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

Final Report

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BWEC
bats and wind energy cooperative

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.

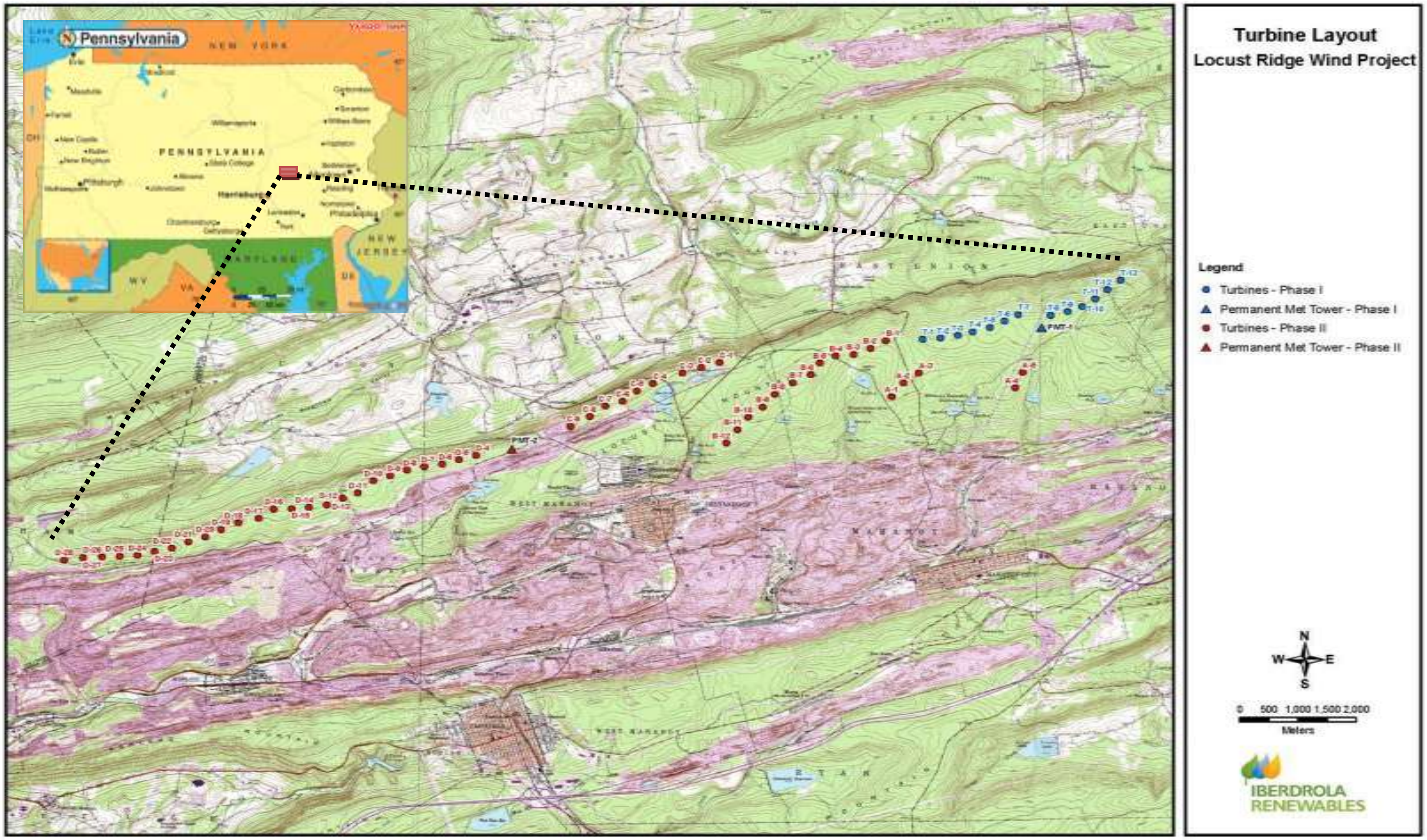
Studies in Scotland suggest that bat activity may be deterred by electromagnetic signals from small, portable radar units. Nicholls and Racey (2009) reported that bat activity and foraging effort per unit time were significantly reduced during experimental trials when their radar antenna was fixed to 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.



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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

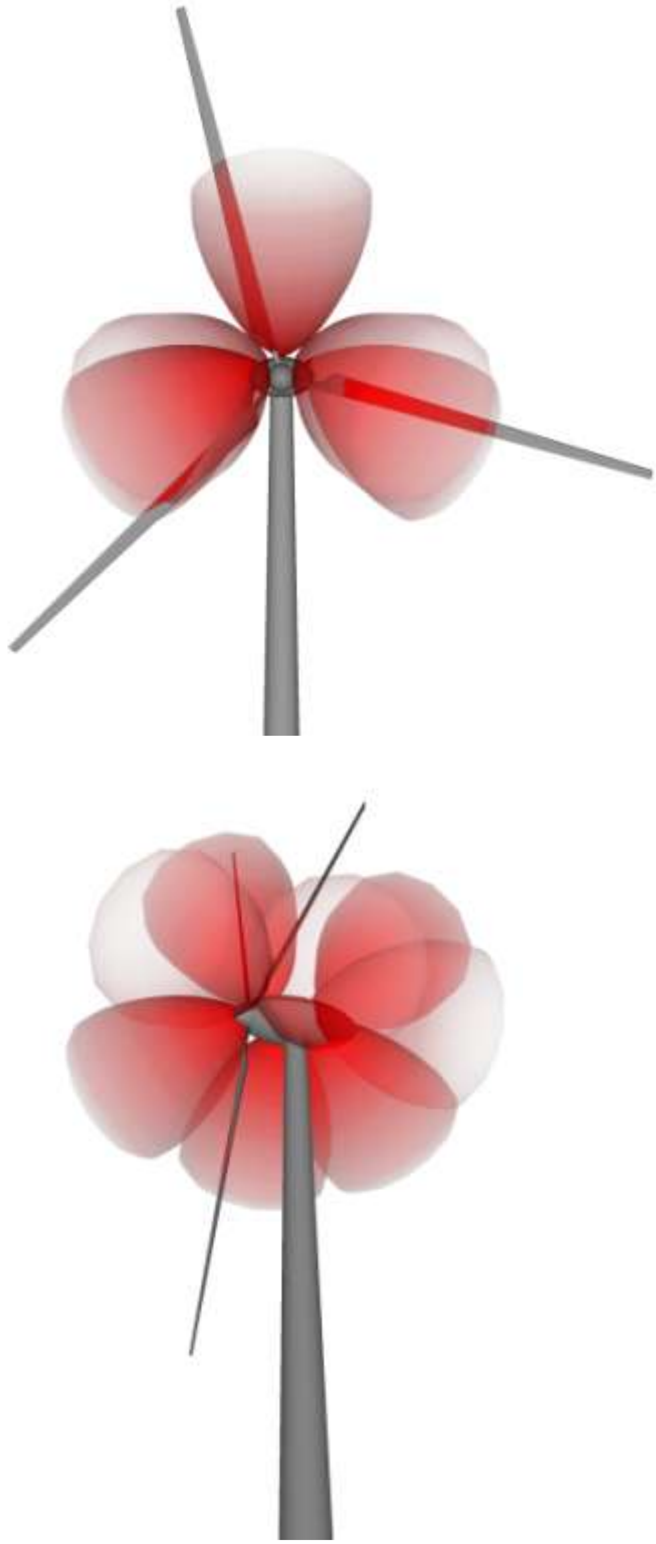
Figure 2. Photos depicting the acoustic deterrent device, its installation, and approximate location on turbines at the Locust Ridge I and II Wind Farms in Pennsylvania.

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, Appendix 1c).



(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).

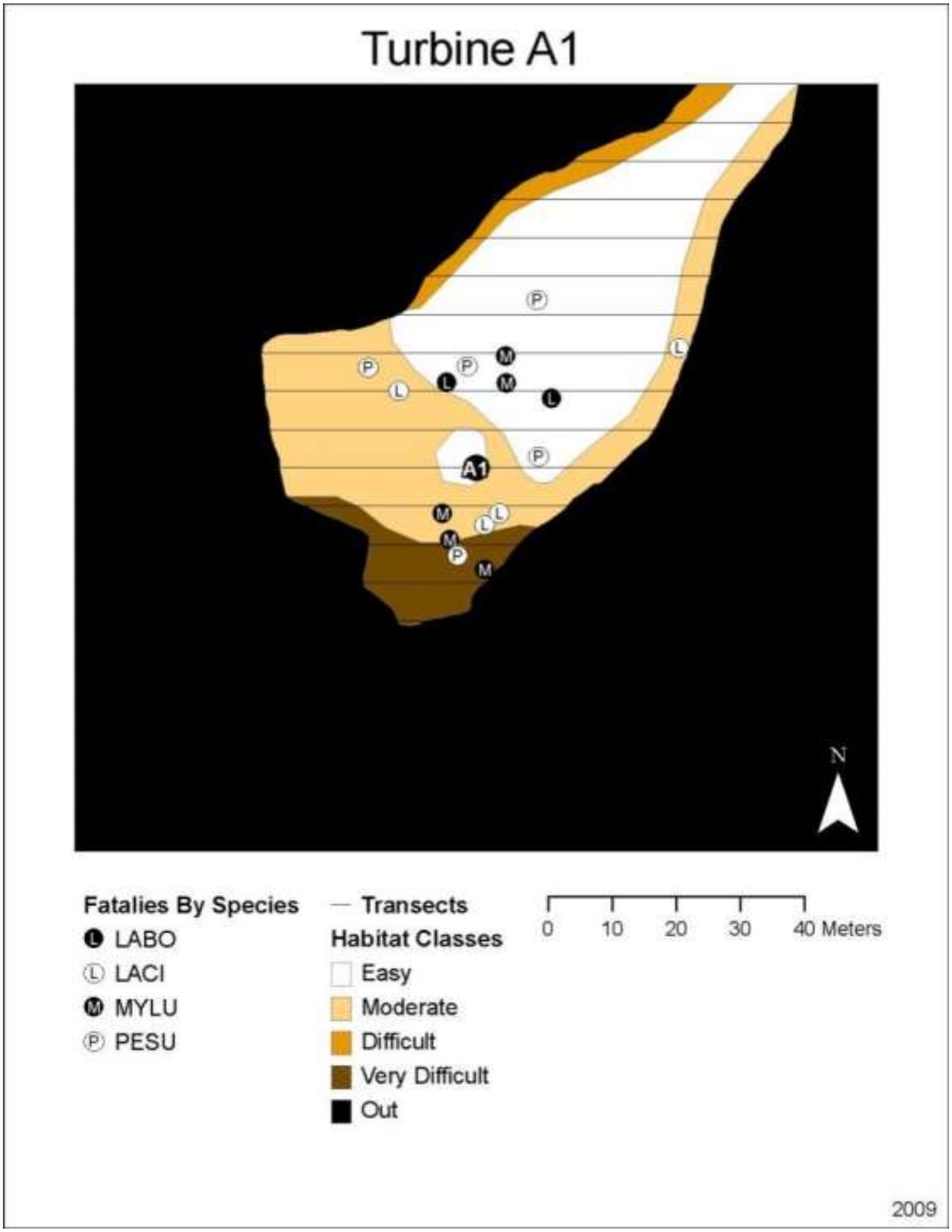
We used the following estimation to base the target signal level of the experimental deterrent: A typical bat emits calls at about 110 dB sound pressure level (SPL) at 10 cm (Surlykke and Kalko 2008). During search phase flight a typical North American species of bat emits about 12 calls per second, 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., $\leq$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.

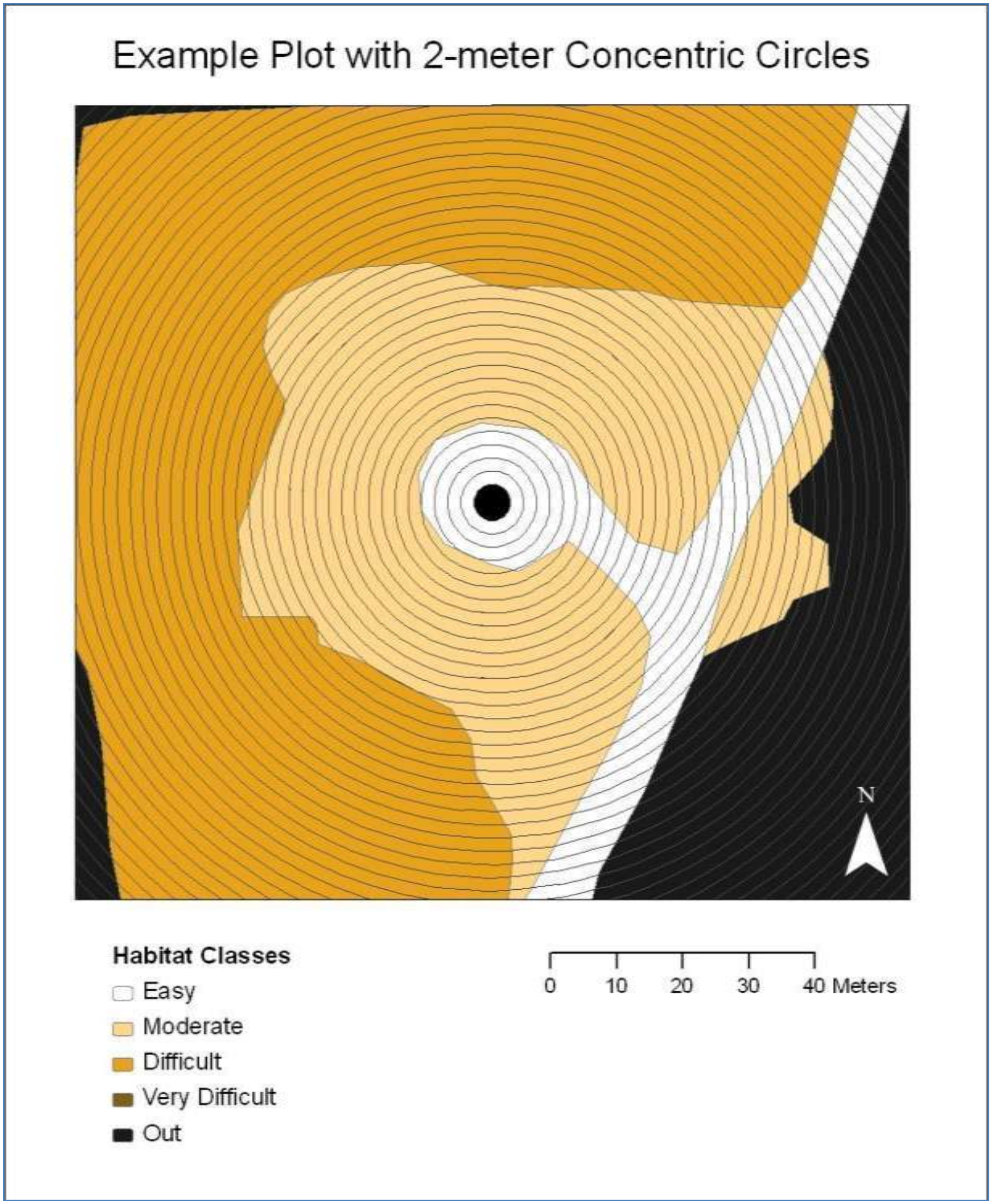
Fatality estimates. We adjusted the number of bat fatalities found by searchers by estimates of searcher efficiency and by the proportion of carcasses expected to persist unscavenged during each interval using the following equation:

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

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 (χ^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 (χ^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.

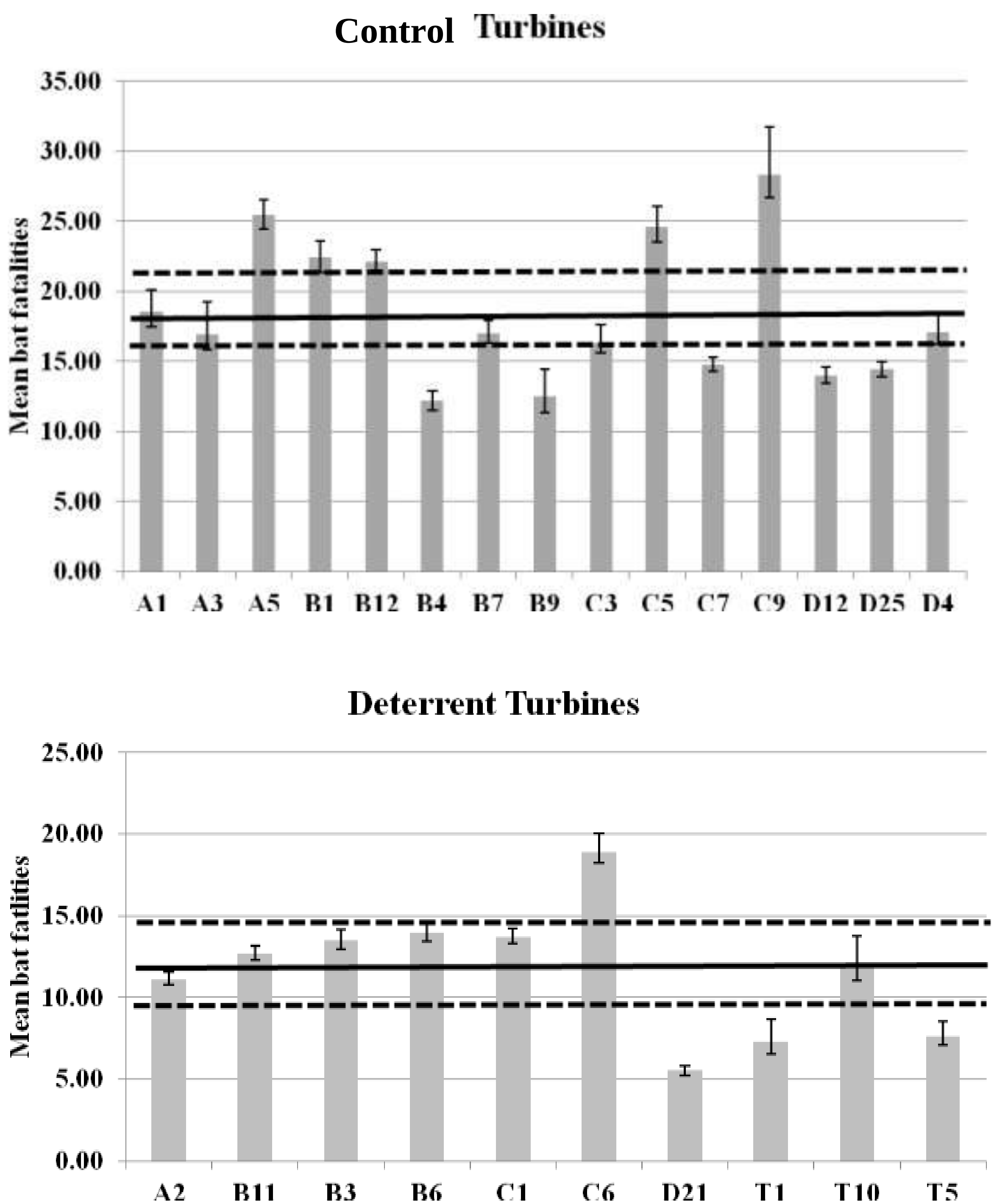
Table 4. Number of each species found (N) and the estimated bat fatalities/turbine (mean and 95% confidence intervals [CI]) for each species of bat per turbine, adjusted for searcher efficiency, carcass removal, and area, at control and Deterrent turbines at the Locust Ridge Wind Project in Columbia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

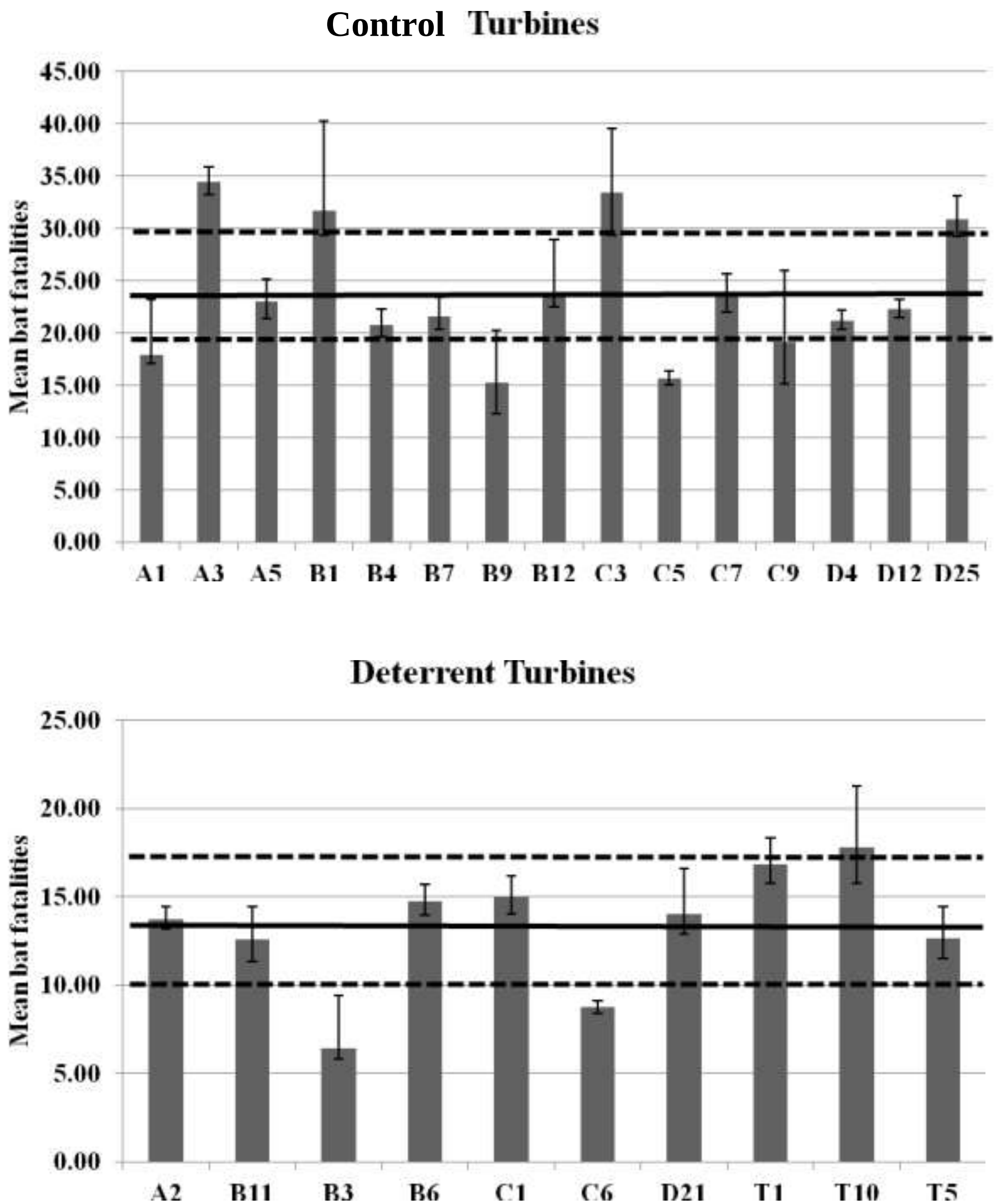
Table 6. Estimated bat fatalities/turbine (mean and 95% confidence intervals [CI]) for each species of bat per turbine, adjusted for searcher efficiency, carcass removal, and area, at control and Deterrent turbines at the Locust Ridge Wind Project in Columbia and Schuylkill Counties, Pennsylvania, 31 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 kHz; Appendix 1). 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.

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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^{o} C and air pressure of 101.325 kPa (kilopascal).

Calculated Decibel Level at Distance and Frequency									
(Assumes 20^{o} 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^{o} 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.

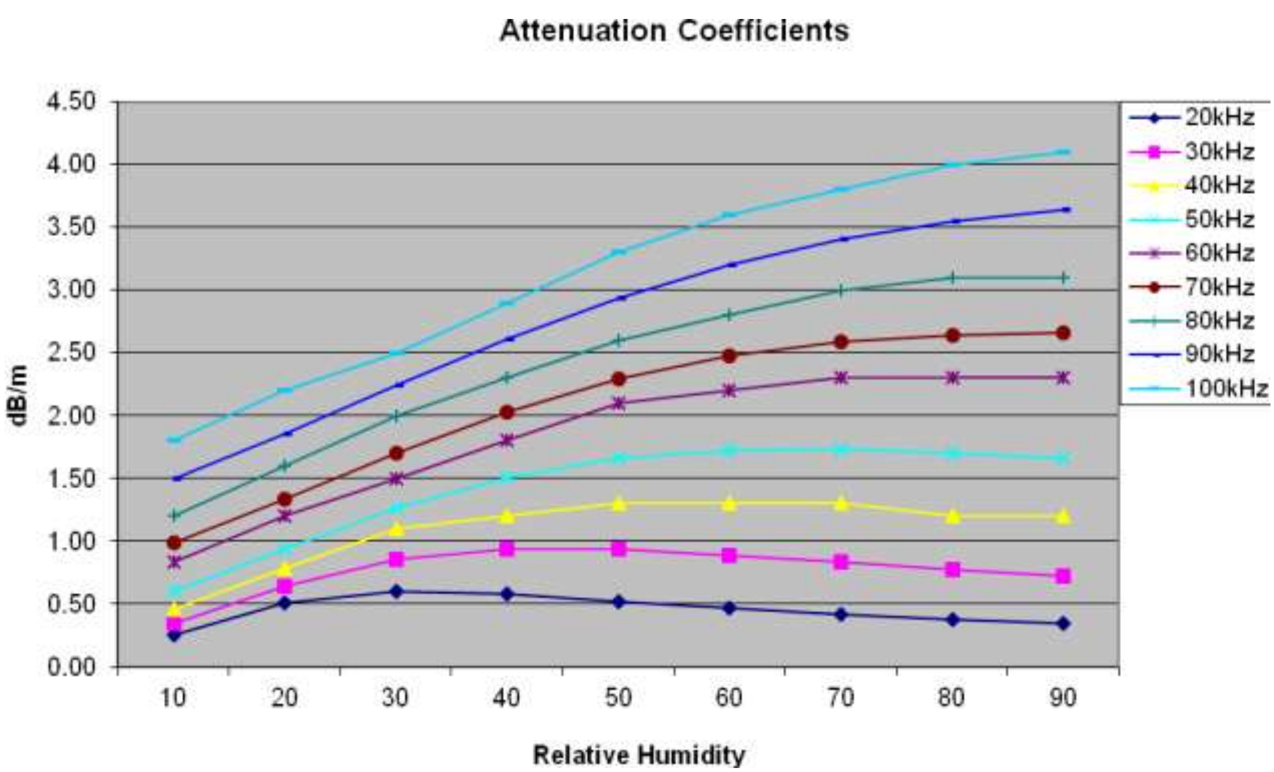
Calculated Decibel Level at Distance and Frequency									
(Assumes 20^{o} C at 80% relative humidity and pressure of 101.325 kPa)									
	Frequency (kHz)								
Distance (m)	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
1	102	107	112	122	122	117	114.5	114.5	117
5	86.5	89.9	93.2	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 1c. Specifications for transducers (16 per device) used in acoustic deterrent devices used in this study.

SensComp, Inc.
36704 Commerce Rd.
Livonia, MI 48150
Telephone: (734) 953-4783
Fax: (734) 953-4518
www.senscomp.com

600 Series Environmental Transducer

SensComp's Series 600 Environmental Grade electrostatic transducer is specifically intended for operation in air at ultrasonic frequencies. This transducer is identical to the 600 Series Instrument Grade Transducer except that the outer housing is made of 304 stainless steel for harsh environments.

Features

50 kHz Electrostatic Transducer
Beam Angle of 15° at -6 dB
Ranges from 6" to 35'
Excellent Receive Sensitivity
Better Suited for Harsh Environments
Stainless Steel Housing, Perforated Protective Cover.
Specifically Intended for Operation in Air at Ultrasonic Frequencies

Part No.

PID# 607281 – Series 600 Environmental Transducer

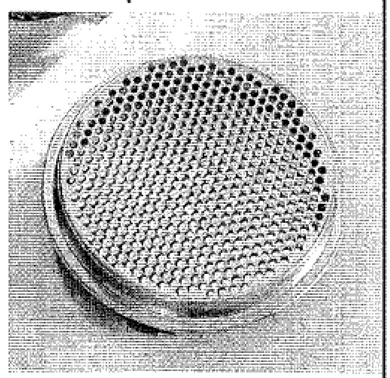
Benefits

Able to Range from 6" to 35'
Excellent Receive Sensitivity

Applications

Level Measurement, Proximity Detection, Presence Detection, Robotics, Educational Products
Operation in Outdoor Environments

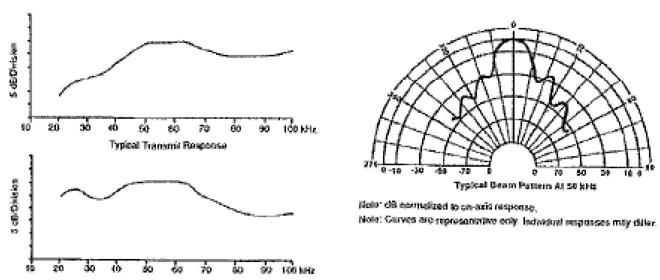
Specifications



Description

The Series 600 ultra sensitive transducers feature ranging capability from 2.5 cm to 15.2 m when used with SensComp drive electronics. They are ideally suited for demanding applications where the most sensitivity possible is the highest priority. These ultrasonic transducers are among the best available when detecting soft targets. They have a broad band frequency response.

Transmit/Receive Response & Beam Pattern



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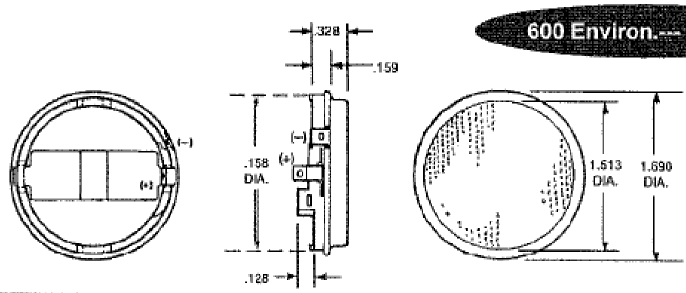


Specifications

Usable Frequency Range
- **Transmitting** .... See Graph
- **Receiving** .... See Graph

Beam Pattern .... See Graph
Typical: 15° at -6dB

Transmitting Sensitivity .... 110 dB min
at 50.0 kHz; 0dB re 20 µPa at 1 meter
(300 VAC_{PP}; 150 VDC bias)

Receiving Sensitivity .... -42 dB min
at 50.0 kHz; 0dB = 1 volt/Pa
(150 VDC bias)

Distance Range .... 0.15 to 10.7 M (0.5 to 35 feet)

Resolution (± 1% over entire range) .... ± 3mm to 3m (± 0.12 to 10 ft)

Weight .... 8.2 gm (0.29 oz)

Suggested DC Bias Voltage 200V

Suggested AC Driving Voltage .... 200V peak

Combined Voltage .... 400V max

Capacitance at 1 kHz (typical) .... 400–500 pf
(at 150 VDC bias)

Operating Temperature .... -30 to +70° C (-20 to 160° F)

Storage Temperature .... -40 to 120° C (-40 to 250° F)

Relative Humidity (non condensing) .... 5% - 95%

Dimension
- **Thickness** .... 0.46 inch
- **Diameter** .... 1.69 inch

Standard Finish
- **Foil** .... Gold
- **Housing** .... 304 Stainless Steel

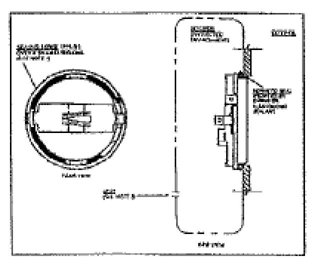
Specifications subject to change without notice

Environmental Characteristics & Exposures

Note: The following tests were performed in an environmentally controlled test facility with the transducer housed in a custom designed test enclosure. The test enclosure protects the transducer sides and back from exposure to any foreign matter. The rear of the transducer is vented to atmosphere pressure.

After each test, the transducers were cleaned and dried as necessary. Measurements were then taken at room temperature.

- Storage Temperature ....-40 TO 120° C (-40 to 250 ° F)
- Salt Spray Exposure (96 hours)....5% salt spray solution at 95 °
- Shock and Vibration......................50 G peak in each direction along 3 perpendicular axes, pulse duration: 6.5 ms; 6 G's RMS 20-2000 Hz for 6 minute.
- Water Immersion (24 hours).........(vent hole sealed)
- Freeze/Thaw Cycle (4 cycles) ......Spray with water, drain, expose to -20° F (-30° C) for 20 minutes, allow to warm to room temperature.
- Chemical Exposure.......................Gasoline, acetone, sulphur dioxide. Samples sprayed with/ exposed to chemical, then placed in120° F (49° C) / 90% relative humidity environment for 24 hours.



No claims are made for performance without an enclosure providing protection equal to or better than the test enclosure described above. Similarly, no claim is made for performance in any other environments or under any other condition than those controlled conditions described herein.

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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