 1985. Long-versus short-range foraging strategies of hoary (*Lasiurus cinereus*) and silver-haired (*Lasionycteris noctivagans*) bats and the consequences for prey selection. Canadian Journal of Zoology 63:2507–2515.

Barclay, R. M. R. 1999. Bats are not birds: a cautionary note on using echolocation calls to identify bats: a comment. Journal of Mammalogy 80:290–296.

Barclay, R. M. R., E. F. Baerwald, and J. C. Gruver. 2007. Variation in bat and bird fatalities at wind energy facilities: assessing the effects of rotor size and tower height. Canadian Journal of Zoology 85:381–387.

Britzke, E. R., and K. L. Murray. 2000. A quantitative method for selection of identifiable search-phase calls using the Anabat system. Bat Research News 41: 33–36.

Britzke, E. R., B. A. Slack, M. P. Armstrong, and S. C. Loeb. 2010. Effects of orientation and weatherproofing on the detection of bat echolocation calls. Journal of Fish and Wildlife Management 1:136–141.

Burnham, K. P., and D. R. Anderson. 2002. Model selection and multimodel inference: a practical information-theoretic approach, second edition. Springer-Verlag, New York, New York, USA.

Collins, J., and G. Jones. 2009. Differences in bat activity in relation to detector height: implications for bat surveys at proposed windfarm sites. Acta Chiropterologica 11:343–350.

Cryan, P. M. 2003. Seasonal distribution of migratory tree bats (*Lasiurus* and *Lasionycteris*) in North America. Journal of Mammalogy 84 579–593.

Cryan, P. M. 2008. Mating behavior as a possible cause of bat fatalities at wind turbines. Journal of Wildlife Management 72:845–849.

Cryan, P. M. 2011. Wind turbines as landscape impediments to the migratory connectivity of bats. Environmental Law 41:355–370.

Cryan, P. M., and A. C. Brown. 2007. Migration of bats past a remote island offers clues toward the problem of bat fatalities at wind turbines. Biological Conservation 139:1–11.

Dürr, T., and L. Bach. 2004. Bat deaths and wind turbines – a review of current knowledge, and the information available in the database for Germany. Bremer Beiträge für Naturkunde und Naturschutz 7:253–264.

Eckert, H. G. 1982. Ecological aspects of bat activity rhythms. Pages 201–242 in T. H. Kunz, editor. Ecology of bats. Plenum Press, New York, New York, USA.

Energy Information Administration (EIA). 2007. Annual energy outlook 2007 with projections to 2030. U.S. Department of Energy, Energy Information Administration, Washington, D.C., USA. http://www.eia.doe.gov/oiaf/aeo/pdf/0383(2007).pdf. Accessed 1 May 2007.

Erickson, J. L., and S. D. West. 2002. The influence of regional climate and nightly weather conditions on activity patterns of insectivorous bats. Acta Chiropterologica 4:17–24.

Fiedler, J. K. 2004. Assessment of bat mortality and activity at Buffalo Mountain Windfarm, eastern Tennessee. Thesis, University of Tennessee, Knoxville, Tennessee, USA.

Fiedler, J. K., T. H. Henry, C. P. Nicholson, and R. D. Tankersley. 2007. Results of bat and bird mortality monitoring at the expanded Buffalo Mountain Windfarm, 2005. Tennessee Valley Athority, Knoxville, Tennessee, USA.

Fleming, T.H. and P. Eby. 2003. Ecology of bat migration. In: Bat Ecology (T.H. Kunz and M.B. Fenton, eds.). University of Chicago Press, Chicago

Findley, J. S. 1993. Bats: a community perspective. Cambridge University Press, New York.

Frick, W.F., J.F. Pollock, A. Hicks, K. Langwig, D.S. Reynolds, G. Turner, C. Buthowski, T.H. Kunz. 2010. An emerging disease causes regional population collapse of a common North American bat species. Science, 329:679-682.

Gannon, W. L., R. E. Sherwin, and S. Haymond. 2003. On the importance of articulating assumptions when conducting acoustic studies of bats. Wildlife Society Bulletin 31:45–61.

Gerard, P. D., D. R. Smith, G. Weerrakkody.1998. Limits of retrospective power anaylsis. Journal of Wildlife Management 62:801-807.

Good, R. E., W. Erickson, A. Merrill, S. Simon, K. Murray, K. Bay, and C. Fritchman. 2011. Bat monitoring studies at the Fowler Ridge Wind Energy Facility, Benton County, Indiana, April 13–October 15, 2010. Unpublished report prepared for Fowler Ridge Wind Farm, by Western EcoSystems Technology, Inc. Cheyenne, WY, USA.

Gruver, J. C. 2002. Assessment of bat community structure and roosting habitat preferences for the hoary bat (*Lasiurus cinereus*) near Foote Creek Rim, Wyoming. Thesis, University of Wyoming, Laramie, Wyoming, USA.

Gruver, J. C., D. I. Solick, and M. K. Sonnenberg. 2009. Comparison of bat activity recorded using different acoustic sampling equipment: Implications for study design at wind-energy facilities. Presented at the 39th Annual North American Symposium on Bat Research, Portland, OR.

Hall, L. S., and G. C. Richards. 1972. Notes on *Tadarida australis* (Chiroptera:molossidae). Australian Mammalogy 1:46.

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

Hayes, J. P. 2000. Assumptions and practical considerations in the design and interpretation of echolocation-monitoring studies. Acta Chiropterologica 2: 225–236.

Hayes, J. P., and J. C. Gruver. 2000. Vertical stratification of bat activity in an old-growth forest in western Washington. Northwest Science 74:102–108.

Hein, C. D., S. B. Castleberry, and K. V. Miller. 2009. Site occupancy of bats in relation to forested corridors. Forest Ecology and Management 257:1200–1207.

Hester S.G., M.B. Grenier. 2005. A conservation plan for bats in Wyoming. Wyoming Game and Fish Department, Nongame Program, Lander, WY.

Horn, J. W., E. B. Arnett, and T. H. Kunz. 2008. Behavioral responses of bats to operating wind turbines. Journal of Wildlife Management 72:123–132.

Jain, A. A., R. R. Koford, A. W. Hancock, and G. G. Zenner. 2011. Bat mortality and activity at a northern Iowa wind resource area. American Midland Naturalist 165: 185–200.

Johnson, G. D. 2005. A review of bat mortality at wind-energy developments in the United States. Bat Research News 46:45–49.

Johnson, G., K, Bay, J. Eddie, and T. Rintz. 2008. Wildlife Baseline Studies for the Glenrock Wind Resource Area Converse County, Wyoming. A report prepared by West, Inc.

Johnson, G., and W. Erickson. 2008. Avian and bat cumulative impacts associated with wind energy development in the Columbia Plateau Ecoregion of eastern Washington and Oregon. A report prepared by by Western EcoSystems Technology, Inc., Cheyenne, WY, USA.

Johnson, G., K, Bay, J. Eddie. 2009. Wildlife Baseline Studies for the Dunlap Ranch Wind Resource Area Carbon County, Wyoming, June 4 2008–May 27 2009. An unpublished report prepared for CH2MHill, Englewood, CO, by Western EcoSystems Technology, Inc., Cheyenne, WY, USA.

Jones, G., D.S. Jacobs T.H. Kunz, M.R. Willig, and P.A. Racey. 2009. Carpe noctem: The importance of bats as bioindicators. Endangered Species Research, 8:93-115.

Jung, T. S., I. D. Thompson, R. D. Titman, and A. P. Applejohn. 1999. Habitat selection by forest bats in relation to mixed-wood stand types and structure in central Ontario. Journal of Wildlife Management 63:1306–1319.

Kalcounis, M.C., K.A. Hobson, R.M. Brigham, and K.R. Hecker. 1999. Bat activity in the boreal forest: importance of stand type and vertical strata. Journal of Mammalogy 80:673–682.

Kerns, J. and P. Kerlinger. 2004. A study of bird and bat collision fatalities at the MWEC Wind Energy Center, Tucker County, West Virginia: annual report for 2003. Technical report prepared by Curry and Kerlinger, LLC. For FPL Energy and MWEC Wind Energy Center Technical Review Committee. Curry and Kerlinger, LLC, Cape May Point, New Jersey, USA.

Kerns, J, W. P. Erickson, and E. B. Arnett. 2005. Bat and bird fatality at wind energy facilities in Pennsylvania and West Virginia. Pages 24–95 *in* E. B. Arnett, editor. Relationships between bats and wind turbines in Pennsylvania and West Virginia: an assessment of bat fatality search protocols, patterns of fatality, and behavioral interactions with wind turbines. A final report submitted to the Bats and Wind Energy Cooperative. Bat Conservation International, Austin, Texas, USA.

Kunz, T.H., and M.B. Fenton (eds.). 2003. Bat Ecology. University of Chicago Press, Chicago

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

Kunz, T. H., E. B. Arnett, B. M. Cooper, W. P. Erickson, R. P. Larkin, T. Mabee, M. L. Morrison, M. Dale. Strickland, J. M. Szewczak. 2007b. Methods and metrics for assessing impacts of wind energy development on nocturnally active birds and bats. Journal of Wildlife Management 71:2449–2486.

Kunz, T. H., E. Braun de Torez, D. Bauer, T. Lobova, and T. H. Fleming. 2011. Ecosystem services provided by bats. Annals of the New York Academy of Sciences. 1223:1–38.

Lacki, M. J., S. K. Amelon, and M. D. Baker. 2007. Foraging ecology of bats in forests. Pages 83–127 *in* M. J. Lacki, A. Kurta, and J. P. Hayes, editors. Conservation and management of bats in forests. Johns Hopkins University Press. Baltimore, Maryland, USA.

Larkin, R. P. 2006. Migrating bats interacting with wind turbines: what birds can tell us. Bat Research News 47:23–32.

Larson, D. J., and J. P. Hayes. 2000. Variability in sensitivity of Anabat II bat detectors and a method of calibration. Acta Chiropterologica 2:209–213.

Mabee, T. J., and N. A. Schwab. 2008. A visual and acoustic study of nocturnal bird and bat migration at the proposed Roaring Brook Wind Project, New York, fall 2007. Unpublished report prepared for PPM Energy, Inc., Lowville, NY, by ABR, Inc., Forest Grove, OR. 48 pp.

McCracken, G. F., E. H. Gillam, J. K. Westbrook, Y. Lee, M. J. Jensen, and B. b. Basley. 2007. Brazilian free-tailed bats (*Tadarida brasiliensis*: Molossidae, Chiroptera) at high altitudes: links to migratory insect populations. Integrative and Comparative Biology 48:107–118.

Menzel, J. M., M. A. Menzel, J. C. Kilgo, W. M. Ford, J. W. Edwards, and G. F. McCracken. 2005. Effect of habitat and foraging height on bat activity in the coastal plain of South Carolina. Journal of Wildlife Management. 69:235–245.

National Research Council. 2007. Ecological impacts of wind-energy projects. National Academies Press, Washington, D.C., USA.

O‟Shea, T. J., M. A. Bogan, and L. E. Ellison. 2003. Monitoring trends in bat populations of the United States and territories: status of the science and recommendations for the future. Wildlife Society Bulletin 31:16–29.

Parsons, S. and J. Szewczak. 2009. Detecting, recording and analyzing the vocalizations of bats, Pp. 91-111, In: Ecological and Behavioral Methods for the Study of Bats (T.H. Kunz, eds.). Johns Hopkins University Press, Baltimore, Maryland.

Pasqualetti M., R. Richter, and P. Gipe. 2004. History of wind energy. Pages 419–433 *in* C. J. Cleveland, editor. Encyclopedia of energy. Volume 6. Academic Press, San Diego, California, USA.

Pierson, E. D. 1998. Tall trees, deep holes, and scarred landscapes: conservation biology ofNorth American bats. Pages 309–325 *in* T. H. Kunz and P. A. Racey, editors. Bat biology and conservation. Smithsonian Institution Press, Washington, D.C., USA.

Piorkowski, M. D., and T. J. O‟Connell. 2010. Spatial pattern of summer bat mortality from collisions with wind turbines in mixed-grass prairie. American Midland Naturalist 164:260–269.

Racey, P. A., and A. C. Entwistle. 2003. Conservation ecology of bats. Pages 680–743 *in* T. H. Kunz and M. B. Fenton, editors. Bat Ecology. University of Chicago Press, Chicago, Illinois, USA.

Redell, D., E. B. Arnett, J. P. Hayes, and M. Huso. 2006. Patterns of pre-construction bat activity at a proposed wind facility in south-central Wisconsin. A final report submitted to the Bats and Wind Energy Cooperative. Bat Conservation International. Austin, Texas, USA.

Reynolds, D. S. 2006. Monitoring the potential impact of a wind development site on bats in the northeast. Journal of Wildlife Management 70:1219–1227.

Sherwin, R. E., W. L. Gannon, and S. Haymond. 2000. The efficacy of acoustic techniques to infer differential use of habitat by bats. Acta Chiropterlogica 2: 145–153.

Sparks, T. H., D. B. Roy, and L. H. Dennis. 2005. The influence of temperature on migration of Lepidoptera into Britain. Global Change Biology 11:507–514.

Speakman, J. R., and D. W. Thomas. 2003. Physiological ecology and energetics of bats. Pages 430–490 *in* T. H. Kunz and M. B. Fenton, editors. Bat ecology. University of Chicago Press, Chicago, Illinois, USA.

Taylor, L. R. 1963. Analysis of the effect of temperature on insects in flight. Journal of Animal Ecology 32:99–117.

Thomas, D. W. 1988. The distribution of bats in different ages of Douglas-fir forests. Journal of Wildlife Management 52:619–626.

Verboom, B., and K. Spoelstra. 1999. Effects of food abundance and wind on the use of tree lines by an insectivorous bat, *Pipistrellus pipistrellus*. Canadian Journal of Zoology 77:1393–1401.

Winhold, L., and A. Kurta. 2006. Are red bats (*Lasiurus borealis*) declining in southern Michigan? Bat Research News 46:22.

Wyoming Game and Fish Department (WGFD). 2010. Wyoming State Wildlife Action Plan. Cheyenne, WY

Young, D. Y. Jr., S. Nomani, W. L. Tidhar, and K. Bay. 2010. NedPower Mount Storm Wind Energy Facility post-construction avian and bat monitoring, July–October 2010. Unpublished report prepared for NedPower Mount Storm, LLC, Houston, TX, prepared by Western EcoSystems Technology, Inc., Cheyenne, WY, USA.

Zuur, A. F., E. N. Ieno, N. J. Walker, A. A. Saveliev, and G. M. Smith. 2009. Mixed effects models and extensions in ecology with R. Springer, New York, New York, USA.

Appendix 1. List of 128 models used to predict probability of activity and expected number of passes for high and low frequency bats at 1.5 m at the RWEP, Wyoming, 2009–2010.

Model	Probability of Activity Model	Count Model
null.mod	1	1
base.loc	L	L
base.temp	L + T	L + T
base.temp*freq	L + T*F	L + T*F
Wind1	L + T*F + WS	L + T*F
Wind2	L + T*F + T*WS	L + T*F
Wind3	L + T*F + F*WS	L + T*F
Wind4	L + T*F + T*F*WS	L + T*F
Wind5	L + T*F	L + T*F + WS
Wind6	L + T*F	L + T*F + T*WS
Wind7	L + T*F	L + T*F + F*WS
Wind8	L + T*F	L + T*F + F*T*WS
Wind9	L + T*F + WS	L + T*F + WS
Wind10	L + T*F + T*WS	L + T*F + WS
Wind11	L + T*F + F*WS	L + T*F + WS
Wind12	L + T*F + T*F*WS	L + T*F + WS
Wind13	L + T*F + WS	L + T*F + T*WS
Wind14	L + T*F + WS	L + T*F + F*WS
Wind15	L + T*F + WS	L + T*F + T*F*WS
Wind16	L + T*F + T*WS	L + T*F + T*WS
Wind17	L + T*F + F*WS	L + T*F + T*WS
Wind18	L + T*F + T*F*WS	L + T*F + T*WS
Wind19	L + T*F + T*WS	L + T*F + F*WS
Wind20	L + T*F + T*WS	L + T*F + T*F*WS
Wind21	L + T*F + F*WS	L + T*F + F*WS
Wind22	L + T*F + T*F*WS	L + T*F + F*WS
Wind23	L + T*F + F*WS	L + T*F + T*F*WS
Wind24	L + T*F + T*F*WS	L + T*F + T*F*WS
Wind25	L + T*F + PctG3.5	L + T*F
Wind26	L + T*F + T*PctG3.5	L + T*F
Wind27	L + T*F + F*PctG3.5	L + T*F
Wind28	L + T*F + T*F*PctG3.5	L + T*F
Wind29	L + T*F	L + T*F + PctG3.5
Wind30	L + T*F	L + T*F + T*PctG3.5
Wind31	L + T*F	L + T*F + F*PctG3.5
Wind32	L + T*F	L + T*F + F*T*PctG3.5
Wind33	L + T*F + PctG3.5	L + T*F + PctG3.5
Wind34	L + T*F + T*PctG3.5	L + T*F + PctG3.5
Wind35	L + T*F + F*PctG3.5	L + T*F + PctG3.5
Wind36	L + T*F + T*F*PctG3.5	L + T*F + PctG3.5
Wind37	L + T*F + PctG3.5	L + T*F + T*PctG3.5
Wind38	L + T*F + PctG3.5	L + T*F + F*PctG3.5
Wind39	L + T*F + PctG3.5	L + T*F + T*F*PctG3.5
Wind40	L + T*F + T*PctG3.5	L + T*F + T*PctG3.5
Wind41	L + T*F + F*PctG3.5	L + T*F + T*PctG3.5

Appendix 1. Continued.

Model	Probability of Activity Model	Count Model
Wind42	L + T*F + T*F*PctG3.5	L + T*F + T*PctG3.5
Wind43	L + T*F + T*PctG3.5	L + T*F + F*PctG3.5
Wind44	L + T*F + T*PctG3.5	L + T*F + T*F*PctG3.5
Wind45	L + T*F + F*PctG3.5	L + T*F + F*PctG3.5
Wind46	L + T*F + T*F*PctG3.5	L + T*F + F*PctG3.5
Wind47	L + T*F + F*PctG3.5	L + T*F + T*F*PctG3.5
Wind48	L + T*F + T*F*PctG3.5	L + T*F + T*F*PctG3.5
Wind49	L + T*F + PctG5	L + T*F
Wind50	L + T*F + T*PctG5	L + T*F
Wind51	L + T*F + F*PctG5	L + T*F
Wind52	L + T*F + T*F*PctG5	L + T*F
Wind53	L + T*F	L + T*F + PctG5
Wind54	L + T*F	L + T*F + T*PctG5
Wind55	L + T*F	L + T*F + F*PctG5
Wind56	L + T*F	L + T*F + F*T*PctG5
Wind57	L + T*F + PctG5	L + T*F + PctG5
Wind58	L + T*F + T*PctG5	L + T*F + PctG5
Wind59	L + T*F + F*PctG5	L + T*F + PctG5
Wind60	L + T*F + T*F*PctG5	L + T*F + PctG5
Wind61	L + T*F + PctG5	L + T*F + T*PctG5
Wind62	L + T*F + PctG5	L + T*F + F*PctG5
Wind63	L + T*F + PctG5	L + T*F + T*F*PctG5
Wind64	L + T*F + T*PctG5	L + T*F + T*PctG5
Wind65	L + T*F + F*PctG5	L + T*F + T*PctG5
Wind66	L + T*F + T*F*PctG5	L + T*F + T*PctG5
Wind67	L + T*F + T*PctG5	L + T*F + F*PctG5
Wind68	L + T*F + T*PctG5	L + T*F + T*F*PctG5
Wind69	L + T*F + F*PctG5	L + T*F + F*PctG5
Wind70	L + T*F + T*F*PctG5	L + T*F + F*PctG5
Wind71	L + T*F + F*PctG5	L + T*F + T*F*PctG5
Wind72	L + T*F + T*F*PctG5	L + T*F + T*F*PctG5
Wind73	L + T*F + PctG6.5	L + T*F
Wind74	L + T*F + T*PctG6.5	L + T*F
Wind75	L + T*F + F*PctG6.5	L + T*F
Wind76	L + T*F + T*F*PctG6.5	L + T*F
Wind77	L + T*F	L + T*F + PctG6.5
Wind78	L + T*F	L + T*F + T*PctG6.5
Wind79	L + T*F	L + T*F + F*PctG6.5
Wind80	L + T*F	L + T*F + F*T*PctG6.5
Wind81	L + T*F + PctG6.5	L + T*F + PctG6.5
Wind82	L + T*F + T*PctG6.5	L + T*F + PctG6.5
Wind83	L + T*F + F*PctG6.5	L + T*F + PctG6.5
Wind84	L + T*F + T*F*PctG6.5	L + T*F + PctG6.5
Wind85	L + T*F + PctG6.5	L + T*F + T*PctG6.5
Wind86	L + T*F + PctG6.5	L + T*F + F*PctG6.5
Wind87	L + T*F + PctG6.5	L + T*F + T*F*PctG6.5
Wind88	L + T*F + T*PctG6.5	L + T*F + T*PctG6.5

Appendix 1. Continued.

Model	Probability of Activity Model	Count Model
Wind89	L + T*F + F*PctG6.5	L + T*F + T*PctG6.5
Wind90	L + T*F + T*F*PctG6.5	L + T*F + T*PctG6.5
Wind91	L + T*F + T*PctG6.5	L + T*F + F*PctG6.5
Wind92	L + T*F + T*PctG6.5	L + T*F + T*F*PctG6.5
Wind93	L + T*F + F*PctG6.5	L + T*F + F*PctG6.5
Wind94	L + T*F + T*F*PctG6.5	L + T*F + F*PctG6.5
Wind95	L + T*F + F*PctG6.5	L + T*F + T*F*PctG6.5
Wind96	L + T*F + T*F*PctG6.5	L + T*F + T*F*PctG6.5
Wind97	L + T*F + PctG3.5L6.5	L + T*F
Wind98	L + T*F + T*PctG3.5L6.5	L + T*F
Wind99	L + T*F + F*PctG3.5L6.5	L + T*F
Wind100	L + T*F + T*F*PctG3.5L6.5	L + T*F
Wind101	L + T*F	L + T*F + PctG3.5L6.5
Wind102	L + T*F	L + T*F + T*PctG3.5L6.5
Wind103	L + T*F	L + T*F + F*PctG3.5L6.5
Wind104	L + T*F	L + T*F + F*T*PctG3.5L6.5
Wind105	L + T*F + PctG3.5L6.5	L + T*F + PctG3.5L6.5
Wind106	L + T*F + T*PctG3.5L6.5	L + T*F + PctG3.5L6.5
Wind107	L + T*F + F*PctG3.5L6.5	L + T*F + PctG3.5L6.5
Wind108	L + T*F + T*F*PctG3.5L6.5	L + T*F + PctG3.5L6.5
Wind109	L + T*F + PctG3.5L6.5	L + T*F + T*PctG3.5L6.5
Wind110	L + T*F + PctG3.5L6.5	L + T*F + F*PctG3.5L6.5
Wind111	L + T*F + PctG3.5L6.5	L + T*F + T*F*PctG3.5L6.5
Wind112	L + T*F + T*PctG3.5L6.5	L + T*F + T*PctG3.5L6.5
Wind113	L + T*F + F*PctG3.5L6.5	L + T*F + T*PctG3.5L6.5
Wind114	L + T*F + T*F*PctG3.5L6.5	L + T*F + T*PctG3.5L6.5
Wind115	L + T*F + T*PctG3.5L6.5	L + T*F + F*PctG3.5L6.5
Wind116	L + T*F + T*PctG3.5L6.5	L + T*F + T*F*PctG3.5L6.5
Wind117	L + T*F + F*PctG3.5L6.5	L + T*F + F*PctG3.5L6.5
Wind118	L + T*F + T*F*PctG3.5L6.5	L + T*F + F*PctG3.5L6.5
Wind119	L + T*F + F*PctG3.5L6.5	L + T*F + T*F*PctG3.5L6.5
Wind120	L + T*F + T*F*PctG3.5L6.5	L + T*F + T*F*PctG3.5L6.5
Wind121	L + T*F + WS	L + T*F
Wind122	L + T*F + T*WS	L + T*F
Wind123	L + T*F + F*WS	L + T*F
Wind124	L + T*F + T*F*WS	L + T*F
Wind125	F*PctG3.5L6.5	F*PctG3.5L6.5
Wind126	T*F*PctG3.5L6.5	F*PctG3.5L6.5
Wind 127	F*PctG3.5L6.5	T*F*PctG3.5L6.5
Wind128	T*F*PctG3.5L6.5	T*F*PctG3.5L6.5

Appendix 2. List of 40 models used to predict probability of activity and expected number of passes for low frequency bats and hoary bats at 44 m at the RWEP, Wyoming, 2009–2010.

Model	Probability of Activity Model	Count Model
null.mod	1	1
base.loc	L	L
base.temp	L + T	L + T
Wind1	L + T + WS	L + T
Wind2	L + T	L + T + WS
Wind3	L + T + WS	L + T + WS
Wind4	L + T*WS	L + T
Wind5	L + T*WS	L + T + WS
Wind6	L + T	L + T*WS
Wind7	L + T + WS	L + T*WS
Wind8	L + T*WS	L + T*WS
Wind9	L + T + PctG3.5	L + T
Wind10	L + T	L + T + PctG3.5
Wind11	L + T + PctG3.5	L + T + PctG3.5
Wind12	L + T*PctG3.5	L + T
Wind13	L + T*PctG3.5	L + T + PctG3.5
Wind14	L + T	L + T*PctG3.5
Wind15	L + T + PctG3.5	L + T*PctG3.5
Wind16	L + T*PctG3.5	L + T*PctG3.5
Wind17	L + T + PctG5	L + T
Wind18	L + T	L + T + PctG5
Wind19	L + T + PctG5	L + T + PctG5
Wind20	L + T*PctG5	L + T
Wind21	L + T*PctG5	L + T + PctG5
Wind22	L + T	L + T*PctG5
Wind23	L + T + PctG5	L + T*PctG5
Wind24	L + T*PctG5	L + T*PctG5
Wind25	L + T + PctG6.55	L + T
Wind26	L + T	L + T + PctG6.55
Wind27	L + T + PctG6.55	L + T + PctG6.55
Wind28	L + T*PctG6.55	L + T
Wind29	L + T*PctG6.55	L + T + PctG6.55
Wind30	L + T	L + T*PctG6.55
Wind31	L + T + PctG6.55	L + T*PctG6.55
Wind32	L + T*PctG6.55	L + T*PctG6.55
Wind33	L + T + PctG3.5L6.5	L + T
Wind34	L + T	L + T + PctG3.5L6.5
Wind35	L + T + PctG3.5L6.5	L + T + PctG3.5L6.5
Wind36	L + T*PctG3.5L6.5	L + T
Wind37	L + T*PctG3.5L6.5	L + T + PctG3.5L6.5
Wind38	L + T	L + T*PctG3.5L6.5
Wind39	L + T + PctG3.5L6.5	L + T*PctG3.5L6.5
Wind40	L + T*PctG3.5L6.5	L + T*PctG3.5L6.5

Appendix 3. Model selection for the confidence set and baseline models by year, height and phonic group at the RWEP, Wyoming, 2009-2010. AIC = AIC values, ΔAIC = difference in AIC units between the given model and the "best" model, Wt = Akaike weight for the model, Rel. Wt = , Cumm Wt = sum of Akaike weight for given model and all previous models, pR^2 = Nagelkerke‟s pseudo-R^2, aR^2 = additional R^2.

Year/Height/Group	Probability Model	Count Model	AIC	ΔAIC	Wt	Rel. Wt	Cumm. Wt	pR^2	aR^2
2009/1.5m/Both	T*F*WS	WS	1232.183	0.000	0.212	1.000	0.212	0.356	0.070
	F*WS	WS	1233.080	0.897	0.136	1.566	0.348	0.350	0.063
	T*F*WS	L+T	1233.164	0.981	0.130	1.633	0.478	0.352	0.066
	F*WS	L+T	1234.060	1.878	0.083	2.557	0.561	0.346	0.059
	T*F*WS	F*WS	1234.132	1.949	0.080	2.650	0.641	0.356	0.070
	T*F*WS	T*WS	1234.179	1.997	0.078	2.714	0.719	0.356	0.070
	T*F*WS	T*F*WS	1234.331	2.148	0.073	2.928	0.792	0.361	0.075
	F*WS	F*WS	1235.029	2.846	0.051	4.150	0.843	0.350	0.063
	F*WS	T*WS	1235.076	2.893	0.050	4.249	0.893	0.350	0.063
	F*WS	T*F*WS	1235.228	3.045	0.046	4.584	0.939	0.355	0.068
	L+T*F	L+T*F	1272.658	40.475	0.000	>1000	1.000	0.287	0.000
	L+T	L+T	1279.694	47.512	0.000	>1000	1.000	0.265	-0.022
	L	L	1380.259	148.076	0.000	>1000	1.000	0.095	-0.192
	1	1	1414.726	182.544	0.000	>1000	1.000	0.000	-0.287
2009/44m/Low	WS	WS	668.867	0.000	0.305	1.000	0.305	0.325	0.089
	PctL6.5	PctL6.5	669.813	0.946	0.190	1.605	0.495	0.322	0.086
	WS	T*WS	670.793	1.927	0.116	2.620	0.611	0.325	0.089
	T*WS	WS	670.867	2.000	0.112	2.718	0.723	0.325	0.089
	T*PctL6.5	PctL6.5	671.690	2.823	0.074	4.102	0.798	0.322	0.086
	PctL6.5	T*PctL6.5	671.780	2.913	0.071	4.292	0.869	0.322	0.086
	L+T	WS	684.715	15.849	0.000	>1000	0.999	0.266	0.031
	L+T	L+T	691.574	22.708	0.000	>1000	1.000	0.236	0.000
	1	1	730.184	61.317	0.000	>1000	1.000	0.000	-0.236
	L	L	737.837	68.970	0.000	>1000	1.000	0.037	-0.198

Appendix 3. Continued.

Year/Height/Group	Probability Model	Count Model	AIC	ΔAIC	Wt	Rel. Wt	Cumm. Wt	pR^2	aR^2
2009/44m/Hoary	WS	WS	362.719	0.000	0.137	1.000	0.137	0.243	0.063
	WS	L+T	363.424	0.704	0.097	1.422	0.234	0.231	0.051
	PctG3.5L6.5	L+T	363.694	0.974	0.084	1.628	0.318	0.230	0.050
	PctL6.5	L+T	363.972	1.252	0.073	1.870	0.392	0.229	0.049
	PctG3.5L6.5	PctG3.5L6.5	364.247	1.528	0.064	2.147	0.455	0.236	0.056
	T*WS	WS	364.259	1.540	0.064	2.160	0.519	0.245	0.065
	PctL6.5	PctL6.5	364.263	1.544	0.063	2.164	0.582	0.236	0.056
	WS	T*WS	364.624	1.904	0.053	2.591	0.635	0.243	0.063
	PctG3.5L6.5	T*PctG3.5L6.5	364.828	2.109	0.048	2.870	0.683	0.242	0.063
	T*PctL6.5	L+T	364.875	2.156	0.047	2.938	0.730	0.233	0.054
	T*WS	L+T	364.964	2.244	0.045	3.072	0.775	0.233	0.053
	T*PctL6.5	PctL6.5	365.167	2.447	0.040	3.400	0.815	0.241	0.061
	T*PctG3.5L6.5	L+T	365.344	2.625	0.037	3.715	0.852	0.231	0.052
	T*PctG3.5L6.5	PctG3.5L6.5	365.897	3.178	0.028	4.899	0.880	0.238	0.058
	T*WS	T*WS	366.164	3.445	0.025	5.597	0.905	0.245	0.065
	PctL6.5	T*PctL6.5	366.262	3.543	0.023	5.878	0.928	0.236	0.056
	T*PctG3.5L6.5	T*PctG3.5L6.5	366.478	3.759	0.021	6.550	0.949	0.244	0.064
	L+T	L+T	372.869	10.150	0.001	159.962	0.995	0.180	0.000
	1	1	388.997	26.277	0.000	>1000	1.000	0.000	-0.180
	L	L	397.905	35.186	0.000	>1000	1.000	0.038	-0.142

Appendix 3. Continued.

Year/Height/Group	Probability Model	Count Model	AIC	ΔAIC	Wt	Rel. Wt	Cumm. Wt	pR^2	aR^2
2010/1.5m/Both	F*PctG5	T*F*PctG5	1734.634	0.000	0.118	1.000	0.118	0.158	0.043
	F*PctG5	F*PctG5	1734.681	0.047	0.115	1.024	0.233	0.153	0.038
	F*PctG6.5	F*PctG6.5	1734.858	0.223	0.106	1.118	0.339	0.152	0.037
	F*PctG6.5	PctG6.5	1735.428	0.793	0.079	1.487	0.419	0.149	0.034
	F*PctG6.5	T*F*PctG6.5	1735.720	1.086	0.069	1.721	0.487	0.157	0.042
	F*WS	F*WS	1735.839	1.205	0.065	1.826	0.552	0.151	0.036
	F*PctG6.5	T*PctG6.5	1736.265	1.631	0.052	2.260	0.604	0.150	0.035
	F*PctG5	PctG5	1736.405	1.771	0.049	2.424	0.653	0.148	0.033
	F*PctG5	T*PctG5	1736.466	1.832	0.047	2.499	0.700	0.150	0.035
	F*WS	T*F*WS	1737.491	2.857	0.028	4.173	0.728	0.154	0.039
	T*F*PctG6.5	F*PctG6.5	1737.822	3.188	0.024	4.922	0.752	0.154	0.039
	F*PctG6.5	L+T	1738.099	3.465	0.021	5.655	0.773	0.142	0.028
	T*F*PctG5	T*F*PctG5	1738.286	3.651	0.019	6.207	0.792	0.159	0.044
	T*F*PctG5	F*PctG5	1738.332	3.698	0.019	6.354	0.811	0.153	0.038
	F*PctG5	L+T	1738.372	3.738	0.018	6.483	0.829	0.142	0.027
	T*F*PctG6.5	PctG6.5	1738.392	3.758	0.018	6.545	0.847	0.150	0.035
	L+T	L+T	1748.231	13.597	0.000	896.649	0.999	0.112	-0.003
	L+T*F	L+T*F	1753.889	19.254	0.000	>1000	1.000	0.115	0.000
	L	L	1761.758	27.124	0.000	>1000	1.000	0.087	-0.028
	1	1	1802.856	68.222	0.000	>1000	1.000	0.000	-0.115
2010/44m/Low									
	L+T	T*WS	823.113	0.000	0.409	1.000	0.409	0.095	0.049
	T*WS	T*WS	824.957	1.844	0.163	2.514	0.572	0.103	0.057
	WS	T*WS	825.068	1.955	0.154	2.657	0.725	0.095	0.049
	1	1	827.136	4.022	0.055	7.472	0.780	0.000	-0.046
	L+T	L+T	831.821	8.708	0.005	77.771	0.941	0.046	0.000
	L	L	832.636	9.523	0.003	116.918	0.959	0.027	-0.019

Appendix 3. Continued.

Year/Height/Group	Probability Model	Count Model	AIC	ΔAIC	Wt	Rel. Wt	Cumm. Wt	pR^2	aR^2
2010/44m/Hoary	L+T	T*WS	554.396	0.000	0.174	1.000	0.174	0.110	0.033
	L+T	T*PctL6.5	555.323	0.927	0.109	1.590	0.283	0.106	0.029
	WS	T*WS	556.395	2.000	0.064	2.718	0.347	0.110	0.033
	L+T	PctL5	556.564	2.169	0.059	2.957	0.406	0.093	0.016
	L+T	PctL6.5	556.799	2.403	0.052	3.325	0.458	0.092	0.015
	L+T	WS	556.980	2.584	0.048	3.640	0.506	0.091	0.014
	L+T	PctL3.5	557.144	2.749	0.044	3.952	0.550	0.091	0.013
	L+T	T*PctL5	557.199	2.804	0.043	4.063	0.593	0.099	0.021
	PctL6.5	T*PctL6.5	557.217	2.821	0.042	4.099	0.635	0.107	0.029
	T*WS	T*WS	558.064	3.669	0.028	6.261	0.663	0.112	0.034
	L+T	L+T	558.356	3.961	0.024	7.246	0.687	0.077	0.000
	1	1	560.228	5.832	0.009	18.470	0.881	0.000	-0.077
	L	L	563.053	8.657	0.002	75.841	1.000	0.040	-0.037

Evaluating the effectiveness of an ultrasonic acoustic deterrent for reducing bat fatalities at wind turbines

Final Report

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EXECUTIVE SUMMARY

We implemented a 2-year study to test the effectiveness of an ultrasonic acoustic deterrent for reducing bat fatalities at wind turbines at the Iberdrola Renewables Locust Ridge I and II Wind Farms located in Columbia and Schuylkill Counties, Pennsylvania. We randomly selected a set of control and treatment turbines that were searched daily in summer and fall 2009 and 2010 and estimates of fatality, adjusted for searcher efficiency, carcass persistence, and habitat and area adjustment, were compared between the two sets of turbines.

In the first year (2009), we randomly selected 10 turbines that were fitted with deterrent devices and 15 control turbines and searched each turbine daily for carcasses from 15 August to 10 October 2009. We did not assess inherent differences between sets of turbines in 2009. In 2010, we attempted to account for potential inherent differences between turbine sets and modified the design to reflect a Before-After Control-Impact (BACI) design. The same sets of turbines were monitored for a period of time prior to implementation of the deterrent treatment (1 May to 26 July 2010), then again during the deterrent implementation period (31 July through 9 October 2010). This design allowed for incorporating initial inherent differences between the two experimental treatment sets prior to implementation of the treatment as a reference for interpreting any differences detected during implementation of the treatment.

In 2009, we estimated 60% higher fatality (95% CI: 26%, 104%) per control turbine than per Deterrent turbine, or conversely, we estimated 21–51% fewer bats were killed per Deterrent turbine than per control turbine during this period. Without accounting for inherent differences, we estimated 18–62% fewer bats were killed per Deterrent turbine than per control turbine in 2010. However, there was marginal evidence that the ratio of control:Deterrent fatalities was greater during the treatment period than in the pre-treatment period; about 10% in the fatality rate between the two sets. Thus, when accounting for this inherent difference, between 2% more and 64% fewer bats were killed per Deterrent turbine relative to control turbines in 2010 after accounting for inherent turbine differences prior to treatment implementation.

We also determined species-specific response to deterrents for those species with adequate sample sizes. We estimated that twice as many hoary bats were killed per control turbine than Deterrent turbine, and nearly twice as many silver-haired bats in 2009. In 2010, although we estimated nearly twice as many hoary bats and nearly 4 times as many silver-haired bats killed per control turbine than at Deterrent turbines during the treatment period, these only represented an approximate 20% increase in fatality relative to the pre-treatment period for these species when accounting for inherent differences between turbine sets.

This study, and previous experiments with earlier prototypes, revealed that broadband ultrasound broadcasts may reduce bat fatalities by affect behavior of bats by discouraging them from approaching the sound source. Yet, the effectiveness of ultrasonic deterrents as a means to prevent bat fatalities at wind turbines is limited by the distance and area that ultrasound can be broadcast; ultra sound attenuates quickly and is heavily influenced by humidity. Humid conditions (nightly average of ~80%) contributed to limited affected airspace during our study. Also, we only deployed 8 deterrent devices on each turbine and did not cover the maximum amount of possible airspace bats could encounter. Also, during both years of the study water

leakage caused some deterrents to malfunction and not all deterrents were operational at all times during the study period. Thus, we contend that our findings may represent a more conservative estimate of the potential reduction achievable through application of the deterrent we tested. However, we caution that we do not yet have a deterrent device ready for operational deployment at wind facilities. With further experimentation and modifications, this type of deterrent method may prove successful and broadly applicable for protecting bats from harmful encounters with wind turbine blades. We anticipate further research and development of acoustic deterrent devices in 2011 and a new field test of the effectiveness of the new prototype in 2013. Future research and development and field studies should attempt to optimize both placement and number of devices on each turbine that would affect the greatest amount of airspace in the rotor-swept area to estimate potential maximum effectiveness of this tool to reduce bat fatalities. Future efforts also must evaluate the cost-effectiveness of deterrents in relation to different curtailment strategies to allow a cost-benefit analysis for mitigating bat fatalities.

Deterrent devices attached to the nacelle of a wind turbine at the Locust Ridge Wind Farm in Pennsylvania (E.B. Arnett, Bat Conservation International)

INTRODUCTION

As wind energy production has steadily increased worldwide, bat fatalities have been reported at wind facilities throughout North America (Johnson 2005, Kunz et al 2007, Arnett et al. 2008, Baerwald and Barclay 2009) and Europe (e.g., Durr and Bach 2004, Brinkman et al. 2006, Rydell et al. 2010) in a wide range of landscapes. Fatality rates observed at large commercial wind facilities on forested ridges in the eastern U.S. have ranged from 20.8–69.6 bats/turbine/year (Arnett et al. 2008), but new reports from the upper Midwest indicate relatively high fatalities at some facilities in this region (e.g., Gruver et al. 2009). Assuming 1) an average of ~12 bats killed per megawatt (MW) of installed capacity, assumed to be per year (Arnett et al. 2008); 2) the current installed capacity in the U.S. (36,698 MW as of September 2010; U.S. Department of Energy 2011) and Canada (4,008 MW as of December 2010; CANWEA 2010) totaling 40,706 MW; and 3) that reported fatality rates are representative and remained constant, the projected average number of bat fatalities in 2010 could have been more than 488,000 bats. Given these fatality rates, the accelerating growth of the wind industry (EIA 2010), and suspected and known population declines in many bat species (Racey and Entwistle 2003, Winhold et al. 2008, Frick et al. 2010), it is imperative to develop and evaluate solutions that can reduce the number of future bat fatalities.

Prior studies have demonstrated that a substantial portion of bat fatalities consistently occur during relatively low-wind conditions over a relatively short period of time during the summer-fall bat migration period (Arnett et al. 2008). Curtailment of turbine operations under these conditions and during this period has been proposed as a possible means of reducing impacts to bats (Kunz et al. 2007, Arnett et al. 2008, Cryan and Barclay 2009). Indeed, recent results from the only two published studies in Canada (Baerwald et al. 2009) and the U.S. (Arnett et al. 2011) indicate that changing turbine ―cut-in speed" (i.e., wind speed at which wind-generated electricity enters the power grid) from the manufactured speed (usually 3.5–4.0 m/s for modern turbines) to between 5.0 and 6.5 m/s resulted in at least a 50% reduction in bat fatalities (and as high as 93%; Arnett et al. 2011) compared to normally operating turbines. While costs of lost power from curtailment can be factored into the economics and financing and power purchase agreements of new projects, altering turbine operations even on a partial, limited-term basis potentially poses operational and financial difficulties for existing projects, so there is considerable interest in developing other solutions to reduce bat fatalities that do not involve turbine shutdowns. Also, changing turbine cut-in speed may not be effective in other regions that experience bat fatalities although this strategy may ultimately prove sufficiently feasible and economical for reducing bat fatalities. Thus, research on alternative mitigation strategies and their associated costs are warranted.

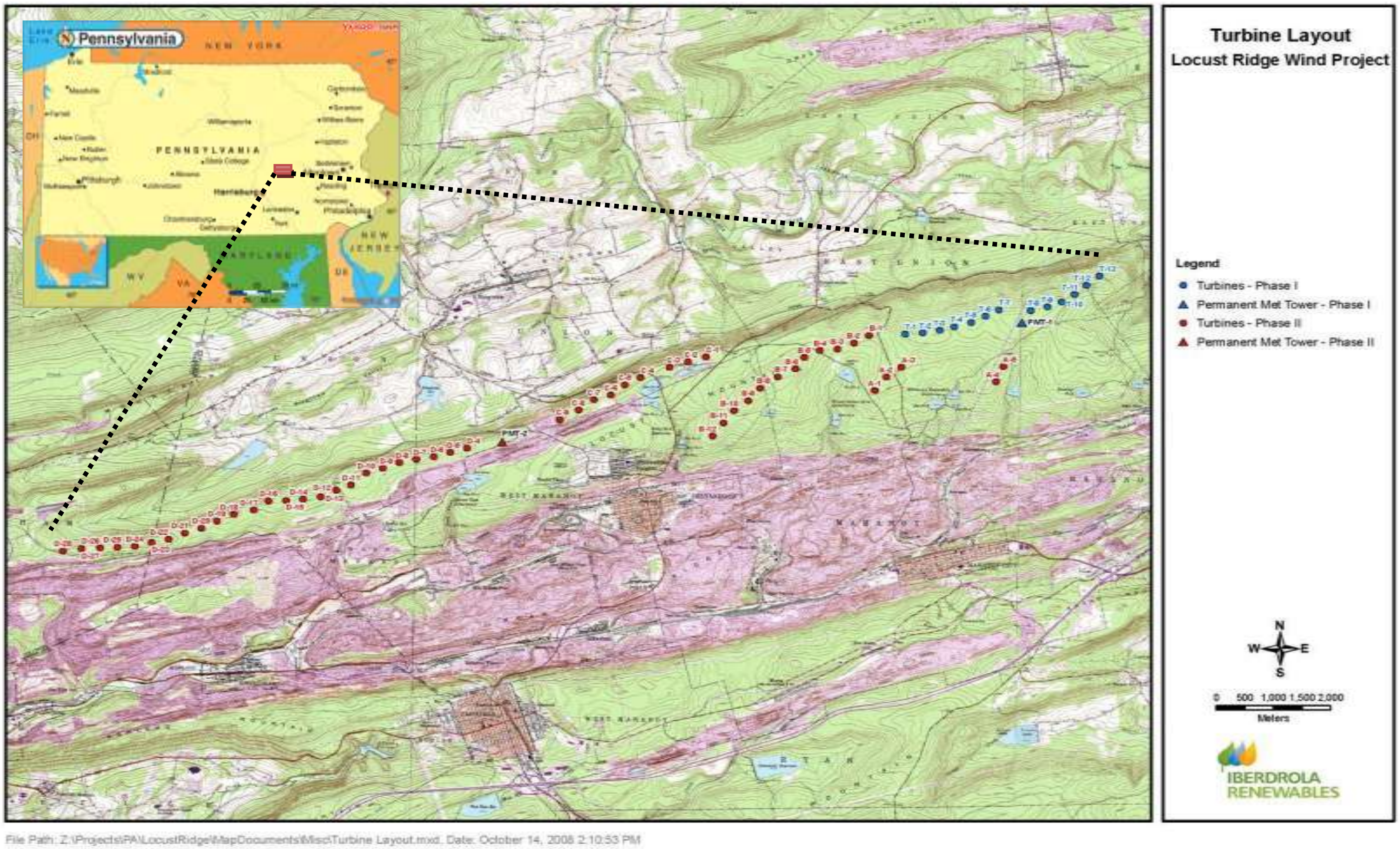
Studies in Scotland suggest that bat activity may be deterred by electromagnetic signals from small, portable radar units. Nicholls and Racey (2009) reported that bat activity and foraging effort per unit time were significantly reduced during experimental trials when their radar antenna was fixed to produce a unidirectional signal that maximized exposure of foraging bats to their radar beam. The effectiveness of radar as a potential deterrent has not been tested at an operating wind facility to determine if bat fatalities could be significantly reduced by these means. Moreover, the effective range of electromagnetic signals as well as the number of radar units needed to affect the most airspace near individual turbines would need to be determined to fully evaluate effectiveness and to allow some cost-benefit analysis relative to other potential deterrents or curtailment (Baerwald et al. 2009, Arnett et al. 2011).

Echolocating bats produce high frequency vocal signals and perceive their surroundings by listening to the features of the echoes reflecting from targets in the path of the sound beam (Griffin 1958). Thus, bats that use echolocation depend heavily on auditory function for orientation, prey capture, communication, and obstacle avoidance. Bats of some species avoid certain territorial social calls emitted by conspecifics (e.g., Barlow and Jones 1997) and are deterred by ―clicks" emitted by noxious moths (e.g., Hristov and Conner 2005). Because echolocating bats depend upon sensitive ultrasonic hearing, broadcasting ultrasound from wind turbines may disrupt or ―jam" their perception of echoes and serve as a deterrent (Spanjer 2006, Szewczak and Arnett 2006). Such masking of echo perception, or simply broadcasting high intensity sounds at a frequency range to which bats are most sensitive, could create an uncomfortable or disorienting airspace that bats may prefer to avoid.

Few studies have investigated the influence of ultrasound broadcast on bat behavior and activity, particularly in the field. Griffin et al. (1963) showed that broadband random ultrasonic noise could mask bat echolocation somewhat but not completely. Mackey and Barclay (1989) concluded that ultrasound broadcasts reduced bat activity and attributed the reduction to greater difficulty in the bats hearing the echoes of insects and thus reduced feeding efficiency. Spanjer (2006) tested the response of big brown bats (*Eptesicus fuscus*) to a prototype eight speaker deterrent device emitting broadband white noise at frequencies ranging from 12.5–112.5 kHz in the laboratory and found that during non-feeding trials, bats landed in a quadrant containing the device significantly less when it was broadcasting broadband noise. Spanjer (2006) also reported that during feeding trials, bats never successfully captured a tethered mealworm when the device broadcasted sound but captured mealworms near the device in about 1/3 of trials when it was silent. Szewczak and Arnett (2006, 2007) tested the same acoustic deterrent in the field and found that when placed by the edge of a small pond, where nightly bat activity was consistent, nightly activity decreased significantly on nights when the deterrent was activated. Horn et al. (2007) tested the effectiveness of a larger, more powerful version of this deterrent device in reducing nightly bat activity and found mixed results; in one experiment bat activity was significantly reduced with deterrents while the other showed no difference in activity levels between treated and untreated turbines.

The goals of this study were to improve the deterrent devices previously tested to maximize capability to broadcast ultrasonic emissions from the nacelle of wind turbines and to test their effectiveness on reducing bat fatalities. The objectives of this study were 1) to conduct carcass searches and field bias trials (searcher efficiency and carcass removal; following Arnett et al. 2009, 2010) to determine rate of bat fatality at turbines; and 2) compare bat fatality rates at turbines treated with the deterrent to untreated turbines.

Figure 1. Location of the Locust Ridge Wind Farm Project and its 64 turbines in Columbia and Schuylkill Counties, east-central Pennsylvania.



STUDY AREA

The Locust Ridge Wind Project is located near the towns of Shenandoah, Mahanoy City, and Brandonville in Columbia and Schuylkill Counties, Pennsylvania (Figure 1) and consists of two facilities. The Locust Ridge I (LRI) Wind Farm has 13 Gamesa G87 2.0 MW turbines, each on 80 m monopoles with a rotor diameter of 87 m and a swept area of 5,945 m^2. There were 51 Gamesa G83 2.0 MW turbines, each on 80 m monopoles with a rotor diameter of 83 m and a swept area of rotor-swept area of 5,411 m^2, at the Locust Ridge II (LRII) Wind Farm. LRII comprised four strings of turbines, including A (n = 5), B (n = 12), C (n = 9), and D (n = 25; Figure 1) strings. The facilities lie within the Appalachian mixed mesophytic forests ecoregion and the moist broadleaf forests that cover the plateaus and rolling hills west of the Appalachian Mountains (Brown and Brown 1972, Strausbaugh and Core 1978). All strings are located on a moderately deciduous forest ridge with evergreen species interspersed. The vegetation surrounding the facility consists of dense thickets of scrub oak (*Quercus berberidifolia*) interspersed with chestnut oak (*Quercus prinus*) and gray birch (*Betula populifolia*) and mature hardwood forests of red oak (*Quercus rubra*), red maple (*Acer rubrum*), yellow birch (*Betula alleghaniensis*), American beech (*Fagus grandifolia*) and scrub oak, with witch-hazel (*Hamamelis virginiana*) and sassafras (*Sassafras albidum*).

METHODS

Turbine Selection and Deterrent Installation

We randomly selected 15 of the 51 turbines located at LR II to be searched as part of a separate study to determine post-construction fatality rates and to meet permitting requirements of the Pennsylvania Game Commission’s (PGC) voluntary agreement for wind energy (PGC 2007). These 15 turbines formed our reference (herein referred to as "control") turbines for comparing with Deterrent turbines. In 2009, unforeseen mechanical and safety issues arose at the LRII site and most of these turbines had to be excluded from our potential treatment group due to potential safety hazards. Thus, we included the 13 turbines at LRI as well as the remaining available turbines at LRII (n = 36 remaining available turbines) when randomly selecting our 10 turbines to be fitted with deterrent devices; 3 turbines were randomly selected from the 13 available at the LRI site and 7 of 36 available at LRII. We did not assess whether there were any potential inherent differences between the two types of turbines, and assumed that there were no confounding differences in our findings.

The deterrent devices used in this study consisted of a waterproof box (~45 x 45 cm, ~0.9 kg) that housed 16 transducers (Figure 2) that emitted continuous broadband ultrasound from 20 to 100 kHz (manufactured by Deaton Engineering, Georgetown, Texas; see Appendix 1 for select specifications). The transducers in these units had an optimum transmission level at their resonant frequency of 50 kHz transmission and reduced transmit levels at higher and lower frequencies over a broadband range of 20–100kHz (see Appendix 1). This frequency range overlaps with the dominant frequency range of all bats known in the study area. Three factors influence the predicted effective transmitted power at a given distance: the original transmitted power (sound pressure level; SPL), attenuation with distance due to the wave front spreading

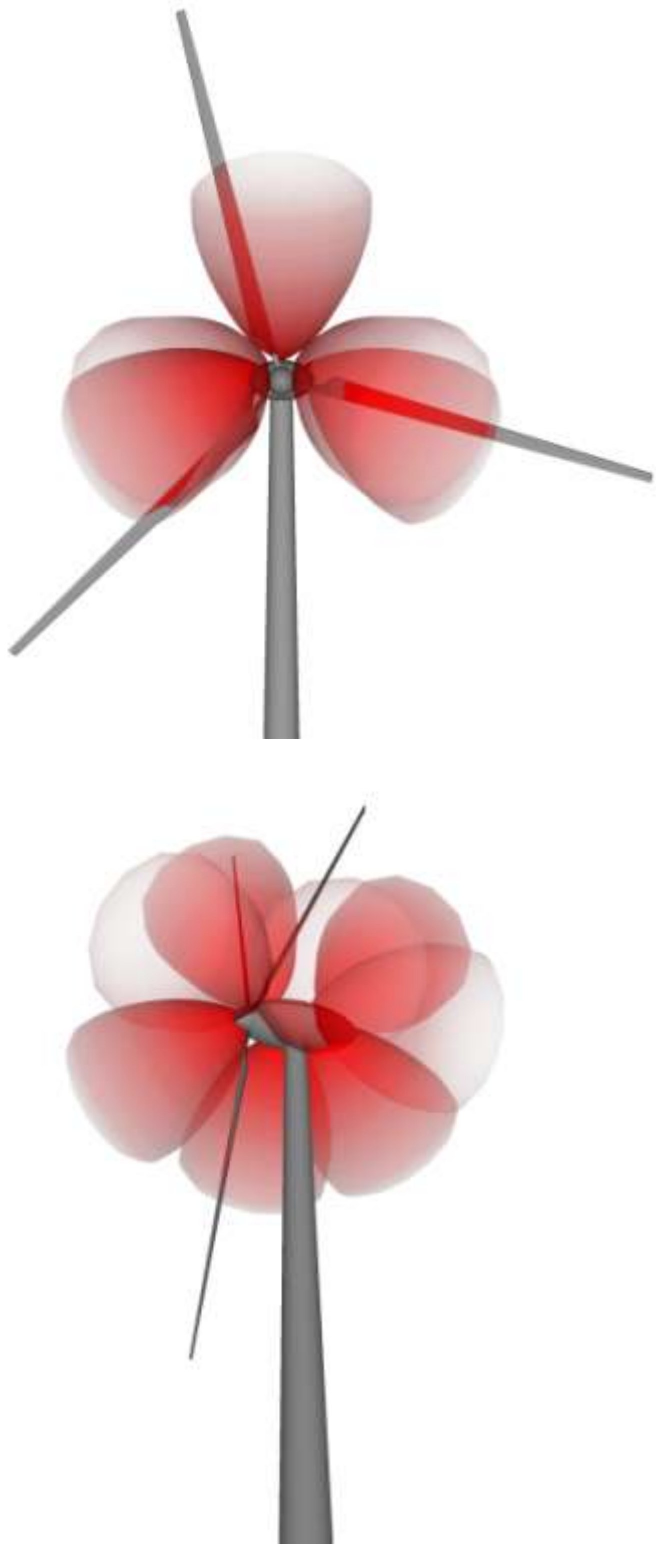
Figure 2. Photos depicting the acoustic deterrent device, its installation, and approximate location on turbines at the Locust Ridge I and II Wind Farms in Pennsylvania.

A deterrent device used in this study (E. Arnett, Bat Conservation International).

Attaching devices to a safety rail on the top of the turbine nacelle (M. Baker, Bat Conservation International).

A wind turbine with six deterrent devices shown (3 mounted on each side of the nacelle; M. Baker, Bat Conservation International).

Figure 3. Depiction of acoustic deterrent placement on the nacelle of turbines and ultrasonic broadcast volume from devices (broadcast volume approximation of data from Senscorp beam pattern data).



(inversely proportional to the square of the distance, frequency independent), and the attenuation (absorption) in air of the sound wave (dependent on frequency, humidity and distance; see Appendix 1 for select specifications and estimated range of transmission under three different levels of humidity and assuming constant temperature and air pressure).

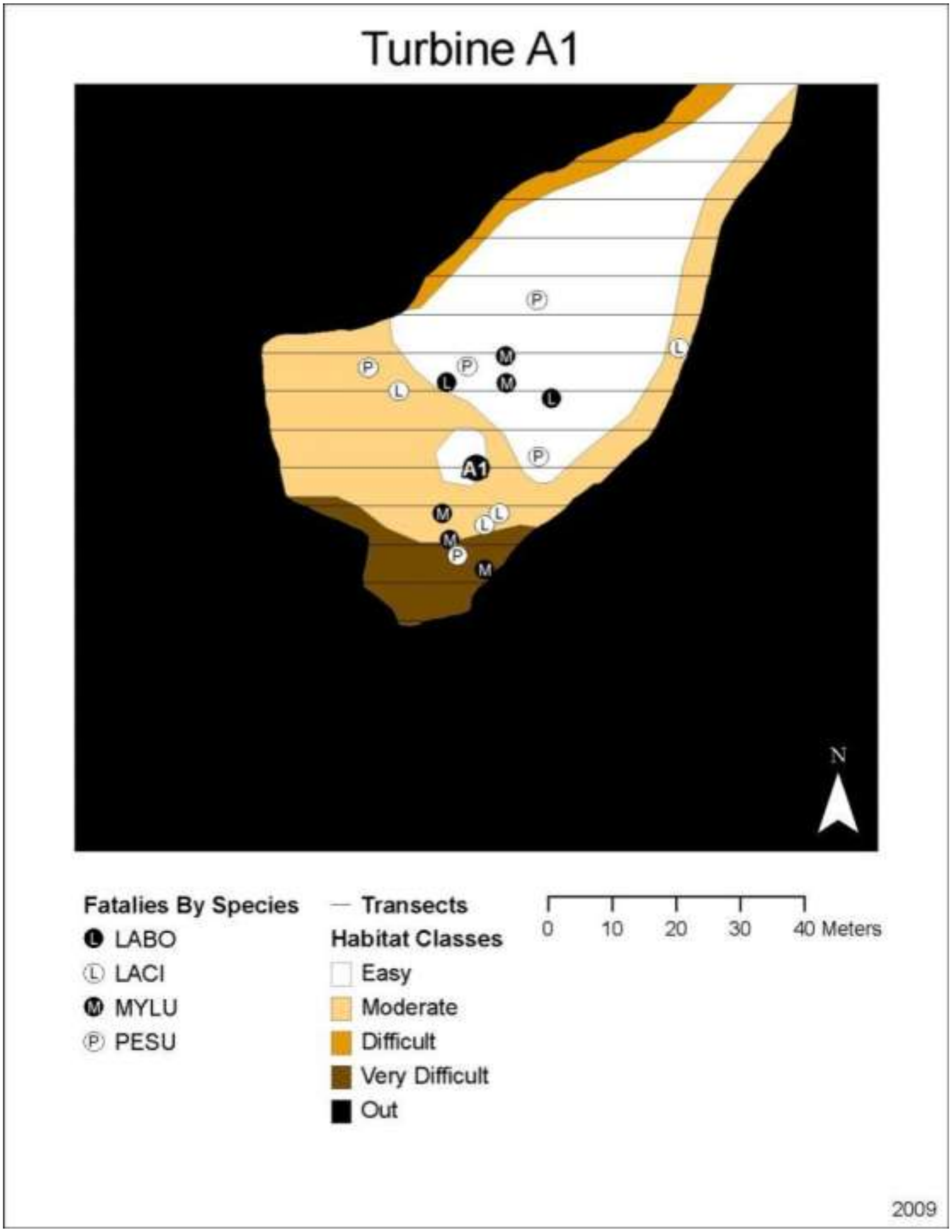
We used the following estimation to base the target signal level of the experimental deterrent: A typical bat emits calls at about 110 dB sound pressure level (SPL) at 10 cm (Surlykke and Kalko 2008). During search phase flight a typical North American species of bat emits about 12 calls per second, each about 5 milliseconds in duration (Fenton 2003, Parsons and Szewczak 2009). Given the speed of sound at 340 m/sec and duration of an open air call, the bat's own call will theoretically mask echoes returning from objects within about 1.5 m (i.e., the bat cannot hear early return echoes while vocalizing). An echo from a target about 1.5 m away will return about 45 dB less than the original 110 dB signal, or at about 65 dB. The bat's next call would mask echoes returning from about 25 m away. By this first order estimation, a bat would theoretically perceive information from returning echoes with amplitudes of ≤65 dB over a range from about 1.5–25 m. Thus, we estimated that a broadband signal of ≥65 dB would begin jamming or masking most bat's echo perception from targets beyond about a 1.5 m range.

We attached 8 individual deterrent devices to the nacelle of each of 10 sample turbines. Three devices on each side of the nacelle were pointed downward with one aimed into the rotor-swept area, one parallel with the monopole, and one aimed toward the back of the nacelle (Figures 2 and 3). Additionally, two devices were aimed at reflector plates; one that projected emissions into the upper part of the rotor-swept area, and one toward the rear of the nacelle (Figures 2 and 3). All devices connected to control boxes that were powered from outlets located in the nacelle and each was set on a timer to operate from ½ hour before sunset to ½ hour after sunrise each night of the study.

Delineation of Carcass Search Plots and Habitat Mapping

We delineated a rectangular plot 126 m north-south by 120 m east-west (60 m radius from the turbine mast in any direction; 15,120 m^2 total area) centered on each turbine sampled; this area represents the maximum possible search area for this study [see Figure 4 for an example]. Transects were set 6 m apart within each plot and in an east-west direction, due to the topography and layout of turbines at this facility (Figure 4). However, dense vegetation and the area cleared of forest at this facility was highly varied and, thus, we eliminated unsearchable habitat (e.g., forest) and usually did not search the entire possible maximum area. We used a Trimble global positioning system (GPS) to map the actual area searched at each turbine (see Figure 4 for an example). The density-weighted area searched was used to standardize results and adjust fatality estimates (see methods). The habitat visibility classes within each plot were also mapped using a GPS unit. We recorded the percent ground cover, height of ground cover (low [<10 cm], medium [11–50 cm], high [>50 cm]), type of habitat (vegetation, brush pile, boulder, etc), and the presence of extreme slope and collapsed these habitat characteristics into visibility classes that reflect their combined influence on carcass detectability (following PGC 2007; see Appendix 2).

Figure 4. Sample search plot at a wind turbine depicting the maximum plot size of 126 m north-south and 120 m east-west, transect lines (searched 3 m on each side), unsearchable area (black), and area encompassed by easy (white), moderate (light tan), difficult (dark tan), and very difficult (brown) visibility habitat.



Fatality Searches

We conducted daily searches at 15 control turbines (A1, A3, A5, B1, B4, B7, B9, B12, C3, C5, C7, C9, D4, D12, D25) and 10 Deterrent turbines (T1, T5, T10, A2, B3, B6, B11, C1, C6, D21) from 15 August to 10 October 2009 and 1 May to 26 July and 31 July to 9 October 2010. Each searcher completed 5–7 turbine plots each day during the study. Searchers walked at a rate of approximately 10–20 m/min. along each transect searching out to 3 m on each side for fatalities. Searches were abandoned only if severe or otherwise unsafe weather (e.g., heavy rain, lightning) conditions were present and searches were resumed that day if weather conditions permitted. Searches commenced at sunrise and all turbines were searched within 8 hr after sunrise.

We recorded date, start time, end time, observer, and weather data for each search at turbines. When a dead bat or bird was found, the searcher placed a flag near the carcass and continued the search. After searching the entire plot, the searcher returned to each carcass and recorded information on date, time found, species, sex and age (where possible), observer name, identification number of carcass, turbine number, perpendicular distance from the transect line to the carcass, distance from turbine, azimuth from turbine, habitat surrounding carcass, condition of carcass (entire, partial, scavenged), and estimated time of death (e.g., ≤1 day, 2 days, etc.). A field crew leader confirmed all species identifications at the end of each day. Disposable nitrile gloves were used to handle all carcasses to reduce possible human scent bias for carcasses later used in scavenger removal trials. Each carcass was placed into a separate plastic bag and labeled. Fresh carcasses, those determined to have been killed the night immediately before a search, were redistributed at random points on the same day for searcher efficiency and scavenging trials. Following PGC's protocol, all downed bats were euthanized, even if no physical injury was observed due to the possibility of barotraumas, following acceptable methods suggested by the American Society for Mammalogists (Gannon et al. 2007); because sedation or anesthesia was not used in our study, we employed cervical dislocation.

Field Bias Trials

Searcher efficiency and removal of carcasses by scavengers was quantified to adjust estimates of total bat and bird fatalities for detection bias. We conducted bias trials throughout the entire study period and searchers were never aware which turbines were used or the number of carcasses placed beneath those turbines during trials. Prior to the study's inception, we generated a list of random turbine numbers and random azimuths and distances (m) from turbines for placement of each bat used in bias trials.

We used only fresh killed bats for searcher efficiency and carcass removal trials during the study. At the end of each day's search, a field crew leader gathered all carcasses from searchers and then redistributed fresh bats at predetermined random points within any given turbine plot's searchable area. Data recorded for each trial carcass prior to placement included date of placement, species, turbine number, distance and direction from turbine, and visibility class surrounding the carcass. We attempted to distribute trial bats equally among the different visibility classes throughout the study period and succeeded in distributing roughly one-third of all trial bats in each visibility class (easy, moderate, and difficult [difficult and very difficult were combined]). We attempted to avoid ―over-seeding" any one turbine with carcasses by placing no more than 4 carcasses at any one time at a given turbine. Because we used fresh bats for searcher efficiency trials and carcass removal trials simultaneously, we did not mark bats with tape or some other previously used methods (e.g., Kerns et al. 2005) that could impart human or other scents on trial bat carcasses. Rather, we used trial bat placement details (i.e. azimuth, distance, sex, species) and signatures from hair and tissue samples (i.e. hair removed between the scapulae and wing punches) to distinguish them from other fatalities landing nearby. Each trial bat was left in place and checked daily by the field crew leader or a searcher not involved with the bias trials at turbines where carcasses were placed. Thus, trial bats were available to be found by searchers on consecutive days during daily searches unless removed by a scavenger. We recorded the day that each bat was found by a searcher, at which time the carcass remained in the scavenger removal trial. If, however, a scavenger removed a carcass before detection it was removed from the searcher efficiency trial and used only in the removal data set. When a bat carcass was found, the searcher determined if a bias trial carcass had been found by looking for markings described above and contacting the crew leader to determine if the location (direction and distance) matched any possible trial bats. All trial bats were left in place for the carcass removal trial. Carcasses were left in place until removed by a scavenger or they decayed and disintegrated to a point beyond recognition. Carcass condition was recorded daily up to 20 days, as present and observable (1) or missing or no longer observable (0).

Statistical Methods

Carcass persistence/removal. Estimates of the probability that a bat carcass was not removed in the interval between searches were used to adjust carcass counts for removal bias. Removal included scavenging, wind or water, or decomposition beyond recognition. In most fatality monitoring efforts, it is assumed that carcass removal occurs at a constant rate that is not dependent on the time since death; this simplifying assumption allows us to estimate fatality when search intervals exceed one day. The length of time a carcass remains on the study area before it is removed is typically modeled as an exponentially distributed random variable. The probability that a carcass is not removed during an interval of length I can be approximated as the average probability of persisting given its death might have occurred at any time during the interval:

$$\hat{r}_{jk} = \hat{\bar{t}}_{jk} * (1 - \exp(-I_{ij} / \hat{\bar{t}}_{jk})) / I_{ij}$$

$\hat{r}_{jk}$ is the estimated probability that a carcass in the k^{th} visibility class that died during the interval preceding the j^{th} search will not be removed by scavengers;

$\hat{\bar{t}}_{jk}$ is the estimated average persistence time of a carcass in the k^{th} visibility class that died during the interval preceding the j^{th} search;

I_{ij} is the length of the effective interval preceding the j^{th} search at the i^{th} turbine;

NOTE: k^{th} visibility class can be expanded to any combination of factors that have been modeled as affecting a carcass's persistence time or probability of detection (e.g. size, season, etc.).

Data from 351 and 408 bat carcasses in 2009 and 2010, respectively, were used in our analysis, with carcass persistence time modeled as a function of visibility class. We fit carcass persistence/removal data for bats to an interval-censored parametric failure time model, with carcass persistence time modeled as a function of size and/or visibility class. We used a relatively liberal alpha of 0.15 to identify factors (e.g., carcass size, visibility classes) that influence bias parameter values (i.e., searcher efficiency and carcass persistence) for removal of bat carcasses.

Searcher efficiency. Estimates of the probability that an observer will visually detect a carcass during a search were used to adjust carcass counts for observer bias. Failure of an observer to detect a carcass on the search plot may be due to its size, color, or time since death, as well as conditions in its immediate vicinity (e.g., vegetation density, shade). In most fatality monitoring efforts, because we cannot measure time since death, it is assumed that a carcass' observability is constant over the period of study, which it likely is not. In this study, searches were conducted daily and carcass persistence times were long, providing an opportunity for a searcher to detect a carcass that was missed on a previous search. The estimator proposed by Huso (2010) and applied in this study assumes that a carcass missed on a previous search will not be observed on a subsequent search, i.e. there are inherent environmental conditions that make the carcass unobservable like heavy foliage, terrain, etc. If this assumption is not met, it can lead to overestimates of fatality. Other estimators assume that a carcass missed on a previous search has the same probability of being observed as it had on the first search, i.e. there is nothing inherent in the environment surrounding the carcass that makes it unobservable, missing it is purely a chance event and that if the carcass is not removed by predators and enough searches are conducted, it will eventually be observed. If this assumption is not met, it can lead to underestimates of fatality. It is likely that neither assumption is appropriate in all cases.

Searcher efficiency trial carcasses were placed on search plots and monitored for 20 days. The day on which a bat carcass was either observed or removed by a scavenger was noted. In these trial data, if a carcass had not been found within the first 8 searches it had essentially no chance of being found. This lends empirical support to the idea that there are some environmental conditions surrounding the carcass that determine its probability of being found. However, several carcasses missed on the first search were found on subsequent searches, lending support to the idea that at least for some carcasses, the probability of missing them is purely a chance event. To allow for some possibility of observing a carcass once having missed it, the set of trial carcasses comprised those found or still observable but not found within the first 8 searches. After accounting for carcasses removed before a searcher had the chance of observing them, we fit data from 139 (2009) and 169 (2010) bat carcasses to a logistic regression model, with odds of observing a carcass given that it persisted, modeled as a function of visibility class. Again, we used a relatively liberal alpha of 0.15 to determine if a significant effect among visibility classes existed. Because we found no bats in the Very Difficult visibility class, SE was not modeled for this class.

Density of carcasses and proportion of area surveyed. Density of carcasses is known to diminish with increasing distance from the turbine (e.g., Kerns et al. 2005), so a simple adjustment to fatality based on area surveyed would likely lead to overestimates, because unsearched areas tend to be farthest from turbines where carcass density is lowest. The calculated function (see below) relating density to distance from a turbine was used to weight each square meter in the plot. The density-weighted fraction of each plot that was actually searched was used as an area adjustment to per-turbine fatality estimates rather than using a simple proportion.

The density of bat carcasses (number of carcasses/m^2) was modeled as a function of distance (m) from the turbine. Because searcher efficiency and visibility class are confounded with distance, only fresh bat carcasses found in Easy visibility class were used for this analysis and all non-incidental data from all searched turbines were used, yielding a total of 172 fresh bat carcasses. We assumed that the carcass persistence time and searcher efficiency would be equal for all carcasses within this class and would not change as a function of distance from the turbine. We also assumed that no bat carcasses killed by turbine blades would fall > 200 m from the turbine. Carcasses were –binned" into 2 m rings (Figure 5) extending from the turbine edge out to the theoretical maximum plot distance. We determined the total area among all search plots that was in the Easy visibility class (m^2) in each ring and calculated carcass density (number of carcasses/m^2) in each ring. Density was modeled as a conditional cubic polynomial function of distance (dist):

If distance $\leq$ 50m, then density = exp (-1.77328 + 0.0346454*dist -0.00271076* $dist^2$ + 0.0000229885* $dist^3$) - 0.01, else density = 0.009363847*exp (-0.05*(distance-50))

Relative density was derived by dividing the predicted density of each m^2 unit by the total predicted density within 200 m of a turbine, providing a density-weight for each m^2 unit. The density weighted area (DWA) of a plot was calculated as the sum of the density weights for all m^2 units within the searchable area. If no portion of a designated plot was unsearchable, the density weight for the plot would be 1.

The physical area surveyed within a plot differed among turbines and ranged from 20–47% of the delineated theoretical maximum search plot, with an average of 31% whereas the weighted density area of plots averaged 62% (range: 44–78%). In addition, using this density weight, we estimated 7.2% of the carcasses killed at a turbine would be found beyond the boundaries of the designated search plot.

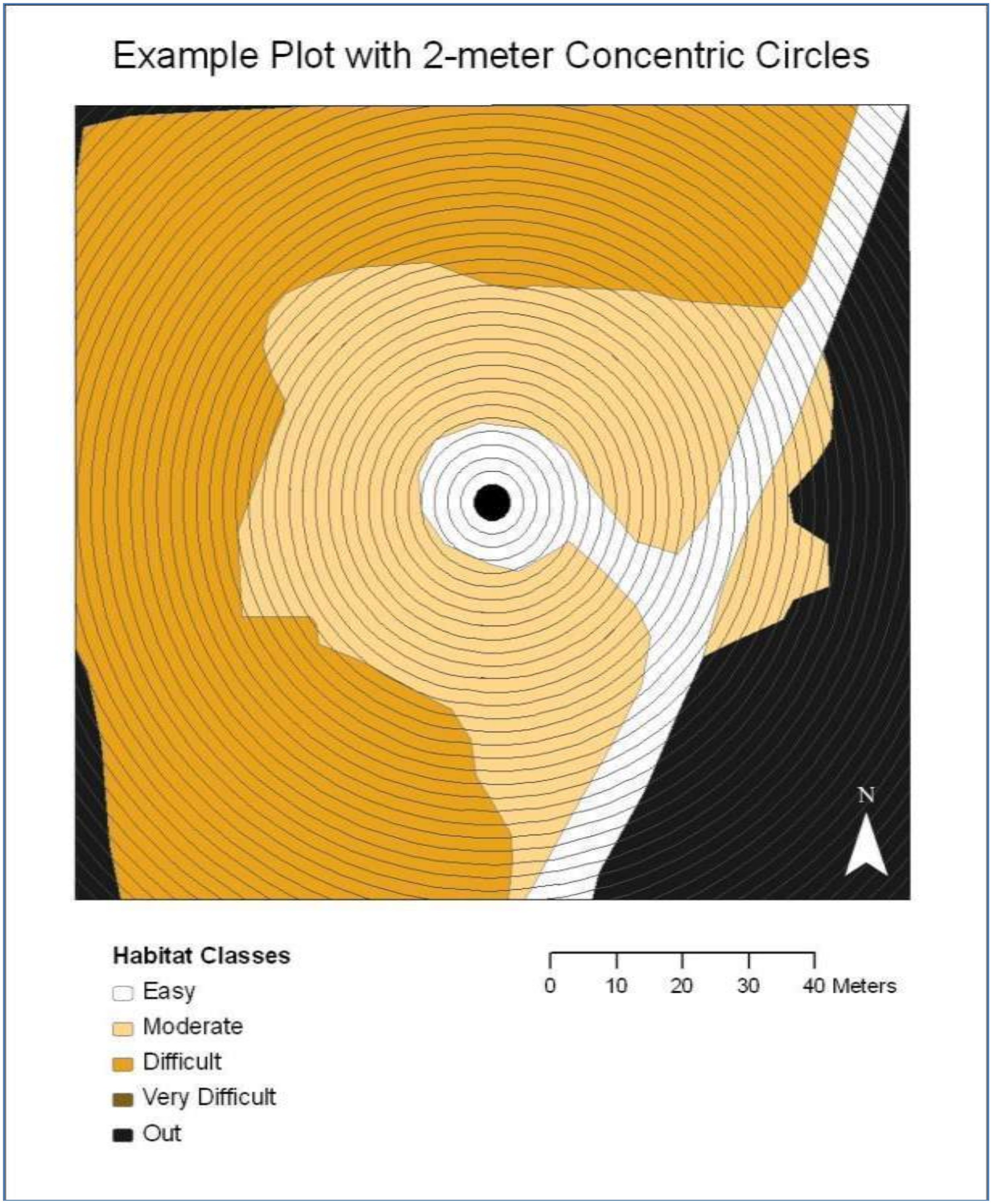
Fatality estimates. We adjusted the number of bat fatalities found by searchers by estimates of searcher efficiency and by the proportion of carcasses expected to persist unscavenged during each interval using the following equation:

$$\hat{f}_{ijk} = \frac{c_{ijk}}{\hat{a}_i * \hat{p}_{jk} * \hat{r}_{jk} * \hat{e}_{jk}}$$

where:

$\hat{f}_{ijk}$ is the estimated fatality in the k^{th} visibility class that occurred at the i^{th} turbine during the j^{th} search;

Figure 5. Hypothetical carcass search plot for a wind turbine illustrating 2 m rings extending from the turbine edge out to the theoretical maximum plot distance and a depiction of ―easy" searchable area (shaded area within line drawing) in the plot, used to develop weights for adjusting fatalities.



c_{ijk} is the observed number of carcasses in the k^{th} visibility class at the i^{th} turbine during the j^{th} search;

$\hat{a}_i$ is the density-weighted proportion of the area of the i^{th} turbine that was searched;

$\hat{p}_{jk}$ is the estimated probability that a carcass in the k^{th} visibility class that is on the ground during the j^{th} search will actually be seen by the observer;

$\hat{r}_j$ is the probability than an individual bird or bat that died during the interval preceding the j^{th} search will not be removed by scavengers; and

$\hat{e}_{jk}$ is the effective interval adjustment (i.e., the ratio of the length of time before 99% of carcasses can be expected to be removed to the search interval) associated with a carcass in the k^{th} visibility class that died during the interval preceding the j^{th} search.

The value for $\hat{p}_{jk}$ was estimated through searcher efficiency trials with estimates given above; $\hat{r}_j$ is a function of the average carcass persistence rate and the length of the interval preceding the j^{th} search; and $\hat{r}_j$, $\hat{e}_j$ and $\hat{p}_{jk}$ are assumed not to differ among turbines, but differ with search interval (*j*) and visibility class (*k*).

The estimated annual per turbine fatality for bats and birds was calculated using a newly derived estimator (Huso 2010; herein referred to as the MH estimator). The equation for the MH estimator for this study is:

$$\hat{f} = \frac{\sum_{i=1}^{10}\sum_{j=1}^{n_i}\sum_{k=1}^{3}\hat{f}_{ijk}}{10}$$

where n_i is the number of searches carried out at turbine *i*, 1= 1, …, 10, and $\hat{f}_{ijk}$ is defined above. The per turbine estimate and confidence limits were multiplied by 64, the total number of turbines, and divided by 0.9279 to adjust for actual density-weighted area searched to give total annual fatality estimates (Cochran 1977). This estimate assumes that no fatalities occurred during the winter, i.e. prior to April and after November. No closed form solution is yet available for the variance of this estimator, so 95% confidence intervals of this estimate were calculated by bootstrapping (Manly 1997). Searcher efficiency was estimated from a bootstrap sample (with replacement) of searcher efficiency data, carcass persistence estimated from a bootstrap sample of carcass persistence data, and these values were applied to the carcass data from a bootstrap sample of turbines to estimate average fatality per turbine. This process was repeated 1000 times. The 2.5^{th} and 97.5^{th} quantiles from the 1,000 bootstrapped estimates formed the 95% confidence limits of the estimated fatality.

Comparison between treatment and control turbines. In 2009, we compared average fatality at control with Deterrent turbines for all bats and for each species using one-way analysis of variance with each turbine as the experimental unit and $\log_e$ transformed estimated total fatalities as the response. In 2010, estimated average bat fatality per turbine at control and Deterrent turbines, during the treatment phase and the period immediately preceding it (pre-treatment phase) was analyzed in a Before-After, Control-Impact design (BACI; Hurlbert 1984, Hewitt et al. 2001) using ANOVA repeated measures with the turbine as the experimental unit, repeatedly measured twice. In both years, the fatality data were log transformed to satisfy assumptions of normality and homogeneity of variance (Steele et al. 1997).

RESULTS

In 2009, we searched 15 control turbines and 10 Deterrent turbines each day between 15 August and 10 October. We found 194 carcasses (135 at control, 59 at Deterrent) of 6 species (Table 2). Two carcasses were not identifiable to species. During the pre-treatment period between 1 May and 26 July 2010, we searched 15 control turbines daily for all but 2 days (16 May and 2 June) and 10 Deterrent turbines daily for all but 4 days (9, 20, 24 25 July 2010) due to heavy rain, or facility maintenance. During the treatment period between 1 August and 15 October, we searched 15 control turbines daily for all but 4 days (26 August; 22, 29, 30 September 2010) and 10 Deterrent turbines daily for all but 3 days (19 August; 9, 30 September 2010) due to heavy rain or facility maintenance. During the pre-treatment period from 1 May to 26 July 2010, we found 59 carcasses comprising 6 species of bats (37 at control, 22 at Deterrent). During the treatment period, we found 223 carcasses comprising 6 species of bats (162 at control, 61 at Deterrent; Table 3). Fatalities were found at all 25 turbines searched and time required to search each plot ranged from 12–100 minutes in both years of the study.

Fatality Estimates in 2009

A total of 278 trial carcasses were used to estimate searcher efficiency in this study. One hundred thirty-nine of the 145 (96%) carcasses in the Easy class that persisted >7 days were found by searchers, while 105 of the 123 (85%) carcasses in the Moderate class that persisted long enough to be observed were found. Eight of 10 (80%) carcasses in the Difficult class were found. A logistic regression model of the odds of detection given persistence as a function of visibility classes was fit to the data and there was strong evidence of a difference in searcher efficiency among the visibility classes ($\chi^2_2 = 10.32$, $p < 0.006$).

Data from 351 scavenger removal trial carcasses were fit to an interval-censored parametric failure time model. Average carcass persistence time was found to be strongly related to visibility classes ($\chi^2_2 = 6.58$, $p = 0.037$). Average persistence time was estimated to be 9.4 days (95% CI: 7.7, 11.7 days), 13.9 days (95% CI: 10.8, 18.3 days) and 8.7 days (95% CI: Deterrent 4.6, 16.1 days) in Easy, Moderate and Difficult visibility classes respectively. Estimates of the probability of a bat carcass persisting for 1 day (r) were 0.948 (95% CI: 0.938, 0.958), 0.964 (95% CI: 0.955, 0.973) and 0.942 (95% CI: 0.900, 0.970), respectively.

The average per-turbine fatality rate at Deterrent turbines was significantly less than at control turbines ($F_{1,23} = 14.7$, $p = 0.0009$). We estimated an average of 11.6 bats (95% CI: 9.4, 14.1) were killed per turbine at Deterrent turbines during this period, compared to 18.4 bats (95%

Table 2. Number of bats by species and age/sex class found under turbines at the Locust Ridge Wind Project, Columbia and Schuylkill Counties, Pennsylvania, 1 April–15 November 2009.

2009

	Adult male	Adult female	Juvenile male	Juvenile female	Unknown	Total
Control						
Big brown	3	-	2	3	2	**10**
Eastern red	6	2	1	-	4	**13**
Hoary	11	8	2	3	6	**30**
Little brown	12	2	6	2	2	**24**
Silver-haired	12	8	3	2	1	**26**
Tri-colored	12	2	8	5	4	**31**
Unknown	-	-	-	-	1	**1**
Sub-total	*56*	*22*	*22*	*15*	*20*	***135***
Deterrent						
Big brown	1	-	2	-	1	**4**
Eastern red	2	3	1	2	1	**9**
Hoary	6	1	-	1	2	**10**
Little brown	9	2	1	-	1	**13**
Silver-haired	1	1	-	1	5	**8**
Tri-colored	3	2	2	4	2	**13**
Unknown	-	-	-	-	2	**2**
Sub-total	*22*	*9*	*6*	*8*	*14*	***59***
Total	**78**	**31**	**28**	**23**	**34**	**194**

Table 3. Number of bats by species and age/sex class found under turbines at the Locust Ridge Wind Project, Columbia and Schuylkill Counties, Pennsylvania, 1 May–26 July (Pre-experiment phase) and 31 July–9 October (experiment phase) 2010.

2010 Pre-treatment period (1 May–26 July)

	Adult male	**Adult female**	**Juvenile male**	**Juvenile female**	**Unknown**	**Total**
Control						
Big brown	5	1	-	-	2	**8**
Eastern red	4	7	-	-	-	**11**
Hoary	6	4	-	-	1	**11**
Little brown	1	2	-	-	-	**3**
Silver-haired	1	1	-	-	-	**2**
Tri-colored	2	-	-	-	-	**2**
Unknown	-	-	-	-	-	**-**
Sub-total	*19*	*15*	-	-	*3*	***37***
Deterrent						
Big brown	5	1	-	-	-	**6**
Eastern red	6	1	-	-	-	**7**
Hoary	4	1	-	1	1	**7**
Little brown	-	-	-	-	-	**-**
Silver-haired	-	-	-	-	-	**-**
Tri-colored	2	-	-	-	-	**2**
Unknown	-	-	-	-	-	**-**
Sub-total	*17*	*3*	-	*1*	*1*	***22***
Total	**36**	**18**	**0**	**1**	**4**	**59**

Table 3. - Continued.

2010 Treatment period (31 July–9 August)

	Adult male	**Adult female**	**Juvenile male**	**Juvenile female**	**Unknown**	**Total**
Control						
Big brown	2	4	2	1	-	**9**
Eastern red	28	19	-	-	3	**50**
Hoary	32	10	4	4	11	**61**
Little brown	6	-	-	-	-	**6**
Silver-haired	9	10	-	-	1	**20**
Tri-colored	8	2	1	1	4	**16**
Unknown	-	-	-	-	-	**-**
Sub-total	*85*	*45*	*7*	*6*	*19*	***162***
Deterrent						
Big brown	1	-	-	-	-	**1**
Eastern red	9	10	-	-	3	**22**
Hoary	11	6	-	2	3	**22**
Little brown	1	1	-	-	1	**3**
Silver-haired	1	1	1	-	2	**5**
Tri-colored	2	2	1	-	3	**8**
Unknown	-	-	-	-	-	**-**
Sub-total	*25*	*20*	*2*	*2*	*12*	***61***
Total	**110**	**65**	**9**	**8**	**31**	**223**

CI: 16.0, 21.3) killed per turbine at control turbines (Figure 6). We estimated 60% higher fatality (95% CI: 26%, 104%) per control turbine than per Deterrent turbine from 15 August to 10 October 2009, or conversely, 21–51% estimated fewer bats were killed per Deterrent turbine than per PGC turbine during this period.

Table 4 presents estimated bat fatalities (mean and 95% confidence intervals) for each species of bat killed per turbine, adjusted for searcher efficiency, carcass removal, and area, at control and Deterrent turbines in 2009. We estimated twice as many hoary bats ($\bar{x}$ = 2.09, 95% CI = 1.18, 4.04) killed per control turbine than Deterrent turbine, and nearly twice as many silver-haired bats ($\bar{x}$ 1.88, 95% CI = 0.92, 5.14), although the estimated effect was not significant for this species (Table 5). Results for other species were highly variable with no statistically significant difference between turbine groups.

Fatality Estimates in 2010

A total of 169 bat carcasses were used to estimate searcher efficiency in this study. Eighty three of 86 (97%) carcasses in the Easy class that persisted >7 days were found by searchers, while 59 of 70 (84%) carcasses in the Moderate class that persisted long enough to be observed were found. Eight of 13 (62%) carcasses in the Difficult class were found. Because no fatalities were found in the Very Difficult class, we removed the 6 bats placed in this class from our analysis. A logistic regression model of the odds of detection given persistence was fit to the visibility classes and there was strong evidence of a difference in searcher efficiency among the visibility classes (χ^2_2 = 14.59, $p < 0.007$).

Data from 408 scavenger removal trial carcasses were fit to an interval-censored parametric failure time model. Average carcass persistence time was found not to be related to visibility class (χ^2_2 = 0.56, $p = 0.907$), but there was moderate evidence that average persistence time was longer before the treatment period than during the treatment period (χ^2_2 = 4.27, p = 0.12). Average persistence time was estimated to be 7.8 days (95% CI: 6.4, 9.6 days) prior to implementation of the treatments and 6.2 days (95% CI: 5.4, 7.1 days) during the implementation of the treatments. This slight difference in average persistence time had little effect on the probability of a carcass persisting through the search interval. The estimated probability of a bat carcass persisting for 1 day (r) was 0.939 (95% CI: 0.926, 0.950) prior to the treatment period and 0.923 (95% CI: 0.912, 0.933) during the treatment period.

Bat fatality data from the pre-treatment period were used to evaluate if there were inherent difference between control and Deterrent turbines. We used a BACI design to determine whether the ratio of average per-turbine fatality at control turbines (n = 15) to Deterrent turbines (n = 10) during implementation of the deterrents was significantly greater than it was in the period immediately preceding implementation of the treatments. There was marginal evidence that the ratio of control:Deterrent fatalities was greater during the treatment period than in the pre-treatment period ($F_{1,23}$ = 3.9, p = 0.061). During the pre-treatment period, prior to implementation of the deterrents, fatality per control turbine was estimated to be 1.09 times greater than per Deterrent turbine (95% CI: 0.74–1.61). While this was not statistically significant, it represented an initial inherent difference of about 10% in the fatality rate between the two sets.

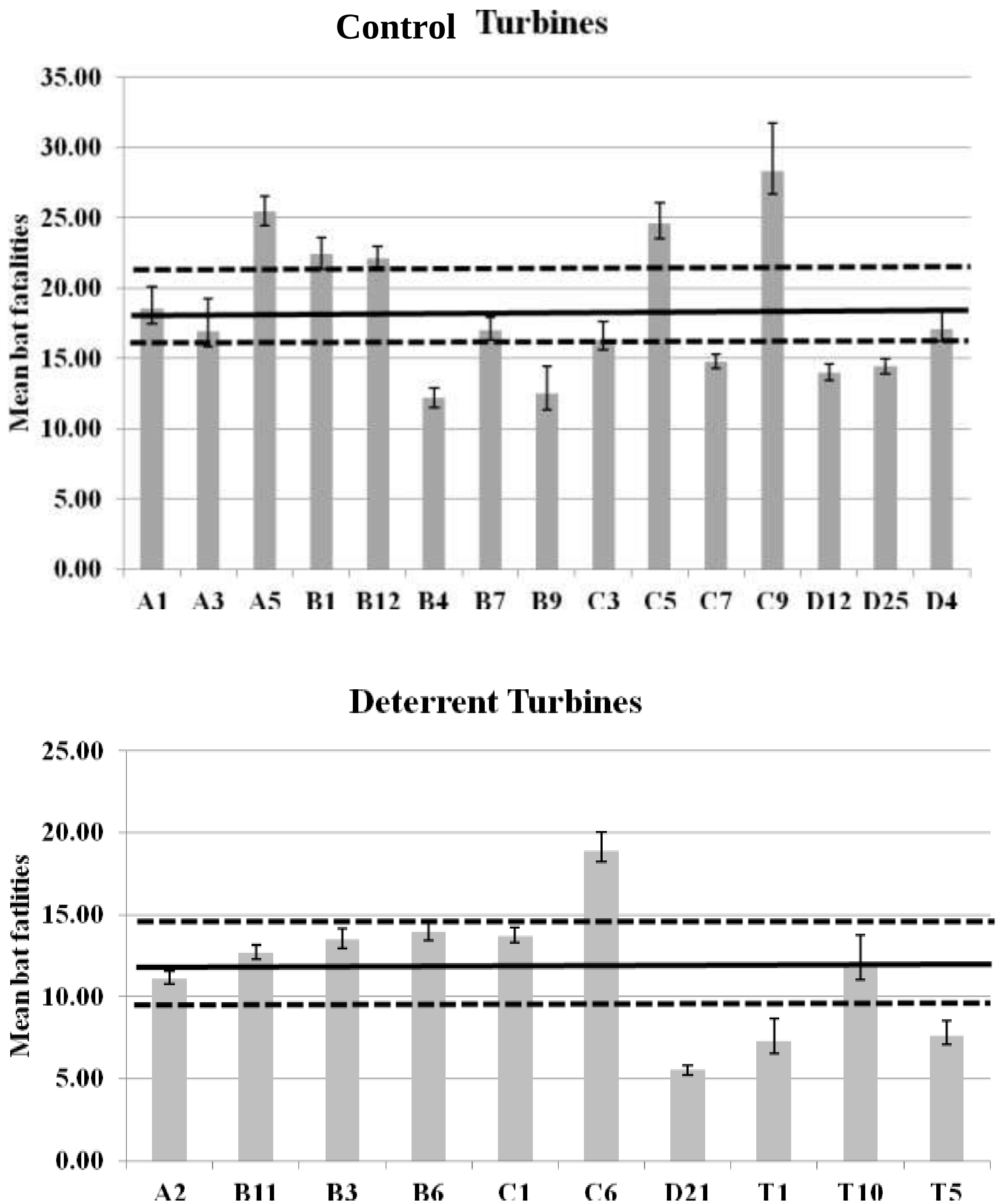
Table 4. Number of each species found (N) and the estimated bat fatalities/turbine (mean and 95% confidence intervals [CI]) for each species of bat per turbine, adjusted for searcher efficiency, carcass removal, and area, at control and Deterrent turbines at the Locust Ridge Wind Project in Columbia and Schuylkill Counties, Pennsylvania, 15 August–10 October 2009.

	Control Turbines				Deterrent Turbines			
Species	**N**	**Mean**	**Lower 95% CI**	**Upper 95% CI**	**N**	**Mean**	**Lower 95% CI**	**Upper 95% CI**
Big brown bat	10	1.34	0.35	2.59	4	0.78	0.20	1.36
Eastern red bat	13	1.81	0.95	2.83	9	1.73	0.73	2.73
Hoary bat	30	4.14	3.13	5.19	10	1.98	1.12	3.22
Little brown bat	24	3.36	2.14	5.05	13	2.66	1.57	3.82
Silver-haired bat	26	3.51	2.08	4.98	9	1.85	0.75	3.27
Tri-colored bat	31	4.15	2.36	6.20	13	2.47	1.29	3.99
Unknown bat	1	0.12	0.10	0.48	1	0.17	0.16	0.51

Table 5. Ratio between bat fatalities per control turbine relative to Deterrent turbines (mean and 95% confidence intervals [CI]) for each species of bat from the Locust Ridge Wind Project in Columbia and Schuylkill Counties, Pennsylvania, 15 August–10 October 2009. Confidence intervals that do not include 1.0 are considered statistically significant (*).

Species	**Mean Ratio Control:Deterrent**	**Lower 95% CI**	**Upper 95% CI**
Big brown bat	1.74	0.41	6.13
Eastern red bat	1.06	0.44	2.75
Hoary bat*	2.09	1.18	4.04
Little brown bat	1.27	0.71	2.36
Silver-haired bat	1.88	0.92	5.14
Tri-colored bat	1.68	0.80	3.58
Unknown bat	0.12	0.00	2.28

Figure 6. Mean estimated bat fatalities/turbine (± 95% confidence intervals) for all species of bat, adjusted for searcher efficiency, carcass removal, and area, for each control and Deterrent turbine in relation to overall mean (solid line; 95% confidence intervals dashed lines) for each group at the Locust Ridge Wind Project in Columbia and Schuylkill Counties, Pennsylvania, 15 August–10 October 2009.



During the treatment period, we estimated an average of 12.8 bats (95% CI: 9.5, 17.2) were killed per turbine at Deterrent turbines compared to 22.9 bats (95% CI: 18.0, 29.3) killed per turbine at control turbines (Figure 7). Bat fatalities per control turbine was estimated to be 1.8 times greater than per Deterrent turbine (95% CI: 1.22–2.64); in other words, 18–62% fewer bats killed per Deterrent turbines relative to control turbines during the treatment. As stated above, however, fatality per control turbine was estimated to be 1.09 times greater than per Deterrent turbine (95% CI: 0.74–1.61) prior to implementation of the treatment. Thus, the ratio of fatality per control turbine relative to Deterrent turbines after implementing the treatment was estimated to be 1.64 times greater than the pre-treatment period ratio (95% CI: 0.98, 2.76). In other words, between 2% more and 64% fewer bats were killed per Deterrent turbine relative to control turbines after accounting for inherent turbine differences prior to treatment implementation.

Estimated bat fatalities (mean and 95% confidence intervals) for each species of bat killed per turbine, adjusted for searcher efficiency, carcass removal, and area, at control and Deterrent turbines in 2010 are presented in Table 6. In 2010, we were able to compare the fatality rates during treatment with what was occurring at the same locations pre-treatment. Prior to implementation of the deterrents, we estimated 1.47 times as many hoary bats (95% CI = 0.39, 3.42) and 1.32 times as many silver-haired bats (95% CI = 0.47, 3.27) killed per control turbine than Deterrent turbine. So although we estimated nearly twice as many hoary bats ($\bar{x}$ = 1.88, 95% CI = 1.19, 2.82) and nearly 4 times as many silver-haired bats ($\bar{x}$ = 3.78, 95% CI = 1.12, 12.82; Table 7) killed per control turbine than Deterrent turbine during the treatment period, these represented only about a 20% increase in fatality relative to the pre-treatment period. High variation among turbines, small numbers of carcasses found and frequent zero-counts of these and other species at each turbine prevented formal statistical tests of these ratios using the BACI design.

DISCUSSION

Previous research has indicated difficulty to mask or ―jam” bats' echolocation except under specific conditions (e.g., Griffin et al. 1963, Møhl and Surlykke 1989). Indeed, bats can actually adjust their echolocation under jamming conditions (e.g., Ulanovsky et al. 2004, Gillam and McCracken 2007). Bats are, however, likely ―uncomfortable” when broadband ultrasound is present because it forces them to shift their call frequencies to avoid overlap, which in turn will lead to suboptimal use of echolocation or they may not echolocate at all (Griffin 1958, Ulanovsky et al. 2004).

In contrast to previously tested acoustic ―repellers” (Hurley and Fenton 1980), the device we have developed shows some promise for deterring bats from the surrounding airspace near wind turbines. This study represents the first field test of a deterrent device to reduce bat fatalities at wind turbines by comparing fatalities at treated and untreated turbines. Our findings generally corroborate with previous conclusions that a regime of presumably uncomfortable or disorienting ultrasound can deter bats from occupying such a treated airspace (Spanjer 2006, Szewczak and Arnett 2006, 2007, Horn et al. 2007). While the response we observed (~18–62%

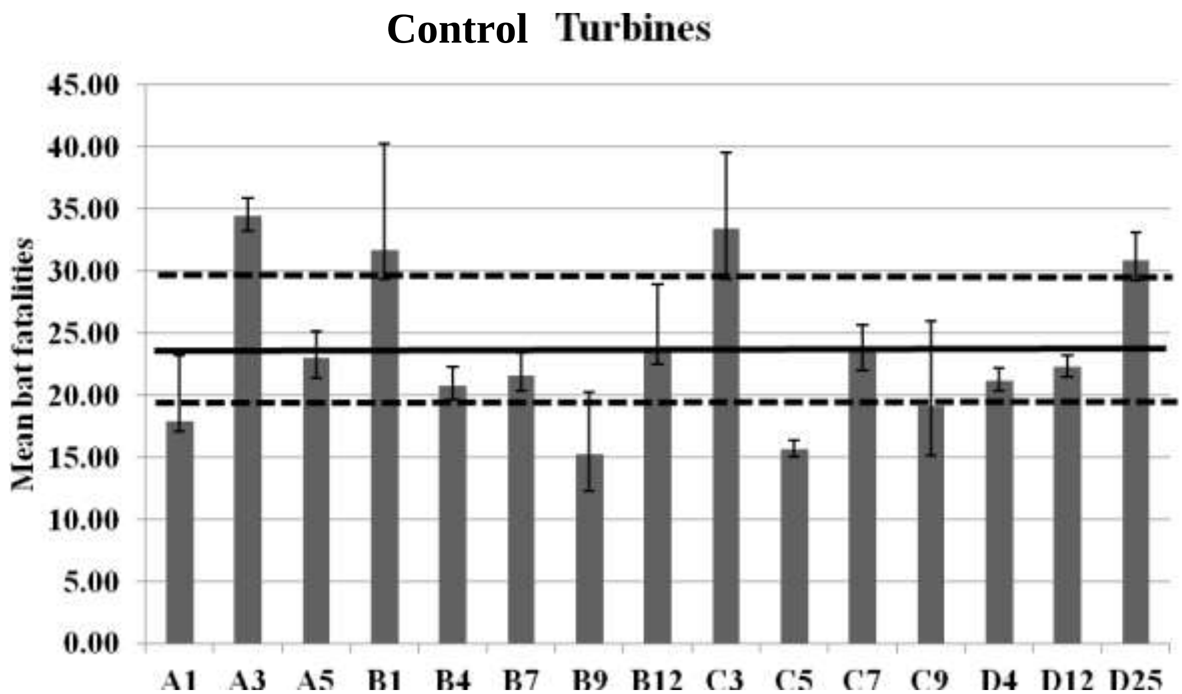
Table 6. Estimated bat fatalities/turbine (mean and 95% confidence intervals [CI]) for each species of bat per turbine, adjusted for searcher efficiency, carcass removal, and area, at control and Deterrent turbines at the Locust Ridge Wind Project in Columbia and Schuylkill Counties, Pennsylvania, 31 July–9 October 2010.

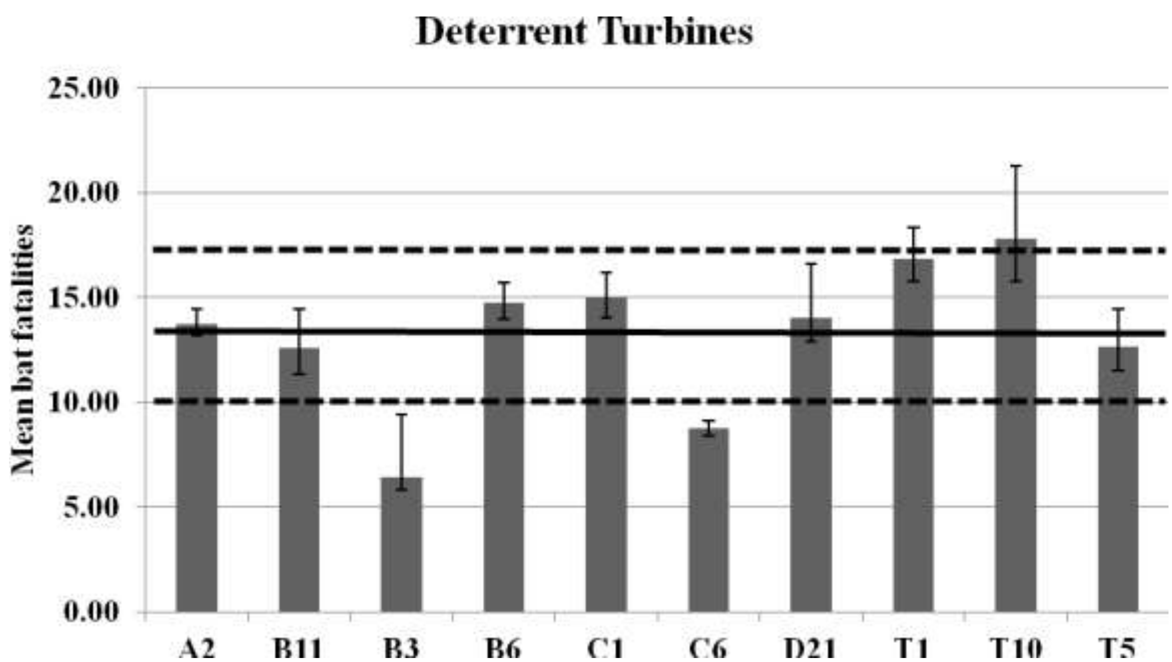
	Control Turbines				Deterrent Turbines			
Species	**N**	**Mean**	**Lower 95% CI**	**Upper 95% CI**	**N**	**Mean**	**Lower 95% CI**	**Upper 95% CI**
Big brown bat	9	1.19	0.39	2.12	2	0.38	0.23	0.85
Eastern red bat	50	7.16	5.32	9.27	22	4.77	2.70	6.92
Hoary bat	61	9.12	7.08	11.70	22	5.02	3.37	7.31
Little brown bat	6	0.87	0.39	1.38	3	0.65	0.20	1.27
Silver-haired bat	20	2.87	1.48	4.47	5	1.00	0.18	2.03
Tri-colored bat	16	2.32	1.37	3.38	8	1.55	0.91	2.23

Table 7. Ratio between bat fatalities per control turbine relative to deterrent turbines (mean and 95% confidence intervals [CI]) for each species of bat from the Locust Ridge Wind Project in Columbia and Schuylkill Counties, Pennsylvania, 31 July–9 October 2010. Confidence intervals that do not include 1.0 are considered statistically significant (*).

Species	**Mean Ratio Control:Deterrent**	**Lower 95% CI**	**Upper 95% CI**
Big brown bat	3.72	0.70	7.87
Eastern red bat	1.59	0.93	2.78
Hoary bat*	1.88	1.19	2.82
Little brown bat	1.72	0.43	5.22
Silver-haired bat*	3.78	1.12	12.82
Tri-colored bat	1.59	0.84	2.96

Figure 7. Mean estimated bat fatalities (+ 95% confidence intervals) for all species of bat, adjusted for searcher efficiency, carcass removal, and area, for each control and Deterrent turbine in relation to overall mean (solid line; 95% confidence intervals dashed lines) for each group at the Locust Ridge Wind Project in Columbia and Schuylkill Counties, Pennsylvania, 31 July–9 October 2010.





reduction in fatality) generally falls within the range of variation among turbines we studied in 2009, nothing in the statistical evaluation of the data suggested that our random selection of the 10 treatment turbines somehow skewed the mortality rates among the turbines we chose. We acknowledge that 3 of our Deterrent turbines had to be located on the Locust Ridge I portion of the facility where no control turbines were selected. While this could have influenced the results, we noted in 2009 that two of these three turbines (T1 and T5) had fewer mean fatalities relative to the overall mean for deterrent turbines (Figure 6), while in 2010, the mean fatalities of all three of these turbines were generally equal to or greater than the overall mean for deterrents. Fatalities at other turbines in both the control and Deterrent set also varied from one year to the next and we do not believe data from the three turbines from Locust Ridge I biased our findings. In 2010, we examined potential inherent difference between the two sets of turbines and our findings suggested only a minor difference existed in fatalities between control and Deterrent turbines prior to implementation of the treatment. However, we caution that data from our pre-treatment period in 2010 was collected prior to migration of migratory tree roosting species and the ratio of migrant to non-migrant species was different between these two periods in our study. Thus, different levels of fatality, different species composition, and possibly different behaviors of the bats during the two phases may have influenced our findings regarding inherent differences between control and Deterrent turbines. Future field tests of deterrent devices should better account for potential differences in fatalities among different species when determining inherent variation among sample turbines.

The effectiveness of ultrasonic deterrents as a means to prevent bat fatalities at wind turbines is limited by the distance and area that ultrasound can be broadcast. Unfortunately, the rapid attenuation of ultrasound, which is heavily influenced by humidity (see Appendix 1), in air limits the effective range that it can be broadcast. Nightly humidity in this region of Pennsylvania averaged 86.5% in August 2009, 84.8% in September 2009, 80% in August 2010, and 76.8% in September 2010 (source http://climate.met.psu.edu/www_prod/). Assuming a constant temperature of 20^{o} C and air pressure of 101.325 kPa and 80% humidity, the theoretical distance to "jam" bats at the assumed 65 dB level only extends to 20 m for the 20-30 kHz range, and declines to only 5-10 m for the upper frequency ranges of broadcast (70-100 kH). Ultrasound emission in the perpendicular plane of the rotor-swept area may be adequate to affect approaching bats, particularly those species influenced at the lower frequencies. However, it is clear that effective emissions in the parallel plane of the rotor-swept area will be difficult if not impossible to achieve based on sound attenuation in humid environments. The effective airspace would be different and larger in more arid environments, however (Appendix 1). We also note that some devices were not operating all the time during our study, due to malfunctions. Although we were unable to account for this factor in our analysis, clearly the affected airspace was reduced when some devices were inactive, which further influenced our findings.

We assume that as bats encounter a gradient of increasingly strong emissions as they approach the deterrent device, they will respond by flying opposite to that gradient to escape the effect of the emissions. However, at present we know little about the general responses that various species have upon entering a large field of ultrasound emissions. It is therefore important to consider our assumptions when interpreting the results of this and our past studies of deterrents. Although our acoustic deterrent device could only generate a limited effective volume of uncomfortable airspace, bats could have detected the presence of such airspace from a greater range, possibly beyond the rotor swept area. Bats previously experiencing the discomfort of ultrasound broadcast may avoid approaching other treated towers, which they could detect as treated from beyond the zone of discomfort. In this way, ultrasound broadcast may effectively serve as acoustic beacons to direct bats away from wind turbines. Over time, bats may learn to avoid all turbines from their experience with those equipped with deterrents. Conversely, bats may habituate to the presence of ultrasound emissions and acoustic deterrents may actually lose their effectiveness over time. However, Szewczak and Arnett (2007) reported that bats did not appear to habituate or accommodate to the presence of ultrasound emitted from a previous prototype deterrent. They found that over the five to seven days of monitored treatment, the number of bats entering the treated airspace declined to 4% of control levels, less than half of the first night of treatment. Just as bat capture success in mist nets declines on successive nights as bats apparently learn the presence of the nets and thereafter avoid them (Kunz et al 2009), Szewczak and Arnett (2007) speculated that after experiencing a disagreeable encounter with the ultrasound treated airspace bats may opt to subsequently avoid it. In practice, the actual decline of activity at any treated site will likely depend upon the immigration of naïve bats into the area. We did not monitor bat activity via night vision cameras (see Szewczak and Arnett 2006, 2007) or with thermal imaging cameras (Horn et al. 2007, 2008) and, thus, were unable to assess activity patterns of bats simultaneous with fatality searches. It is possible that insects preyed on by bats in this region were deterred from the turbines, which could represent the ultimate cause of avoiding treated turbines. Indeed, studies have demonstrated that ultrasound can repel insects (e.g., Belton and Kempster 1962) and influence their reproduction (Huang et al. 2011). However, we did not assess insect abundance and suggest future studies should attempt to address causal factors of avoidance including affect on insect prey.

The effectiveness of acoustic deterrents will likely vary among different species of bats. Hoary bats, for example, employ the lowest frequency range of the species we studied (~20–25 kHz) and may be affected more so than other species that use higher frequencies and perhaps fly at further distances from the device. Hoary bats had significantly fewer fatalities at turbines with deterrents relative to those without them in both years, and silver-haired bats also had fewer fatalities at turbines with deterrents in 2010. In 2010, however, we were able to compare the fatality rates during treatment with what was occurring at the same locations pre-treatment and after accounting for inherent differences between turbine sets prior to treatment, hoary and silver-haired bats killed per control turbine relative to Deterrent turbines during the treatment period represented about a 20% increase in fatality over the pre-treatment period. High variation among turbines, small numbers of carcasses found and frequent zero-counts of these and other species at each turbine prevented formal statistical tests of these ratios using the BACI design. Species-specific effectiveness warrants further investigation in a study with more power to detect differences among species. Such future studies hopefully will also elucidate whether deterrents can eventually serve as a mitigation tool for minimizing or eliminating take of threatened or endangered species such as the Indiana bat (*Myotis sodalis*). The limited range of ultrasound broadcast from a wind turbine tower or nacelle might have only a moderate contribution toward reducing impacts of bats randomly flying through the rotor-swept area. However, for bats that may be drawn to and approach turbine towers as potential roosts or gathering sites (Kunz et al. 2007, Cryan 2008), the combination of effective range and learned avoidance response to ultrasound broadcast may have longer term effects in reducing bat mortality at wind turbines.

This study, and previous experiments with earlier prototypes, revealed that broadband ultrasound broadcasts may affect bat behavior directly by discouraging them from approaching the sound source, or indirectly by reducing the time bats spend foraging near a turbine if insects are repelled by ultrasound (e.g., Belton and Kempster 1962, Huang et al. 2011; also recognizing not all insects have ears to detect ultrasound) and ultimately reduce bat fatalities at wind turbines. However, variation among turbines yielded inconclusive evidence of a strong effect of deterrents on bat fatality and while the approach may hold some promise, further refinement and investigation is needed. We did experience technical issues in both years of the study, including water leakage, that rendered some deterrents inoperable during portions of the study period which clearly influenced our findings. Thus, results from this study may reflect a more conservative estimate of potential fatality reduction achievable through application of the deterrent device we tested. Still, we caution that the response estimated in this study (~18–62%) falls generally within the range of variation for bat fatalities among turbines in this and other studies in the region (e.g., Arnett 2005, Arnett et al. 2009, 2010). Additionally, deterrents resulted in lower reductions in bat fatality relative to curtailing turbine operations by increasing cut-in speeds (44–93%; Arnett et al. 2011). We further caution that it would be premature and unwarranted to conclude or interpret from these initial results that this technology provides an operational deterrent device ready for broad-scale deployment at wind facilities. While we do not consider acoustic deterrents to be an acceptable mitigation strategy at this time, with further experimentation and modifications, this type of deterrent method may prove successful and broadly applicable for protecting bats from harmful encounters with wind turbine blades. Future research and development and field studies should attempt to improve the device and it's weatherproofing and emission performance, and optimize the placement and number of devices on each turbine that would affect the greatest amount of airspace in the rotor-swept area to estimate potential maximum effectiveness of this tool to reduce bat fatalities. Future efforts also must evaluate the cost-effectiveness of deterrents in relation to different curtailment strategies to allow a cost-benefit analysis for mitigating bat fatalities.

LITERATURE CITED

Arnett, E. B., editor. 2005. Relationships between bats and wind turbines in Pennsylvania and West Virginia: an assessment of bat fatality search protocols, patterns of fatality, and behavioral interactions with wind turbines. A final report submitted to the Bats and Wind Energy Cooperative. Bat Conservation International, Austin, Texas, USA.

Arnett, E. B., K. Brown, W. P. Erickson, J. Fiedler, T. H. Henry, G. D. Johnson, J. Kerns, R. R. Kolford, C. P. Nicholson, T. O'Connell, M. Piorkowski, and R. Tankersley, Jr. 2008. Patterns of fatality of bats at wind energy facilities in North America. Journal of Wildlife Management 72: 61–78.

Arnett, E. B., M. R. Schirmacher, M. M. P. Huso, and J. P. Hayes. 2009. Patterns of bat fatality at the Casselman Wind Project in south-central Pennsylvania. An annual report submitted to the Bats and Wind Energy Cooperative and the Pennsylvania Game Commission. Bat Conservation International. Austin, Texas, USA.

Arnett, E. B., and M. M. P. Huso. 2010. Patterns of bat fatality at the Locust Ridge II Wind Project in Pennsylvania. An annual report submitted to the Bats and Wind Energy Cooperative and the Pennsylvania Game Commission. Bat Conservation International. Austin, Texas, USA.

Arnett, E. B., M. M. P. Huso, M. R. Schirmacher, and J. P. Hayes. 2011. Changing wind turbine cut-in speed reduces bat fatalities at wind facilities. Frontiers in Ecology and the Environment 9: 209–214; doi:10.1890/100103 (published online 1 November 2010).

Baerwald, E. F., and R. M. R. Barclay. 2009. Geographic variation in activity and fatality of migratory bats at wind energy facilities. Journal of Mammalogy 90: 1341–1349.

Baerwald, E. F., J. Edworthy, M. Holder, and R. M. R. Barclay. 2009. A large-scale mitigation experiment to reduce bat fatalities at wind energy facilities. Journal of Wildlife Management 73: 1077–1081.

Barlow, K. E. and G. Jones. 1997. Function of pipistrelle social calls: field data and a playback experiment. Animal Behaviour 53: 991–999.

Belton, P. and R. H. Kempster. 1962. A field test on the use of sound to repel the European corn borer. Entomologia 5: 281–288.

Brinkmann, R., H. Schauer-Weisshahn, and F. Bontadina. 2006. Survey of possible operational impacts on bats by wind facilities in southern Germany. Report to Administrative District of Freiburg—Department 56, Conservation and Landscape Management, Freiburg, Germany. http://www.buero-brinkmann.de/downloads/Brinkmann_Schauer-Weisshahn_2006.pdf. Accessed 25 December 2011.

Brown, R. G., and M. L. Brown. 1972. Woody Plants of Maryland. Port City Press, Baltimore, Maryland, USA.

Canadian Wind Energy Association (CANWEA). 2010. Powering Canada's future. http://www.canwea.ca/pdf/Canada%20Current%20Installed%20Capacity_e.pdf. Accessed 1 February 2011.

Cochran, W. G. 1977. Sampling techniques, 3rd edition. John Wiley & Sons, New York, New York, USA.

Cryan, P. M. 2008. Mating behavior as a possible cause of bat fatalities at wind turbines. Journal of Wildlife Management 72: 845–849.

Cryan, P. M., and R. M. R. Barclay. 2009. Causes of bat fatalities at wind turbines: hypotheses and predictions. Journal of Mammalogy 90: 1330–1340.

Dürr, T., and L. Bach. 2004. Bat deaths and wind turbines – a review of current knowledge, and of the information available in the batabase for Germany. Bremer Beiträge für Naturkunde und Naturschutz 7: 253–264.

Energy Information Administration (EIA). 2010. Annual energy outlook 2010 with projections to 2035. U.S. Department of Energy, Energy Information Administration, Washington, D.C., USA. http://www.eia.doe.gov/oiaf/ieo/world.html. Accessed 15 December 2011.

Fenton, M. B. 2003. Eavesdropping on the echolocation and social calls of bats. Mammal Review 33: 193–204.

Frick, W. F., J. F. Pollock, A. C. Hicks, K. E. Langwig, D. S. Reynolds, G. G. Turner, C. M. Butchkoski, and T. H. Kunz. 2010. An emerging disease causes regional population collapse of a common North American bat species. Science 329: 679–682.

Gannon, W. L., R. S. Sikes, and the Animal Care and Use Committee of the American Society of Mammalogists. 2007. Guidelines of the American Society of Mammalogists for the use of wild mammals in research. Journal of Mammalogy 88: 809–823.

Gillam, E. H., and G. F. McCracken. 2007. Variability in the echolocation of Tadarida brasiliensis: effects of geography and local acoustic environment. Animal Behavior 74: 277–286.

Griffin, D. R. 1958. Listening in the dark. Yale University Press, New Haven, Connecticut, USA.

Griffin, D. R., J. J. G. McCue, and A. D. Grinnell. 1963. The resistance of bats to jamming. Journal of Experimental Zoology 152: 229–250.

Gruver, J., M. Sonnenburg, K. Bay, and W. Erickson. 2009. Post-construction bat and bird fatality study at the Blue Sky Green Field Wind Energy Center, Fond du Lac County, Wisconsin. Report submitted to WE Energies. Western Ecosystems Technology Inc., Cheyenne, Wyoming, USA.

Hewitt, J. E, S. E. Thrush, and V. J. Cummings. 2001. Assessing environmental impacts: Effects of spatial and temporal variability at likely impact scales. Ecological Applications 11: 1502–1516.

Horn, J. W., E. B. Arnett, M. Jensen, and T. H. Kunz. 2007. Testing the effectiveness of an experimental acoustic bat deterrent at the Maple Ridge wind farm. A report submitted to the Bats and Wind Energy Cooperative Bat Conservation International. Austin, Texas, USA.

Horn, J., E. B. Arnett, and T. H. Kunz. 2008. Behavioral responses of bats to operating wind turbines. Journal of Wildlife Management 72: 123–132.

Hristov, N. I. and W. E. Conner. 2005. Sound strategy: acoustic aposematism in the bat-tiger moth arms race. Naturwissenschaften 92: 164–169.

Huang, F., B. Subramanyam, and R. Taylor. 2011. Ultrasound affects spermatophore transfer, larval numbers, and larval weight of *Plodia interpunctella* (Hübner) (Lepidoptera: Pyralidae). Journal of Stored Products Research 39: 413–422.

Hurlbert S. H. 1984. Pseudoreplication and the design of ecological field experiments. Ecological Monographs 54: 187–211.

Hurley, S. and M. B. Fenton. 1980. Ineffectiveness of fenthion, zinc phosphide, DDT and two ultrasonic rodent repellers for control of populations of little brown bats (*Myotis lucifugus*). Bulletin of Environmental Contamination and Toxicology 25: 503–507.

Huso, M. M. P. 2010. An estimator of wildlife fatality from observed carcasses. Environmetrics 22: 318-329. DOI: 10.1002/env.1052.

Johnson, G. D. 2005. A review of bat mortality at wind-energy developments in the United States. Bat Research News 46: 45–49.

Kerns, J, W. P. Erickson, and E. B. Arnett. 2005. Bat and bird fatality at wind energy facilities in Pennsylvania and West Virginia. Pages 24–95 *in* E. B. Arnett, editor. Relationships between bats and wind turbines in Pennsylvania and West Virginia: an assessment of bat fatality search protocols, patterns of fatality, and behavioral interactions with wind turbines. A final report submitted to the Bats and Wind Energy Cooperative. Bat Conservation International, Austin, Texas, USA.

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

Kunz, T. H., R. Hodgkison, and C. Weise. 2009. Methods for capturing and handling bats. Pages 1–35 *in* T. H. Kunz and S. Parsons, editors. Ecological and behavioral methods for the study of bats, 2nd edition. Johns Hopkins University Press, Baltimore, USA.

Mackey, R. L., and R. M. R. Barclay. 1989. The influence of physical clutter and noise on the activity of bats over water. Canadian Journal of Zoology 67: 1167–1170.

Manly, B. F. J. 1997. Randomization and Monte Carlo Methods in Biology. 2nd edition. Chapman and Hall, New York, New York, USA.

Møhl, B. and A. Surlykke. 1989. Detection of sonar signals in the presence of pulses of masking noise by the echolocating bat, *Eptesicus fuscus*. Journal of Comparative Physiology A 165: 119–194.

Nicholls, B., and P. A. Racey. 2009. The aversive effect of electromagnetic radiation on foraging bats—a possible means of discouraging bats from approaching wind turbines. PLoS ONE 4(7): e6246. doi:10.1371/journal.pone.0006246.

Parson, S., and J. M. Szewczak. 2009. Detecting, recording, and analyzing the vocalizations of bats. Pages 91–111 *in* T. H. Kunz and S. Parsons, editors. Ecological and behavioral methods for the study of bats, 2nd edition. Johns Hopkins University Press, Baltimore, USA.

Pennsylvania Game Commission (PGC). 2007. Pennsylvania Game Commission wind energy voluntary cooperation agreement. http://www.pgc.state.pa.us/pgc/lib/pgc/programs/voluntary_agreement.pdf. Accessed 15 December 2011.

Racey, P. A., and A. C. Entwistle. 2003. Conservation ecology of bats. Pages 680–743 *in* T. H. Kunz and M. B. Fenton, editors. Bat Ecology. University of Chicago Press, Chicago, Illinois, USA.

Rydell, J., L. Bach, M. Dubourg-Savage, M. Green, L. Rodrigues, and A. Hedenstrom. 2010. Bat mortality at wind turbines in northwestern Europe. Acta Chiropterologica 12: 261–274.

Spanjer, G. R. 2006. Responses of the big brown bat, *Eptesicus fuscus*, to a proposed acoustic deterrent device in a lab setting. A report submitted to the Bats and Wind Energy Cooperative and the Maryland Department of Natural Resources. Bat Conservation International. Austin, Texas, USA.

Steele, R. G. D, J. H. Torrie, and D. A. Dickie. 1997. Principles and procedures of statistics: a biometrical approach. McGraw-Hill: Boston, USA.

Strausbaugh, P. D., and E. L. Core. 1978. Flora of West Virginia. Second edition. Seneca Books, Grantsville, West Virginia, USA.

Surlykke, A., and E. K. V. Kalko. 2008. Echolocating bats cry out loud to detect their prey. PLoS ONE 3(4): e2036. doi:10.1371/journal.pone.0002036.

Szewczak, J. M. and E. B. Arnett. 2006. Preliminary field test results of an acoustic deterrent with the potential to reduce bat mortality from wind turbines. A report submitted to the Bats and Wind Energy Cooperative Bat Conservation International. Austin, Texas, USA.

Szewczak, J. M. and E. B. Arnett. 2007. Field test results of a potential acoustic deterrent to reduce bat mortality from wind turbines. A report submitted to the Bats and Wind Energy Cooperative Bat Conservation International. Austin, Texas, USA.

U.S. Department of Energy. 2011. Wind Powering America: U.S. wind capacity and wind project locations. U.S. Department of Energy, Energy efficiency and renewable program. http://www.windpoweringamerica.gov/wind_installed_capacity.asp. Accessed 1 February 2011.

Ulanovsky, N., M. B. Fenton, A. Tsoar, and C. Korine. 2004. Dynamics of jamming avoidance in echolocating bats. Proceedings of the Royal Society of London B 271: 1467–1475.

Winhold, L., A. Kurta, and R. Foster. 2008. Long-term change in an assemblage of North American bats: are eastern red bats declining? Acta Chiropterologica 10: 359–366.

APPENDIX 1
(Select Specifications for Deterrent Device)

Appendix 1a. Calculated decibel level at different distances and frequencies at two different levels of relative humidity (10 and 40%) for acoustic deterrent devices used in this study. Calculations assume ambient temperature of 20° C and air pressure of 101.325 kPa (kilopascal).

Calculated Decibel Level at Distance and Frequency									
(Assumes 20° C at 10% relative humidity and pressure of 101.325 kPa)									
	Frequency (kHz)								
Distance (m)	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
1	102	107	112	122	122	117	114.5	114.5	117
5	87.0	91.6	96.2	105.6	104.7	99.1	95.7	94.5	95.8
10	79.7	83.9	87.9	96.6	94.4	88.1	83.7	81.0	80.8
15	74.8	78.7	82.0	90.1	86.7	79.7	74.2	70.0	68.3
20	71.0	74.5	77.2	84.6	80.0	72.3	65.7	60.0	56.8
25	67.8	70.8	73.0	79.6	73.9	65.4	57.7	50.6	45.8
30	64.9	67.5	69.1	75.0	68.1	58.9	50.2	41.6	35.3
35	62.3	64.5	65.5	70.7	62.6	52.6	42.8	32.7	24.9
40	59.8	61.6	62.0	66.5	57.2	46.5	35.7	24.1	14.8
45	57.5	58.8	58.7	62.5	52.0	40.6	28.6	15.6	4.7
50	55.3	56.2	55.5	58.6	46.9	34.8	21.7	7.2	-5.2
55	53.2	53.7	52.4	54.7	41.8	29.0	14.9	-1.1	-15.0
60	51.1	51.2	49.3	51.0	36.9	23.3	8.1	-9.4	-24.8

Calculated Decibel Level at Distance and Frequency									
(Assumes 20° C at 40% relative humidity and pressure of 101.325 kPa)									
	Frequency (kHz)								
Distance (m)	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
1	102	107	112	122	122	117	114.5	114.5	117
5	85.7	89.3	93.2	102.0	100.8	94.9	91.3	90.1	91.4
10	76.8	78.5	81.2	88.4	85.8	78.7	73.8	71.0	70.9
15	70.4	70.3	71.7	77.3	73.3	65.0	58.8	54.5	52.9
20	65.0	63.1	63.2	67.2	61.8	52.4	44.8	38.9	35.9
25	60.1	56.4	55.2	57.8	50.8	40.3	31.3	23.9	19.4
30	55.6	50.2	47.7	48.6	40.3	28.5	18.3	9.3	3.4
35	51.4	44.1	40.3	39.7	29.9	17.0	5.4	-5.1	-12.5
40	47.3	38.2	33.2	31.0	19.8	5.7	-7.2	-19.3	-28.1
45	43.4	32.5	26.1	22.4	9.7	-5.5	-19.8	-33.4	-43.7
50	39.6	26.9	19.2	13.9	-0.2	-16.5	-32.2	-47.3	-59.1
55	35.9	21.3	12.4	5.5	-10.0	-27.5	-44.5	-61.2	-74.4
60	32.2	15.9	5.6	-2.8	-19.8	-38.4	-56.8	-75.0	-89.7

Upper Target (dB)	65
lower Trarget (dB)	35

Appendix 1a. - continued.

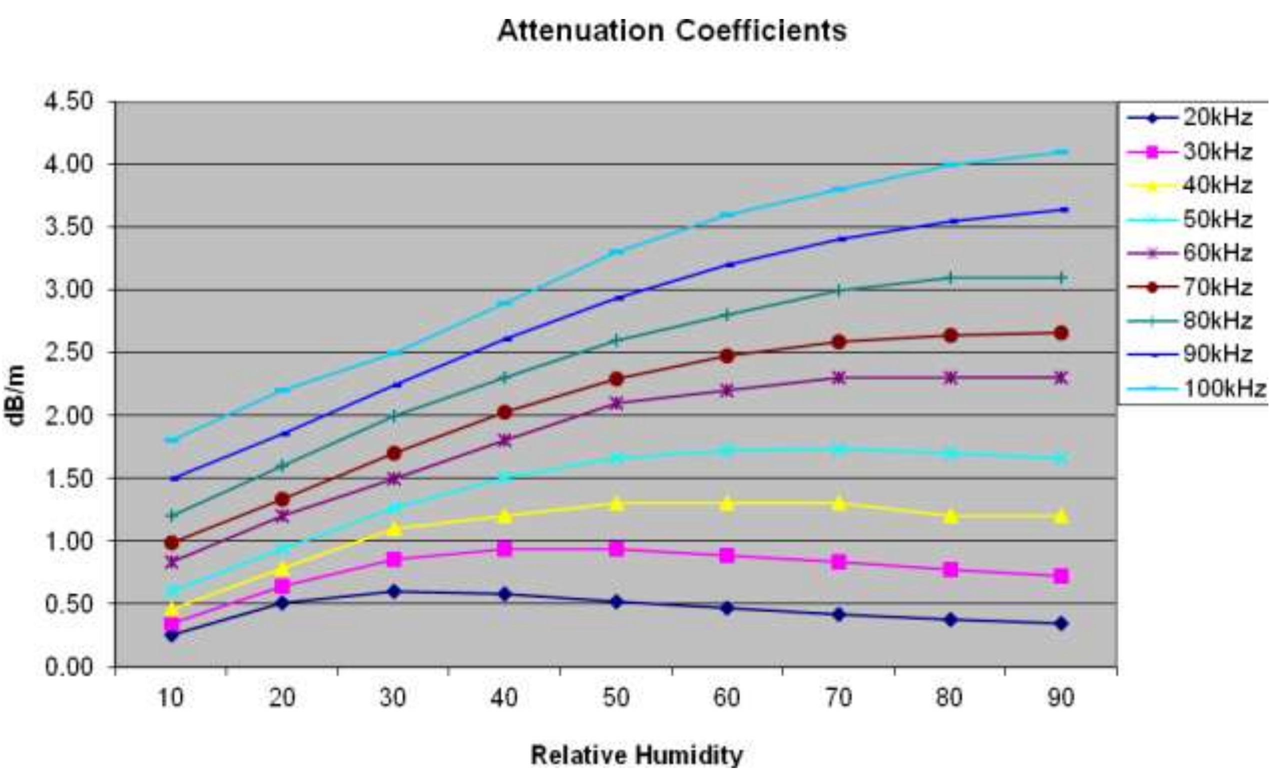
Calculated Decibel Level at Distance and Frequency									
(Assumes 20^{o} C at 80% relative humidity and pressure of 101.325 kPa)									
	Frequency (kHz)								
Distance (m)	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
1	102	107	112	122	122	117	114.5	114.5	117
5	86.5	89.9	93.2	101.2	98.8	92.4	88.1	86.3	87.0
10	78.6	80.0	81.2	86.6	81.3	73.2	66.6	62.6	61.0
15	73.2	72.6	71.7	74.6	66.3	56.5	47.6	41.3	37.5
20	68.8	66.2	63.2	63.5	52.3	40.8	29.6	21.1	15.0
25	64.9	60.4	55.2	53.1	38.8	25.6	12.1	1.4	-7.0
30	61.4	55.0	47.7	42.9	25.8	10.8	-4.9	-17.9	-28.5
35	58.2	49.8	40.3	33.1	12.9	-3.7	-21.8	-36.9	-49.9
40	55.1	44.7	33.2	23.4	0.3	-18.1	-38.4	-55.8	-71.0
45	52.2	39.8	26.1	13.8	-12.3	-32.3	-55.0	-74.6	-92.1
50	49.4	35.0	19.2	4.4	-24.7	-46.5	-71.4	-93.2	-113.0
55	46.7	30.3	12.4	-5.0	-37.0	-60.5	-87.7	-111.8	-133.8
60	44.0	25.7	5.6	-14.3	-49.3	-74.5	-104.0	-130.2	-154.6

Upper Target (dB)	65
lower Trarget (dB)	35

Appendix 1b. Attenuation of sound in air:

The attenuation of sound in air due to viscous, thermal and rotational loss mechanisms is simply proportional to f^2. However, losses due to vibrational relaxation of oxygen molecules are generally much greater than those due to the classical processes, and the attenuation of sound varies significantly with temperature, water-vapor content and frequency. A method for calculating the absorption at a given temperature, humidity, and pressure can be found in ISO 9613-1 (1993). The table and figure below gives values of attenuation in dB m^{-1} for a temperature of 20° C and an air pressure of 101.325 kPa. The uncertainty is estimated to be ± 10%.

Absorption Coefficient (per ISO9613-1) at 20C and pressure of 101.325 kPa									
	Relative Humidity								
Frequency	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**
20	0.26	0.51	0.60	0.58	0.52	0.47	0.42	0.38	0.35
30	0.34	0.65	0.86	0.94	0.94	0.89	0.83	0.78	0.72
40	0.46	0.78	1.10	1.20	1.30	1.30	1.30	1.20	1.20
50	0.60	0.94	1.27	1.51	1.66	1.73	1.74	1.71	1.66
60	0.84	1.20	1.50	1.80	2.10	2.20	2.30	2.30	2.30
70	0.98	1.33	1.70	2.03	2.29	2.47	2.59	2.64	2.66
80	1.20	1.60	2.00	2.30	2.60	2.80	3.00	3.10	3.10
90	1.50	1.85	2.24	2.61	2.93	3.20	3.40	3.55	3.64
100	1.80	2.20	2.50	2.90	3.30	3.60	3.80	4.00	4.10



APPENDIX 2
(Habitat Visibility Classes, Percent Area of Visibility Classes for Turbines)

Appendix 2a. Habitat visibility classes used during this study (following PGC 2007). Data for Classes 3 and 4 were combined during our final analyses.

% Vegetative Cover	Vegetation Height	Visibility Class
≥90% bare ground	≤15 cm tall	Class 1 (Easy)
≥25% bare ground	≤15 cm tall	Class 2 (Moderate)
≤25% bare ground	≤25% > 30 cm tall	Class 3 (Difficult)
Little or no bare ground	≥25% > 30 cm tall	Class 4 (Very Difficult)

Appendix 2b. Percentage of each habitat visibility class for the maximum plot area (120 x 126 m) for each turbine searched for the deterrent study at the Locust Ridge I and II facilities in 2009.

Deterrent:

Turbine	Easy	Moderate	Difficult	Very Difficult	Out
A2	13	10	0	3	74
B3	12	13	0	4	71
B6	13	15	2	2	69
B11	13	10	3	3	71
C1	10	13	0	9	69
C6	15	20	0	5	60
D21	12	20	6	1	61
T1	9	1	14	0	76
T5	17	2	5	10	66
T10	20	0	1	14	64

Control (PGC):

A1	11	8	1	2	78
A3	11	16	1	7	64
A5	10	8	2	4	76
B1	13	30	1	1	55
B4	12	12	0	5	71
B7	12	26	1	1	59
B9	16	18	10	3	53
B12	11	7	2	0	80
C3	11	3	8	1	77
C5	13	11	0	1	75
C7	12	10	1	3	73
C9	12	8	10	16	54
D4	11	9	3	6	71
D12	10	7	5	8	69
D25	15	6	4	0	76

Appendix 2c. Percentage of each habitat visibility class for the maximum plot area (120 x 126 m) for each turbine searched for the deterrent study at the Locust Ridge I and II facilities in 2010.

Deterrent:

Turbine	Easy	Moderate	Difficult	Very Difficult	Out
A2	13	10	0	3	74
B3	12	8	8	0	72
B6	13	15	4	0	69
B11	13	13	0	3	71
C1	10	13	0	6	72
C6	15	20	0	4	60
D21	12	21	3	1	63
T1	0	10	14	0	76
T5	20	0	5	11	64
T10	17	2	9	6	66

Control (PGC):

A1	11	8	1	2	78
A3	11	16	1	7	64
A5	10	8	2	4	76
B1	13	30	1	1	55
B4	12	12	0	5	71
B7	12	26	1	1	59
B9	16	18	10	3	53
B12	11	7	2	0	80
C3	11	3	8	1	77
C5	13	11	0	1	75
C7	12	10	1	3	73
C9	12	8	10	16	54
D4	11	9	3	6	71
D12	10	7	5	8	69
D25	15	6	4	0	76