Effectiveness of an Operational Mitigation Experiment to Reduce Bat Fatalities at the Pinnacle Wind Farm, Mineral County, West Virginia, 2012

Final Report

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April 2013

REPORT CITATION

Hein, C. D., A. Prichard, T. Mabee, and M. R. Schirmacher. 2013. Effectiveness of an Operational Mitigation Experiment to Reduce Bat Fatalities at the Pinnacle Wind Farm, Mineral County, West Virginia, 2012. An annual report submitted to Edison Mission Energy and the Bats and Wind Energy Cooperative. Bat Conservation International. Austin, Texas, USA.

ACKNOWLEDGMENTS

This study was conducted under the auspices of the Bats and Wind Energy Cooperative (BWEC). We wish to thank John Anderson (American Wind Energy Association), Christy Johnson-Hughes (U.S. Fish and Wildlife Service), Bob Thresher and Karin Sinclair (National Renewable Energy Laboratory), Mylea Bayless (Bat Conservation International), Patrick Gilman (U.S. Department of Energy), and Laurie K. Allen (U.S. Geological Survey), who provided oversight for the BWEC for this project. We appreciate the critical reviews provided by Taber Allison and Paul Cryan (BWEC Science Advisors) and Mylea Bayless (BWEC Oversight Advisor).

We thank Edison Mission Energy, in particular Mary Connor and Brad Christopher for their support on this project. We thank the U.S. Fish and Wildlife Service, the West Virginia Division of Natural Resources, the West Virginia Public Service Commission, and members of the Pinnacle Technical Advisory Committee for developing the study proposal. We also thank Molly Albecker, Nicole Beaver, Don J. Hardeman, Daniel Jacobs, Alexandria Marquardt, Tyler Pockette, Vanessa Rojas and Marc Strini for their dedication in the field, and collecting and managing data throughout the study.

EXECUTIVE SUMMARY

In accordance with the West Virginia Public Service Commission (WVPSC) and with guidance from the Technical Advisory Committee, which included members from the WVPSC, U.S. Fish and Wildlife Service, West Virginia Division of Natural Resources, and Edison Mission Energy, we initiated a study in July 2012 to test the effectiveness of an operational mitigation experiment to reduce bat fatalities at the Pinnacle Wind Farm (PWF), Mineral County, West Virginia. Our objective was to determine the difference in bat fatalities at turbines with different operational adjustments. A post-construction fatality monitoring study was conducted at the PWF between 1 March and 30 November 2012, results of which are discussed in a separate report.

The facility lies within the Appalachian mixed mesophytic forests ecoregion composed of moist broadleaf forests, which cover the plateaus and rolling hills west of the Appalachian Mountains. The project consists of 23 Mitsubishi 2.4-MW turbines, with 95 m rotor diameter and 80 m hub height for a total height of approximately 128 m (from base of tower to highest point of the blade), and a manufacturer's cut-in speed of 3.0 m/s. Turbines are fully "feathered" below the manufacturer's cut-in speed. In this position, there is no aerodynamic lift from the blades and thus no rotor rotation. At 3.0 m/s the blades are pitched to generate lift and the rotor starts rotation. Twelve of the 23 turbines at the PWF were randomly selected for the experiment and we rotated three treatments among these turbines: 1) fully operational at 3.0 m/s cut-in speed, 2) increased cut-in speed at 5.0 m/s from sunset to sunrise, and 3) increased cut-in speed at 5.0 m/s for the first four hours past sunset. We used a completely randomized design and treatments were randomly assigned to turbines each night of the experiment, with the night when treatments were applied as the experimental unit. We conducted daily fatality searches between 15 July and 30 September 2012.

We found a total of 186 bat carcasses, of which 31, 89, and 66 were found in July, August, and September, respectively. We recovered carcasses from 6 different species, including eastern red bats (*Lasiurus borealis*), hoary bats (*Lasiurus cinereus*), silver-haired bats (*Lasionycteris noctivagans*)-listed as Imperiled (S2) by West Virginia Division of Natural Resources (WVDNR), tri-colored bats (*Perimyotis subflavus*), big brown bats (*Eptesicus fuscus*), and Seminole bats (*Lasiurus seminolus*). Migratory tree-roosting bats (hoary bats, silver-haired bats, and eastern red bats) comprised 79% (n = 147) of all fatalities, and big brown bats and tri-colored bats, two species impacted by White-nosed Syndrome (WNS), collectively represented 19% (n = 36) of carcasses found. There was no evidence of WNS on any bats recovered during the study. One Seminole bat and 2 unidentified carcasses also were found.

Of the 186 total bat carcasses found, 155 were determined to be fresh (i.e., killed the previous night). Thirty-nine fatalities occurred when turbines were operating at 5 m/s all night, 56 occurred when turbines were operating at 5 m/s during the first four hours past sunset (herein referred to as half night), and 60 occurred when turbines were fully operational. Average nightly wind speeds among turbines across the study showed that over 70% of the time wind speed was above 5 m/s. Average wind speed was only between 3 and 5 m/s (i.e., the time when treatments were implemented) for approximately 17% of the time during the study.

The most parsimonious model in our candidate model set, regardless of whether or not an outlier was included, incorporated the variables date, treatment, proportion of wind speeds between 3–5 m/s and a wind speed by treatment interaction. The fatality rate increased with the proportion of wind speeds between 3–5 m/s for fully operational turbines, increased at a slower rate for turbines undergoing the 5 m/s half night, and did not increase for turbines that experienced the 5 m/s all night treatment, with and without the outlier. The slope for 5 m/s all night turbines was significantly different from fully operational turbines ($P = 0.022$), but the slope for the 5 m/s half night was not significantly different from fully operational turbines ($P = 0.084$).

Our success in implementing an operational mitigation strategy varied with the experimental treatment groups. We found no difference between the 5 m/s half night treatment and fully operational turbines regardless of model. We observed a 47% reduction in bat fatalities for the 5 m/s all night treatment compared to fully operational turbines, but only when we removed an outlier (i.e., a night when 7 fatalities were recovered from a 5 m/s all night treatment turbine) from the dataset. Our lack of a treatment effect likely is a result of the small proportion of time (17%) wind speeds were between 3 and 5 m/s. Based on the best model, which incorporated the proportion of the night that wind speeds were between 3 and 5 m/s, we observed a 72.2% and 81.7% reduction in bat fatalities at 5 m/s all night treatment turbines compared to fully operational turbines, with and without the outlier, respectively.

Presently, our understanding of the sustainability of wind energy impacts on bats is limited by the lack of knowledge of population size, structure and dynamics. Until we have a better understanding of bat populations, our ability to determine whether the reduction in bat fatalities, from operational mitigation measures, is adequate to mitigate the adverse effects of wind energy development remains unknown. Although gathering data to address this issue is a priority, data are not expected to be available in the near future. Given the magnitude and extent of bat fatalities throughout North America, we believe that wind operators should implement operational mitigation strategies, even in the absence of population data.

INTRODUCTION

With the increasing demand for energy globally, many countries are seeking ways to reduce fossil fuel consumption and generate alternate forms of energy. Recently, wind power has gained prominence among renewable resources driven, in part, by supportive government policies and growing economic competitiveness (Ledec et al. 2011). During the past decade, global wind generating capacity has increased 10-fold, and now exceeds 196,000 MW (World Wind Energy Association 2011, Ledec et al. 2011). In North America, wind-energy is one of the fastest growing forms of renewable energy and has been produced commercially for nearly 4 decades (Pasqualetti et al. 2004, National Research Council 2007). In recent years, the U.S. has been a world leader, second only to China, in wind generating capacity, with 51,630 MW as of 30 September 2012 (AWEA 2012a). Currently, West Virginia ranks 20th in the U.S. for installed capacity at 583 MW, with another 310 MW permitted or under construction (AWEA 2012b). Although wind-generated energy reduces carbon and other greenhouse gas emissions associated with climate change, it is not entirely environmentally neutral, because wildlife and habitats can be directly or indirectly impacted by development. Concerns regarding potential cumulative negative impacts of wind energy development on bat populations persist, particularly when many species of bats are known or suspected to be in decline from natural (e.g., white-nose syndrome [WNS]) and other human-induced factors (Pierson 1998, Racey and Entwistle 2003, Winhold and Kurta 2008, Jones et al. 2009, Frick et al. 2010). Because bats provide numerous ecosystem services (e.g., insect suppression), adverse impacts of wind development on local bat populations could disrupt the ecological health and stability of a region (Kunz et al. 2011).

The period of highest risk for bats tends to occur during relatively low-wind conditions when bats are migrating south in late summer through early fall (Arnett et al. 2008, Rydell et al. 2010). Previous studies indicate that bats suppress their activity during certain weather conditions (e.g., periods of rain, low temperatures, and strong winds (Erickson and West 2002, Reynolds 2006, Horn et al. 2008, Weller and Baldwin 2012) and appear to be less vulnerable to turbines under these conditions. Thus, altering turbine operations when bats are most at risk was proposed as a possible means of reducing impacts to bats by Kunz et al. (2007) and Arnett et al. (2008). Raising turbine cut-in speeds (i.e., the wind speed at which the generator is connected to the grid and producing electricity) from the manufactured speed (usually 3.5–4.0 m/s for modern turbines) by 1.5–3.0 m/s during periods of high risk for bats has been shown to significantly reduce bat fatalities compared to fully operating turbines (Baerwald et al. 2009, Arnett et al. 2011).

One means of reducing bat fatalities at wind energy facilities is to alter turbine operations during periods when bats are most at risk. Data from existing operating wind projects indicates a substantial portion of total bat fatalities occurs at times when wind speeds are relatively low during the fall bat migration (Arnett 2005, Johnson 2005, Kunz et al. 2007, Arnett et al. 2008). Thus, some alteration of turbine operations during the period of highest risk has been proposed as a possible means of reducing impacts to bats (Kunz et al. 2007, Arnett et al. 2008). Results from recent studies in Canada (Baerwald et al. 2009), Pennsylvania (Arnett et al. 2011), West Virginia (Young et al. 2011, 2012), and Indiana (Good et al. 2011, 2012) indicate that changing turbine operations (e.g., raising the turbine cut-in speed and feathering turbine blades under a designated cut-in speed) resulted in significant reductions (approximately 45–93%) in bat fatalities. Altering turbine operations, even on a limited-term basis poses operational and financial difficulties for wind energy facilities, but may ultimately prove to be an economically feasible and ecologically viable solution to reducing impacts to bats. To that end, more studies are needed across a range of environmental conditions; different temperatures, different cut-in speeds, and hours of operation to assess fully the efficacy of operational mitigation to reduce bat fatalities, as well as the inherent economic and operational implications.

OBJECTIVES

In accordance with the West Virginia Public Service Commission (WVPSC) and with guidance from the Technical Advisory Committee, which included members from the WVPSC, U.S. Fish and Wildlife Service, West Virginia Division of Natural Resources, and Edison Mission Energy, we initiated a study in July 2012 to test the effectiveness of an operational mitigation strategy to reduce bat fatalities at the Pinnacle Wind Farm (PWF). Twelve of the 23 turbines at the PWF were selected for the experiment and we rotated three treatments among these turbines: 1) fully operational (i.e., operating at the normal manufacturer's cut-in speed of 3.0 m/s), 2) cut-in speed set at 5.0 m/s from sunset to sunrise, and 3) cut-in speed set at 5.0 m/s for the first four hours past sunset (herein referred to as 5 m/s half night). Treatments were randomly assigned each night and each turbine received each treatment an equal number of nights. Decisions on whether to begin or cease a treatment were based on a 3-minute average of wind speed. During the 2012 field season, we also conducted a post-construction fatality monitoring study to determine fatality patterns at the PWF (see Hein et al. 2013).

STUDY AREA

The PWF is located near the town of Keyser in Mineral County, West Virginia (Fig. 1). The PWF is situated along a 3.5 mile stretch of privately owned land, along a wooded ridge-top on Green Mountain. The PNW consists of 23 Mitsubishi 2.4-MW turbines, with 95 m rotor diameter and 80 meter hub height for a total height of approximately 128 m (from base of tower to highest point of the blade), and a manufacturer's cut-in speed of 3 m/s. Turbines are fully "feathered" below the manufacturer's cut-in speed. In this position, there is no aerodynamic lift from the blades and thus no rotor rotation. At 3.0 m/s the blades are pitched to generate lift and the rotor starts rotation. The facility lies within the Appalachian mixed mesophytic forests ecoregion composed of moist broadleaf forests, that cover the plateaus and rolling hills west of the Appalachian Mountains (Brown and Brown 1972, Strausbaugh and Core 1978). The elevation of the project area varies from 766 to 869 m above mean sea level.

METHODS

Delineation of Carcass Search Plots and Habitat Mapping. We initiated an operational mitigation study following protocols outlined in the Technical Advisory Committee proposal dated January 2011. We conducted daily searches at 12 turbines from 15 July–30 September 2012. We used a random numbers table to randomly select 11 of the available 23 turbines to be searched during a post-construction monitoring study at the PWF in 2012 (Hein et al. 2013). We used the remaining 12 turbines for the operational mitigation experiment (turbines 1, 2, 5, 7, 9, 11, 13, 14, 16, 19, 21, and 22). We attempted to delineate a rectangular plot 126 m east-west by 120 m north-south (15,120 m^2 total area) centered on each turbine sampled; this area represents the maximum possible search area for this study (see Fig. 2 for an example). We set transects 6 m apart within each plot and observers searched 3 m on each side of the transect line. We considered contiguous forest cover and areas unsafe to search as unsearchable habitat (e.g. steep terrain) and eliminated them from our search plots. Because the area cleared of forest varied by search plot, actual searchable area differed among turbines. We used a Trimble GeoXT (Trimble Navigation Limited, Sunnyvale, CA) global positioning system (GPS) to map the actual area searched at each turbine (Appendix 1). The density weighted area searched was used to standardize results and adjust fatality estimates (see below). We mapped the habitat visibility classes within each plot with a GPS unit.

Fatality Searches. We conducted a "clean-out" search of each plot, in conjunction with our first search day of the study, to remove carcasses killed prior to 15 July. Each day, we randomly selected the order of turbine searches to ensure turbines were searched at different times across the study. Field technicians did not search the same turbines on consecutive days, and the direction in which transects were walked changed daily. We abandoned searches only when heavy rain, lightning, snow, or turbine maintenance created a safety hazard, as determined by the lead field biologist; searches were resumed that day if conditions permitted. Searches commenced within 15 minutes of sunrise, and we attempted to search all turbines within 8 hr after sunrise. We recorded date, start time, end time, turbine number, weather, and observer for each search. When a dead bat was found, the searcher placed a rock pile near the carcass, noted the time, contacted the crew leader, and continued the search. In most cases the crew leader, but on rare events the searcher after searching the entire plot, recorded information on a fatality data sheet, including date, species, sex and age (when possible), observer name, 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) based on condition of the carcass (e.g., eyes, smell, insects). We visually examined each bat carcasses for obvious signs of white-nose syndrome using the Reichard scoring index (Reichard and Kunz 2009). The lead field biologist (M. R. Schirmacher, a USFWS Indiana bat qualified surveyor) confirmed all species identifications. We used rubber gloves to handle all carcasses to reduce possible human scent bias for carcasses later used in scavenger removal trials. We placed each carcass in a labeled plastic bag and stored them in a secured and dedicated freezer at the Operations and Maintenance office building. We obtained a USFWS Special Purpose Utility Permit for Migratory Bird Mortality Monitoring (MB74673A-0) and a Scientific Collecting Permit (No. 2012.077) from the West Virginia Division of Natural Resources to handle bird and bat carcasses.

Field Bias Trials. Although we conducted bias trials during the experiment, they were not necessary to determine the effectiveness of the operational treatments because this is a comparative experiment and not a monitoring study intended to provide estimates of overall fatality rates. Searcher efficiency and carcass removal trials are typically conducted in order to correct for imperfect detection when estimating fatality rates, but because all comparisons were done within the statistical block (that is, the turbine), adjustments for detectability differences between turbines were not necessary. We assigned operation treatments to each turbine each night and experimentally ‘blocked’ on the turbine, so that on any given night one of the twelve turbines was randomly assigned to be fully operational, have a raised cut-in speed of 5 m/s for the entire night, or have a raised cut-in speed of 5 m/s for the first four hours past sunset. Blocking is a statistical tool used to reduce the variability within the blocking factor, or in our case, the variability in searchable area or carcass removal rate among turbines. Because we randomly assign turbines to treatment conditions, the variability within the block is less than the variability between blocks, which allowed us to more precisely estimate the treatment effect (that is, the differences in fatality among the three treatment groups).

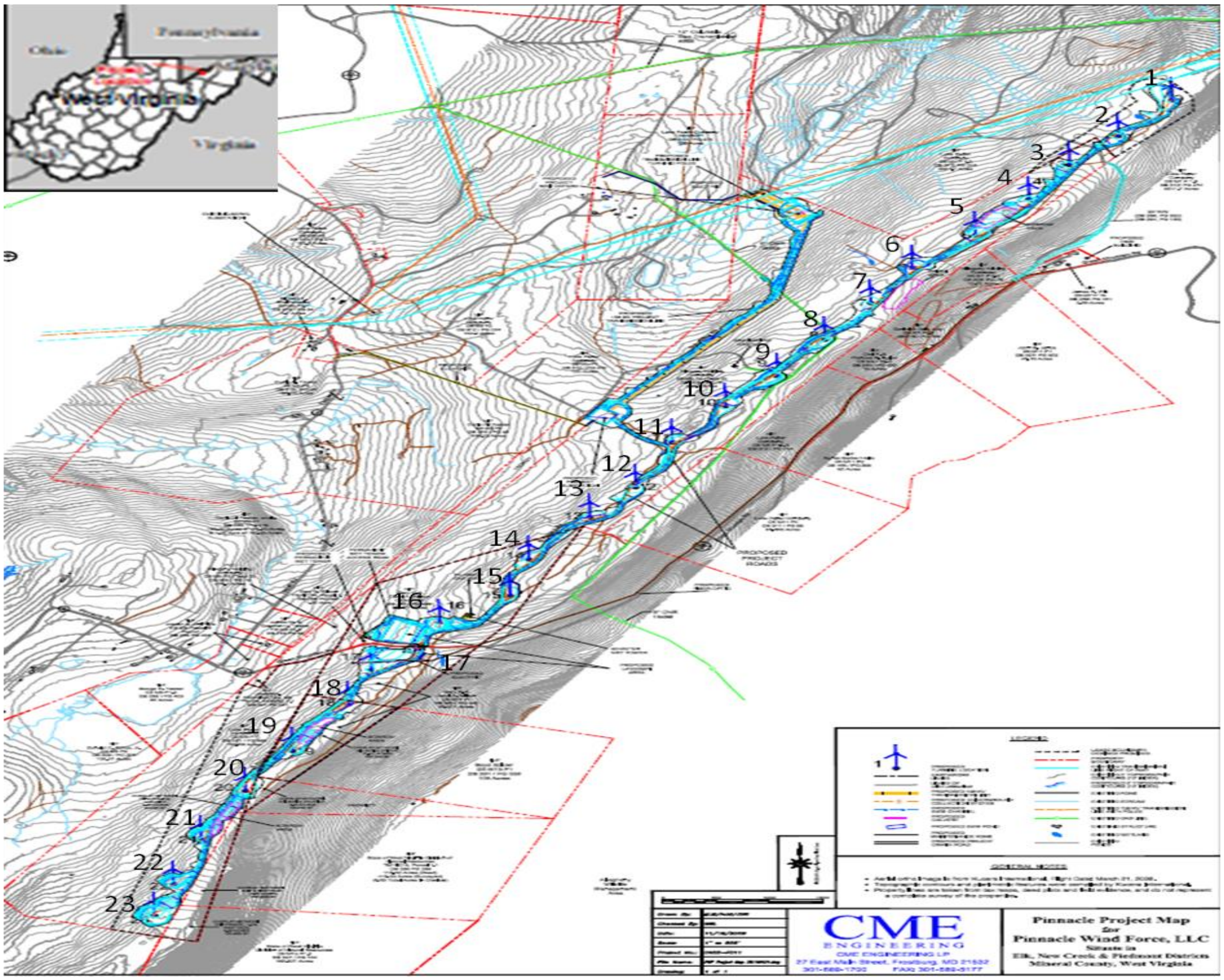

Figure 1. Location of the Pinnacle Wind Farm near Keyser, Mineral County, West Virginia.

Density of carcasses and proportion of area surveyed. The actual area surveyed within a plot varies among turbines and from the delineated theoretical maximum search plot. Density of carcasses is known to diminish with increasing distance from the turbine (e.g., Kerns et al. 2005). A simple adjustment to fatality based on area surveyed would likely lead to over estimates, because unsearched areas tend to be farthest from turbines. The size and configuration of the area searched can greatly affect the proportion of actual fatality represented in the searched area. To accurately estimate the fraction of carcasses landing in the sampled areas, we calculated the total area in each visibility category within each 2-m band from the base of each turbine. We also calculated the number of carcasses (either bird or bat) that were found in each 2-m distance band and visibility class. We used a Poisson regression to model the number of bats what were found, by distance from turbine and visibility class. Distance was treated as a continuous independent variable and visibility class was treated as a categorical independent variable. We used Akaike's Information Criterion for small samples (AIC_c) to select between linear and a quadratic logistic models (Burnham and Anderson 2002). The methods described follow those of Huso and Dalthorp (in press). The best model was used to predict the number of fatalities that would have been found in the entire search area if the entire area was in the easy visibility class. We used as our estimates of the density-weighted proportion, the number of bat fatalities predicted to fall in the searchable area divided by the total number predicted in the entire plot.

Statistical Methods. For each turbine night, we calculated the number of 'fresh' (i.e., killed the previous night) bat fatalities found the next day. We also determined which treatment group the turbine was in (fully operational, 5 m/s all night, or 5 m/s half night), the proportion of the night wind speeds were between 3–5 m/s, the proportion of the night wind speeds were greater than 5 m/s, and the proportion of the night that turbine operations were altered (the proportion of time the wind speed was 3–5 m/s while operational mitigation was in effect).

We tested 13 different models to determine the best variables to describe the occurrence of bat fatalities among turbines. All models were overdispersed Poisson Regression models with the number of fatalities at each turbine for each night as the response variable. The scale parameter was estimated based on the Pearson chi-square score to account for overdispersion in the data and increase standard errors appropriately. The distance-weighted proportion of the area searched (natural log transformed) was included as an offset term to account for different search areas among different turbines. One turbine (turbine 1) had 7 fatalities in one night (July 30th) while in the 5 m/s all night treatment, the second highest number of fatalities was 5 at turbine 9 while in the fully operational treatment. To determine if this 7-fatality outlier was having a strong effect on the results we analyzed the data both with and without this value.

Model selection was conducted using a Quasi-Akaike's Information Criterion score corrected for small sample sizes (QAICc; Burnham and Anderson 2002). Model fit for a Poisson model was adjusted by dividing by the overdispersion parameter for the most complex model to calculate the QAICc value (Richards 2008). This effectively increases the penalty for adding parameters relative to model selection parameters that are uncorrected for overdispersion, thus ensuring that an overly complex model is not selected. For each parameter, we calculated the model-averaged parameter estimate by weighting by the Akaike's weight (ω_i).

All models except the intercept only model included date as a quadratic term because there was a strong pattern in fatalities with date. The first day of the study was set to 0 to facilitate interpretation of model parameters. The quadratic form of date was compared to models with a linear or cubic form and found to have a lower QAICc. Other variables in the model set included treatment group, proportion of wind speeds 3–5 m/s, proportion of wind speeds >5 m/s, and proportion of time turbine operations were altered. We also tested an interaction term of treatment by proportion of wind speeds 3–5 m/s. All models were included with and without the turbine number blocking variable.

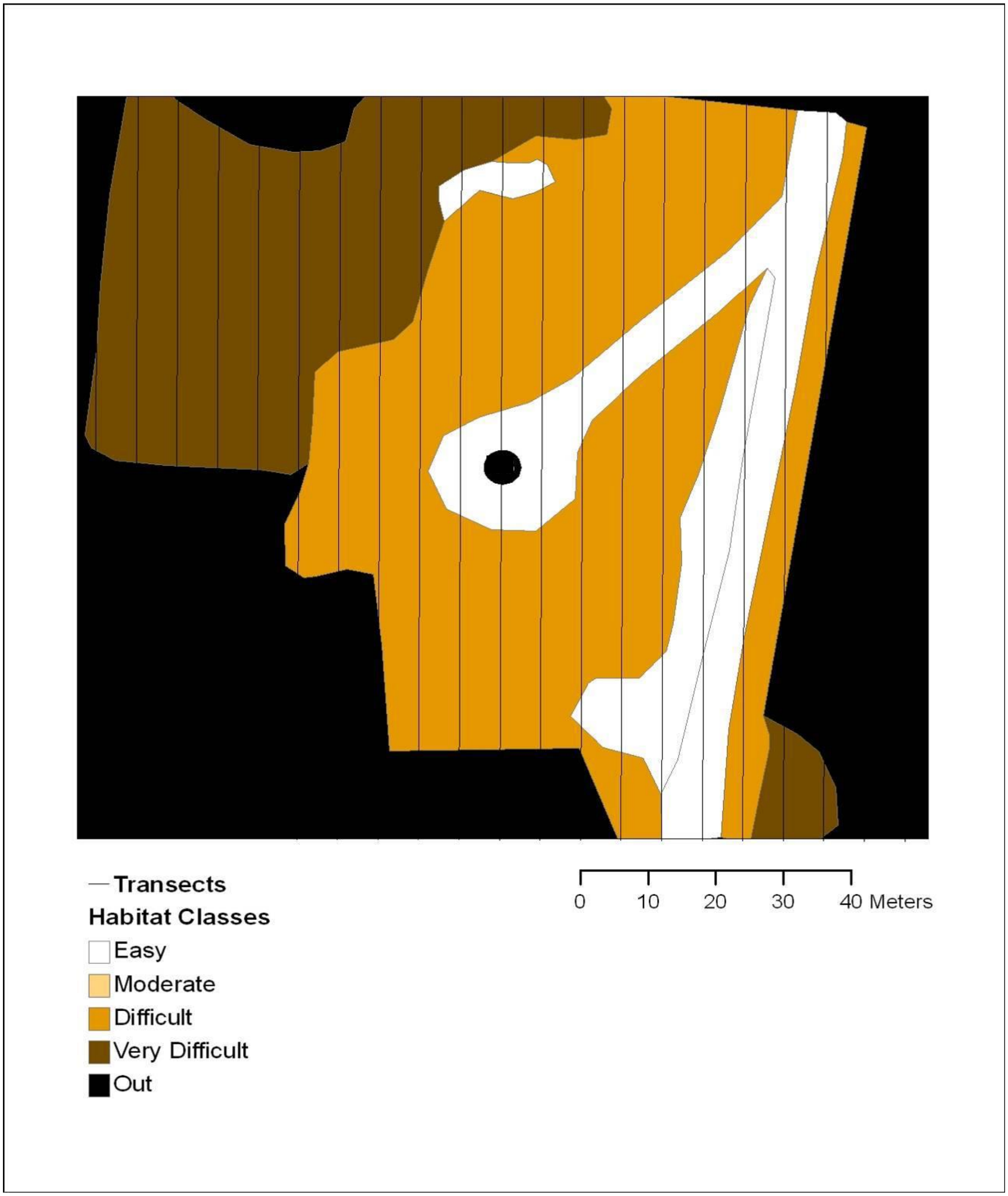

Figure 2. Example carcass search plot at a wind turbine depicting the maximum plot size of 126 m east-west and 120 m north-south, 6 m wide transect lines (searched 3 m on each side), unsearchable area (black), and area encompassed by easy (white), moderate (light tan), difficult (dark tan), and very difficult (brown) visibility habitat.

RESULTS

Fatality Searches. We were able to search turbines 98.5% of the time during daily searches. We were unable to search a plot or partially search a plot on 14 occasions because of unsafe weather conditions (i.e., thunderstorms, snow, ice) or maintenance activities. Because of the differences among turbine plot sizes, average search time varied across the site ranging from 25 minutes for turbine 13 to 43 minutes each for turbines 1 and 2 (Table 1). There also was variation in search times within each turbine plot because of different searchers or weather conditions. The density weighted area varied among turbines from 0.485 at turbine 13 to 0.685 at turbine 11 (Table 2).

Bat Fatality. We found a total of 186 bat carcasses, of which 31, 89, and 66 were found in July, August and September, respectively (Fig. 3). The number of carcasses recovered varied by turbine ranged from 9 carcasses at turbines 13 and 19 to 21 carcasses at turbines 2 and 21 (Table 3). We recovered carcasses from 6 different species, including eastern red bats, hoary bats, silver-haired bats, tri-colored bats, big brown bats, and Seminole bats (Table 4). For most species, we recovered more males than females, particularly for eastern red bats. Migratory tree-roosting bats (i.e., eastern red bats, hoary bats, and silver-haired bats) comprised 79% (n = 147) of fatalities. Big brown bats and tri-colored bats, two species impacted by WNS, collectively represented 19% (n = 36) of carcasses found. We found no evidence of WNS on any bat recovered during the study.

Table 1. Mean search times, in minutes (min), for each turbine with the associated standard deviation for the 12 turbines searched daily at the Pinnacle Wind Farm, Mineral County, West Virginia, 15 July–30 September 2012.

Turbines	Mean search time (min)	SD (min)
1	43	8
2	43	8
5	39	7
7	37	8
9	32	9
11	39	7
13	25	5
14	28	5
16	33	9
19	41	8
21	30	6
22	35	8

Table 2. Estimated density-weighted proportion of searched area for bats during daily searches of 12 turbines at the Pinnacle Wind Farm, Mineral County, West Virginia, 15 July–30 September 2012.

Daily Turbines	**Bats**
1	0.650
2	0.682
5	0.644
7	0.643
9	0.512
11	0.685
13	0.485
14	0.574
16	0.628
19	0.623
21	0.587
22	0.666

Table 3. Total number of bat carcasses, by turbine, recovered during daily searches of 12 turbines at the Pinnacle Wind Farm, Mineral County, West Virginia, 15 July–30 September 2012.

Daily Turbines	**Bats**
1	19
2	21
5	16
7	18
9	13
11	14
13	9
14	17
16	14
19	9
21	21
22	15
Total	**186**

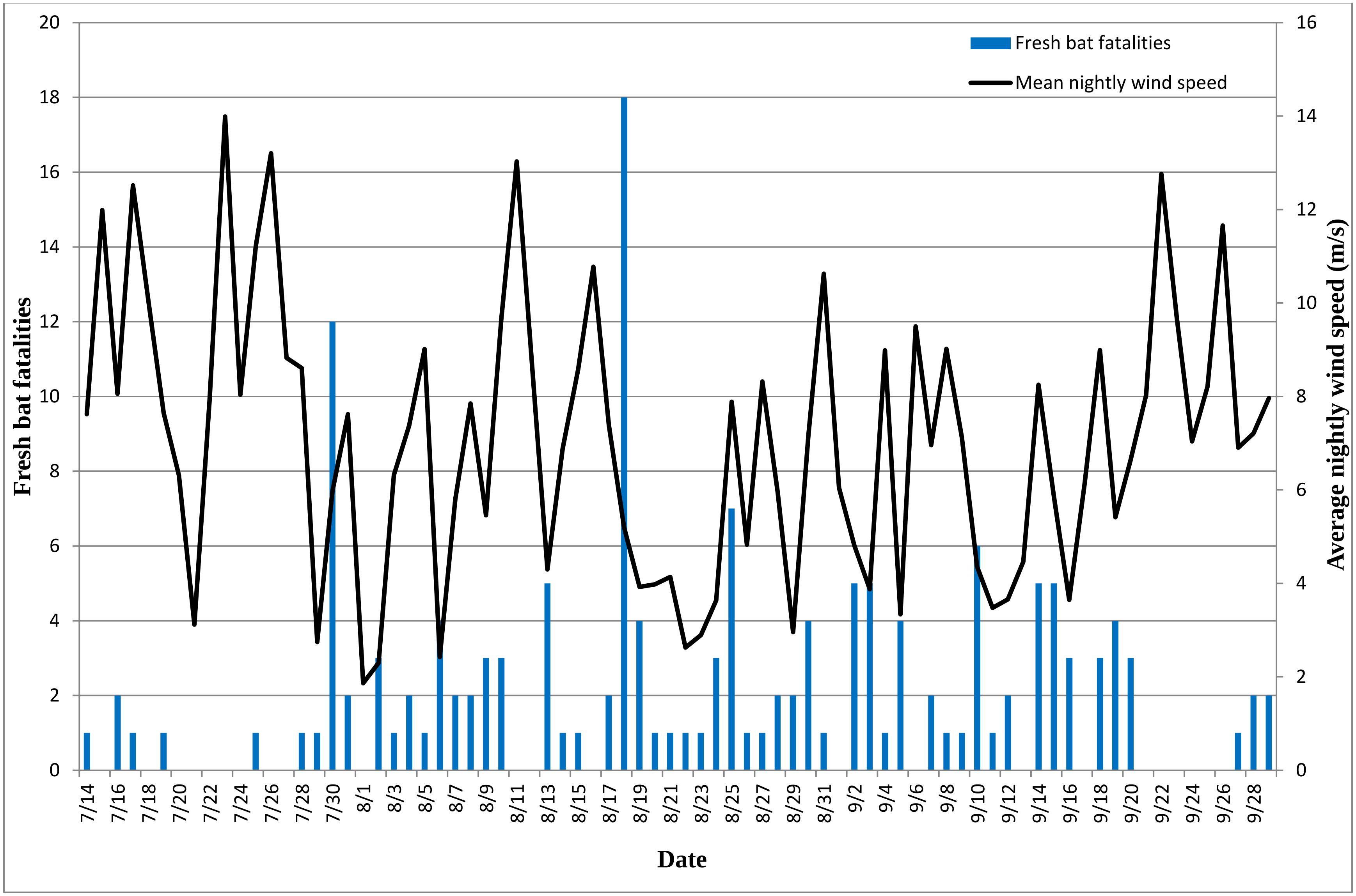

Figure 3. Number of fresh (i.e., killed the night before) bat carcasses recovered during daily searches of 12 turbines, and average nightly wind speed at the Pinnacle Wind Farm, Mineral County, West Virginia, 15 July–30 September 2012.

Table 4. Total number of bat carcasses, by species, age, and sex, recovered during daily searches of 12 turbines at the Pinnacle Wind Farm, Mineral County, West Virginia, 15 July–30 September 2012.

	Adult			**Juvenile**			**Unknown**			
Species	**Female**	**Male**	**Unknown**	**Female**	**Male**	**Unknown**	**Female**	**Male**	**Unknown**	**Total**
Eastern red bat	15	41	2	4	8	0	1	2	5	**78**
Hoary bat	20	26	1	0	1	0	0	1	7	**56**
Silver-haired	3	8	1	0	0	0	0	0	1	**13**
Tri-colored bat	3	11	2	2	3	0	1	0	1	**23**
Big brown bat	3	2	0	5	1	0	0	1	1	**13**
Seminole bat	0	1	0	0	0	0	0	0	0	**1**
Unknown	0	0	0	0	0	0	0	0	2	**2**
Total	**44**	**89**	**6**	**11**	**13**	**0**	**2**	**4**	**17**	**186**

Comparison of Treatments. Of the 186 total bat carcasses found, 155 were determined to be fresh and used to relate to the previous night's treatment (Fig. 4). In general, we observed no consistent pattern of number of fresh bat fatalities with average nightly wind speed (Fig. 3). Thirty-nine fatalities occurred when turbines were operating at 5 m/s all night, 56 occurred when turbines were operating at 5 m/s half-night, and 60 occurred when turbines were fully operational. Average nightly wind speeds among turbines across the study showed that wind speed was above 5 m/s over 70% of the time (Fig. 5). Average nightly wind speed was only between 3 and 5 m/s (i.e., the time when treatments were implemented) for approximately 17% of the time during the study.

The most parsimonious model in our candidate model set included the variables date, treatment, proportion of wind speeds between 3–5 m/s and a wind speed by treatment interaction (Table 6a). This model had relatively high support ($\omega_i = 0.589$). The second best model that included date and the proportion of wind speed between 3–5 m/s was 1.91AIC_c units higher. Results were similar without the outlier, but the best model had greater weight ($\omega_i = 0.948$; Table 6b). For the best model, the number of fatalities increased with date until 18 August, including all data, and 23 August, excluding the outlier, and then declined after that date. The fatality rate increased with the proportion of wind speeds between 3–5 m/s for fully operational, increased at a slower rate for turbines undergoing the 5 m/s half night treatment, and did not increase for turbines that experienced the 5 m/s all night treatment, with and without the outlier (Table 7a,b; Fig. 6a,b). The slope for 5 m/s all night turbines was significantly different from fully operational turbines (*P* = 0.022), but the slope for the 5 m/s half night treatment was not significantly different from the fully operational turbines (*P* = 0.084). Adding the turbine variable did not improve the model, suggesting that there was not large heterogeneity in fatality rates among turbines.

With the model including only the variables date and treatment group and with all data points, differences among the three treatments were not statistically significant (*P* = 0.255). However, based on the best model, the effectiveness of the treatments depended on the proportion of the night that wind speed was between 3 and 5 m/s. For example, if that proportion equals 50%, then fatality is reduced by 72.2% (95% CI: 32.3–88.6%) when turbine cut-in speed is raised to 5 m/s all night. Removing the outlier resulted in a statistically significant difference among the three treatments (*P* = 0.036) for the model including date and treatment group. However, only the 5 m/s all night treatment was significantly different from fully operating turbines ($\beta = -0.627$; SE = 0.255; *P* = 0.014). For the model with just date and treatment, the fatalities for the 5 m/s all night treatment were estimated to be 46.6% (95%CI: 12.0–77.6%) that of fully operating turbines. Removing the outlier and using the best model, and assuming the proportion of the night that wind speed is between 3 and 5 m/s is equal to 50%, we found an 81.7% (95% CI: 54.3–92.7%) reduction in fatalities at 5 m/s treatment turbines compared to fully operating turbines. The 5 m/s half night treatment turbines were never statistically different from fully operating turbines regardless of model or whether or not the outlier was included.

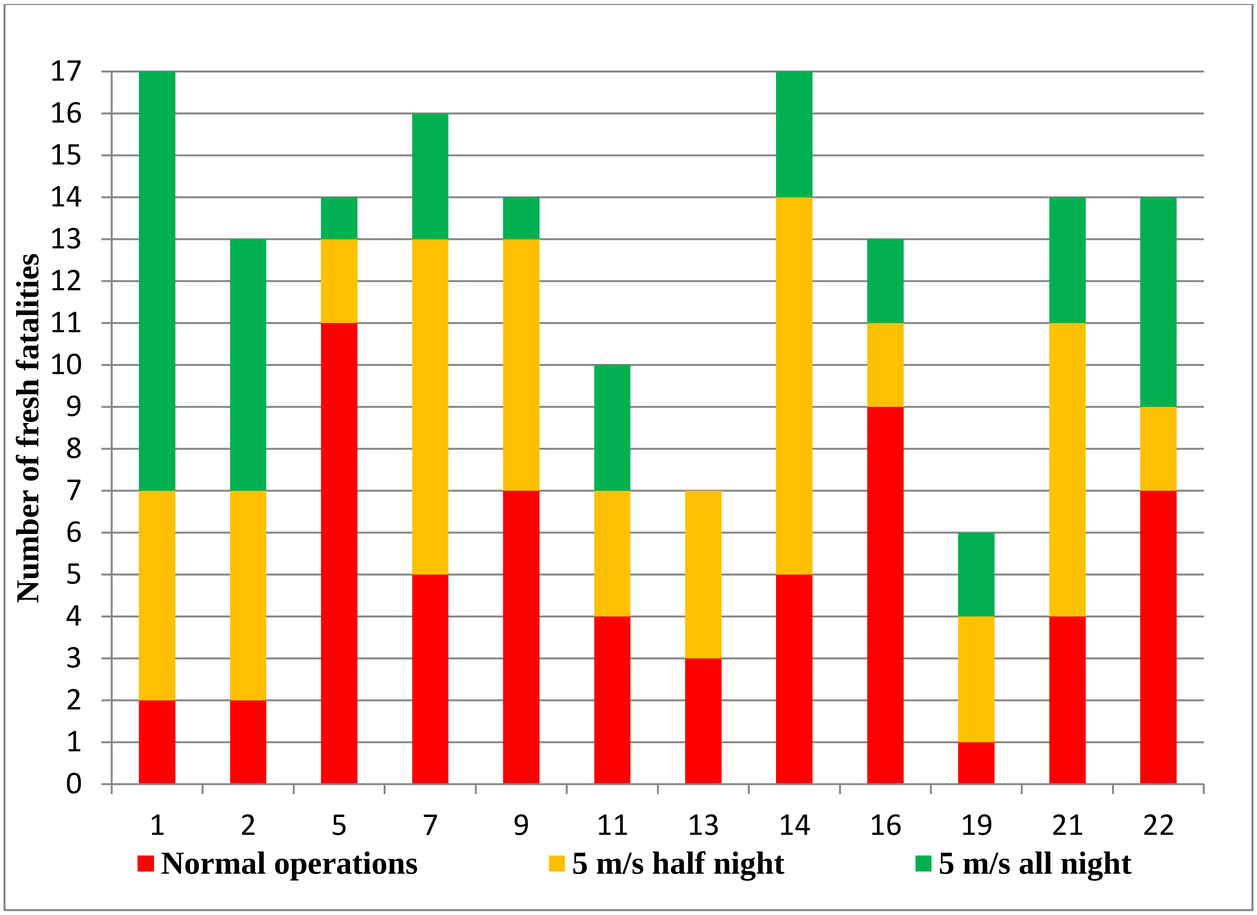

Figure 4. Number of fresh (i.e., killed the previous night) bat carcasses, by turbine and treatment, recovered during daily searches at the Pinnacle Wind Farm, Mineral County, West Virginia, 15 July–30 September 2012.

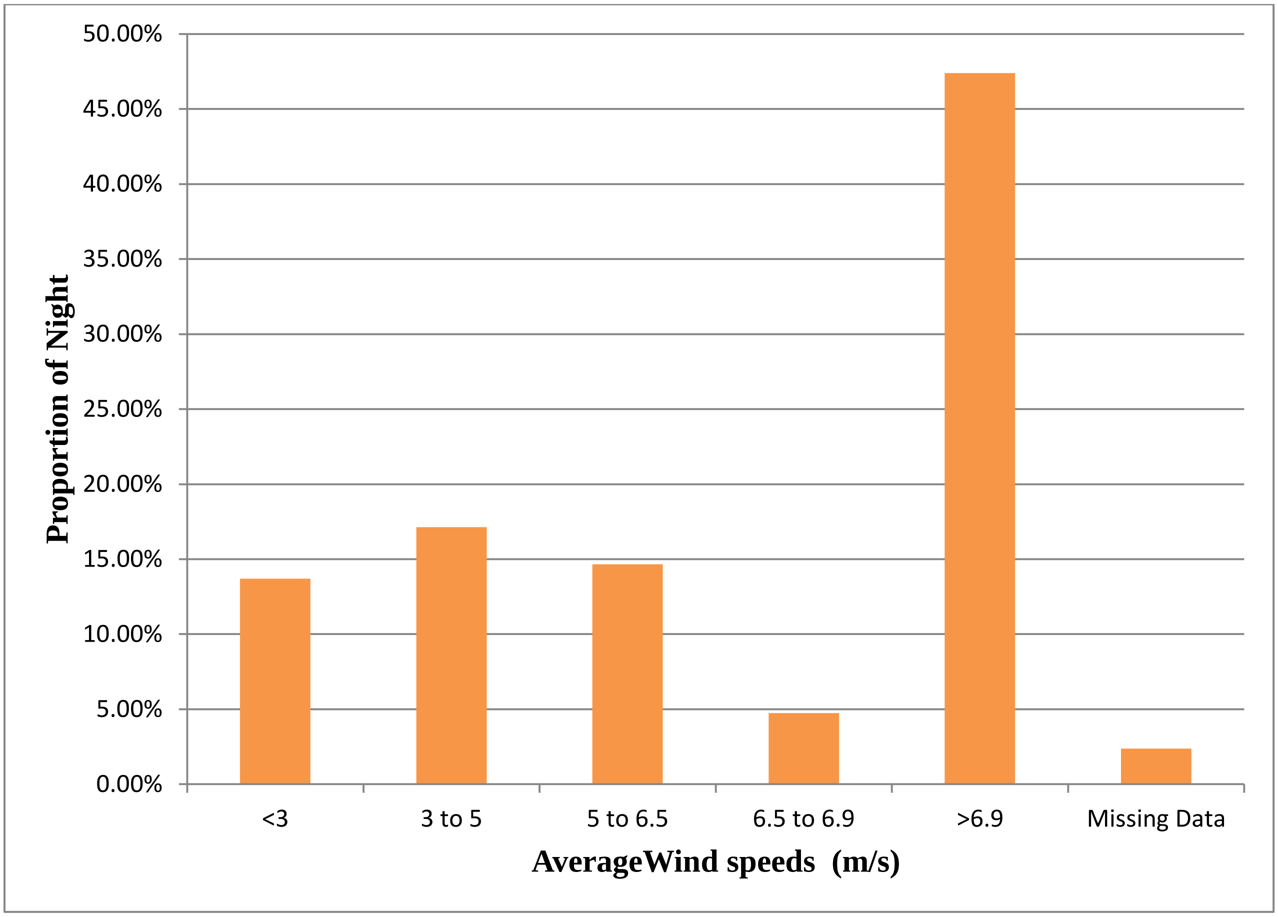

Figure 5. Average nightly wind speed (m/s) at 12 turbines during the 75 day study period at the Pinnacle Wind Facility, Mineral County, West Virginia, 15 July–30 September 2012.

Table 6a. Model-selection results (overdispersed Poisson regression) for analyses of observed nightly bat fatalities at 12 turbines over 75 nights. The best model contained the variables date (as a quadratic term), proportion of time wind speed was between 3 and 5 m/s, and the interaction between wind speed and treatment.

Model[a]	***n***[b]	**K**[c]	**QAIC$_c$**[d]	**ΔQAIC$_c$**[e]	**w$_i$**[f]
DateSq, Prop. Wind 3-5, Treatment, Wind*Treatment	936	9	574.15	0.00	0.589
DateSq, Prop. Wind 3-5	936	5	576.06	1.91	0.227
DateSq	936	4	578.99	4.84	0.052
DateSq, Prop. Curtailed	936	5	579.01	4.86	0.052
DateSq, Prop. Wind >5	936	5	579.29	5.13	0.045
DateSq, Treatment	936	6	579.87	5.72	0.034
DateSq, Turbine, Prop. Wind 3-5, Treatment, Wind*Treatment	936	20	589.00	14.84	0.000
DateSq, Turbine, Prop. Wind 3-5 m/s	936	16	590.96	16.81	0.000
Intercept Only	936	2	591.48	17.32	0.000
DateSq, Turbine	936	15	594.06	19.90	0.000
DateSq, Turbine, Prop. Curtailed	936	16	594.06	19.91	0.000
DateSq, Turbine, Prop. Wind >5 m/s	936	16	594.47	20.31	0.000
DateSq, Turbine, Treatment	936	17	595.04	20.88	0.000

[a] DateSq=Date as a quadratic term, 14 July was set to zero; Prop. Wind 3-5=proportion of time windspeed was between 3-5 m/s; Prop. Wind >5= proportion of time the windspeed was above 5 m/s; Treatment=Curtailed all night, curtailed half night, or fully operational; Turbine= individual turbine numbers; Prop. Curtailed= proportion of time the turbine was stopped when windspeed was 3-5 m/s .

[b] Sample size.

[c] Number of estimable parameters in the approximating model.

[d] Quasi-Akaike's Information Criterion, corrected for small sample size.

[e] Difference in value between the QAIC$_c$ of the current model and that of the best approximating model.

[f] Akaike Weight = Probability that the current model (i) is the best approximating model in the candidate set.

Table 6b. Model-selection results (overdispersed Poisson regression) for analyses of observed nightly bat fatalities at 12 turbines over 75 nights, with one outlier removed. The best model contained the variables date (as a quadratic term), proportion of time wind speed was between 3 and 5 m/s, and the interaction between wind speed and treatment.

Model[a]	***n***[b]	**K**[c]	**QAIC$_c$** [d]	**ΔQAIC$_c$** [e]	**w$_i$** [f]
DateSq, Prop. Wind 3-5, Treatment, Wind*Treatment	935	9	652.35	0.00	0.948
DateSq, Prop. Curtailed	935	5	659.92	7.56	0.022
DateSq, Treatment	935	6	660.54	8.18	0.016
DateSq, Prop. Wind 3-5	935	5	661.93	9.57	0.008
DateSq	935	4	664.02	11.67	0.003
DateSq, Prop. Wind >5	935	5	664.25	11.90	0.002
DateSq, Turbine, Prop. Wind 3-5, Treatment, Wind*Treatment	935	20	665.64	13.29	0.001
DateSq, Turbine, Prop. Curtailed	935	16	673.36	21.01	0.000
DateSq, Turbine, Treatment	935	17	674.04	21.69	0.000
DateSq, Turbine, Prop. Wind 3-5 m/s	935	16	675.41	23.05	0.000
DateSq, Turbine	935	15	677.51	25.15	0.000
DateSq, Turbine, Prop. Wind >5 m/s	935	16	677.77	25.42	0.000
Intercept Only	935	2	682.99	30.64	0.000

[a] DateSq=Date as a quadratic term, 14 July was set to zero; Prop. Wind 3-5=proportion of time wind speed was between 3-5 m/s; Prop. Wind >5= proportion of time the wind speed was above 5 m/s; Treatment=Curtailed all night, curtailed half night, or fully operational; Turbine= individual turbine numbers; Prop. Curtailed= proportion of time the turbine was stopped when wind speed was 3-5 m/s.

[b] Sample size.

[c] Number of estimable parameters in the approximating model.

[d] Quasi-Akaike's Information Criterion, corrected for small sample size.

[e] Difference in value between the QAIC$_c$ of the current model and that of the best approximating model.

[f] Akaike Weight = Probability that the current model (i) is the best approximating model in the candidate set.

Table 7a. Model-weighted parameter estimates, standard error (SE), and *P*-value of variables included in the analysis of nightly bat fatalities from 12 turbines at the Pinnacle Wind Farm, Mineral County, West Virginia, 15 July–30 September 2012.

Variable[a]	Mean	SE	95% CI	*P*-value[b]
Intercept	–2.668	0.487	(-3.622, -1.741)	<0.001***
Date	0.071	0.024	(0.023, 0.119)	0.004**
Date Squared	–0.0010	0.0003	(-0.002, -0.0004)	0.001***
Trmt=Curtailed	0.216	0.427	(-0.621, 1.053)	0.613
Trmt =Half Curtailed	0.368	0.392	(-0.400, 1.136)	0.348
Trmt =Fully Operational	0	–	–	–
Trmt =Curtailed*Prop. Wind3-5	–3.067	1.339	(-5.692, -0.442)	0.022*
Trmt =Half Curtailed*Prop. Wind3-5	–2.021	1.170	(-4.314, 0.272)	0.084
Trmt =Fully Operational*Prop. Wind 3-5	0	–	–	–
Prop. Curtailed	–1.018	0.788	(-2.563, 0.527)	0.197
Prop. Wind >5	–0.388	0.298	(-0.972, 0.196)	0.193
Prop. Wind 3-5	2.359	1.044	(0.313, 4.405)	0.024**

[a] DateSq=Date as a quadratic term, 14 July was set to zero; Prop. Wind 3-5=proportion of time wind speed was between 3-5 m/s; Prop. Wind >5= proportion of time the wind speed was above 5 m/s; Trmt=Curtailed all night, curtailed half night, or fully operational; Turbine= individual turbine numbers; Prop. Curtailed= proportion of time the turbine was stopped when wind speed was 3-5 m/s.

[b] Significance of *P*-value: * <0.05, ** <0.01, *** <0.001.

Table 7b. Model-weighted parameter estimates, standard error (SE), and *P*-value of variables included in the analysis of nightly bat fatalities near 12 turbines (with one outlier was removed) at the Pinnacle Wind Farm, Mineral County, West Virginia, 15 July–30 September 2012.

Variable	Mean	SE	95% CI	*P*-value[a]
Intercept	–3.027	0.466	(-3.941, -2.112)	<0.001***
Date	0.081	0.023	(0.036, 0.126)	<0.001***
Date Squared	–0.001	0.0003	(-0.002, -0.0004)	0.001***
Trmt =Curtailed	0.182	0.381	(-0.566, 0.929)	0.634
Trmt =Half Curtailed	0.387	0.343	(-0.285, 1.059)	0.259
Trmt =Fully Operational	0	–	–	–
Trmt =Curtailed*Prop. Wind3-5	–3.791	1.317	(-6.373, -1.210)	0.004**
Trmt =Half Curtailed*Prop. Wind3-5	–2.014	1.035	(-4.043, 0.015)	0.052
Trmt =Fully Operational*Prop. Wind 3-5	0	–	–	–
Prop. Curtailed	–1.756	0.783	(-3.290, -0.222)	0.025*
Prop. Wind >5	–0.369	0.278	(-0.915, 0.177)	0.177
Prop. Wind 3-5	2.706	0.744	(1.247, 4.165)	<0.001***

[a] DateSq=Date as a quadratic term, 14 July was set to zero; Prop. Wind 3-5=proportion of time wind speed was between 3-5 m/s; Prop. Wind >5= proportion of time the wind speed was above 5 m/s; Trmt=Curtailed all night, curtailed half night, or fully operational; Turbine= individual turbine numbers; Prop. Curtailed= proportion of time the turbine was stopped when wind speed was 3-5 m/s.

[b] Significance of *P*-value: * <0.05, ** <0.01, *** <0.001.

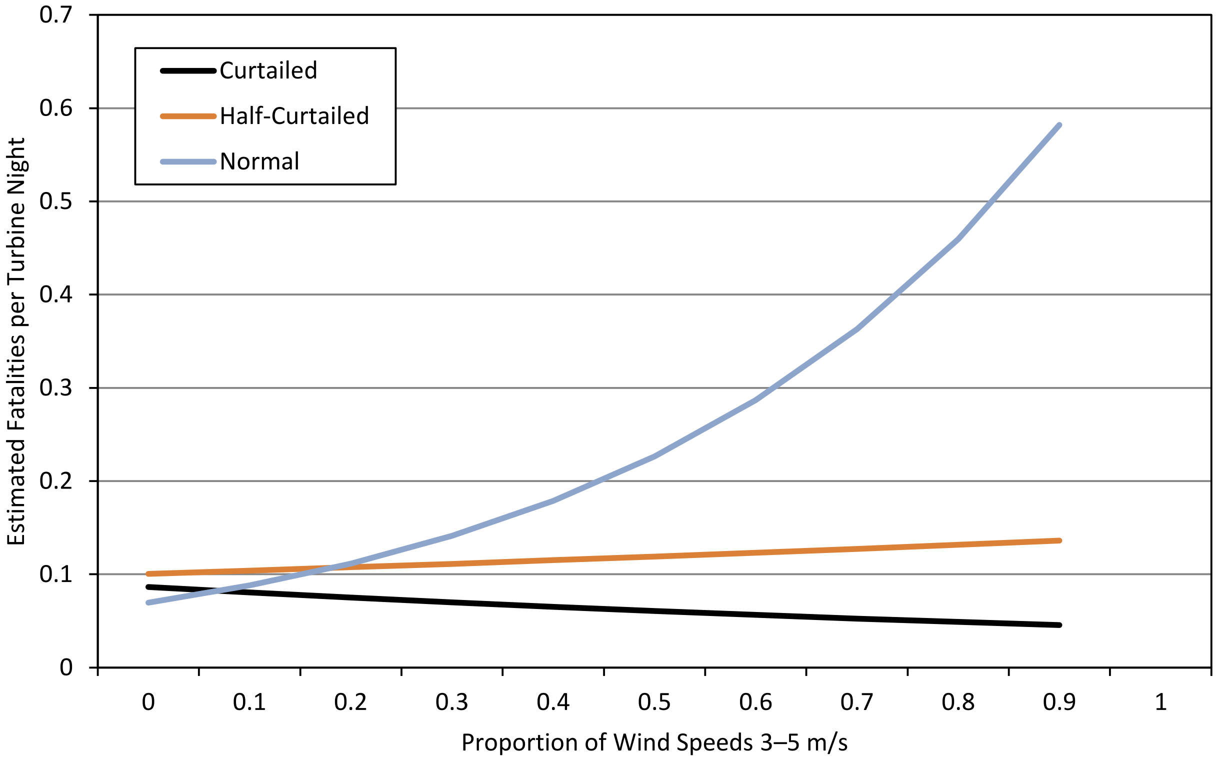

Figure 6a. The estimated relationship between the proportion of wind speed between 3–5 m/s and the estimated fatalities per turbine per night.

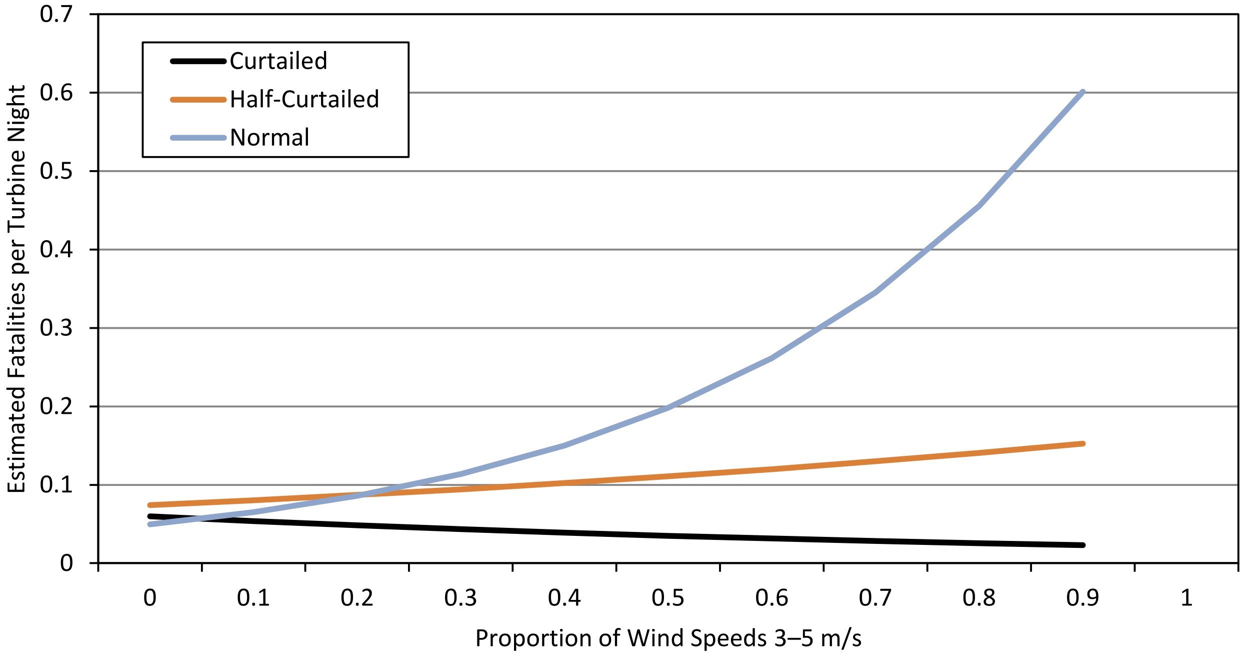

Figure 6b. The estimated relationship between the proportion of wind speed between 3–5 m/s and the estimated fatalities per turbine per night, with one outlier removed.

DISCUSSION

Operational mitigation studies consistently show significant reductions in bat fatalities when turbines are either feathered below normal cut-in speeds or feathered up to raised cut-in speeds (Baerwald et al. 2009, Young et al. 2010, Arnett et al. 2011, Good et al. 2011, 2012). Our success in implementing an operational mitigation strategy varied with the experimental treatment groups. We found no difference between the 5 m/s half night treatment and fully operating turbines regardless of model. Our results differ from those of Young et al. (2011), that showed a 47% (included all nights of the study) and 72% (including only nights when the treatments were in effect) reduction in bat fatalities at turbines that were feathered below normal cut-in speed (4 m/s) for the first five hours past sunset. Our lack of treatment effect likely is a result of the small proportion of time wind speeds were between 3 and 5 m/s. Similarly, Arnett et al. (2011) were unable to differentiate the amount of time different cut-in speed treatments (5.0 m/s and 6.5 m/s) were in effect because wind speeds were seldom between the two treatments. It also is possible our treatment cut-in speed for this site was too low or our half night treatment did not encompass the entire period in which bats were most active. Ours is only the second study to investigate operational mitigation during different periods of the night. Additional data are needed to determine whether this is a feasible method of maximizing wind energy production and minimizing bat fatalities.

We observed a 47% reduction in bat fatalities for the 5 m/s all night treatment compared to fully operating turbines, but only when we removed an outlier (i.e., a night when 7 fatalities were recovered from a 5 m/s all night treatment turbine) from the dataset. Based on the best model, which incorporated the proportion of the night that wind speeds were between 3 and 5 m/s, we observed a 72.2% reduction in bat fatalities, when this proportion equaled 50%. With the outlier removed, using the best model and incorporating a 50% proportion of the night wind speeds were between 3 and 5 m/s, bat fatalities were reduced by 81.7%. At the PWF, wind speeds between 3 and 5 m/s only occurred for 17% of the time during the study, thus limiting the amount of time the treatments were in effect. Similarly, Young et al. (2012) were unable to demonstrate a significant difference between treatments and noted that the amount of time treatments would have been in effect was <10%

Operational mitigation strategies to reduce bat activity are based on studies showing that both bat activity and fatality decrease with increasing wind speed during the summer–fall migration period (Arnett et al. 2008, Rydell et al. 2010). Bat activity and fatality also typically decrease with lower temperatures, precipitation, and conditions associated with the passage of storm fronts (Erkert 1982, Erickson and West 2002, Kerns et al. 2005, Reynolds 2006, Cryan and Brown 2007, Arnett et al. 2008, Horn et al. 2008, Rydell et al. 2011, Weller and Baldwin 2012). Adverse weather conditions may suppress insect abundance and activity or make flying inefficient. Weller and Baldwin (2012) suggested incorporating other weather variables, in addition to wind speed, could aid in developing predictive models and optimize operational mitigation strategies by minimizing the time required to alter turbine operations. If bat activity at the PWF remains high throughout the night, perhaps incorporating other weather variables can help optimize wind production and minimize bat fatalities.

Numerous factors influence the logistics and financial costs of changing the cut-in speed of wind turbines to reduce bat fatalities, including the type and size of wind turbines, software system available to program turbine operations, market or contract prices of power, power purchase agreements and associated fines for violating delivery of power, and variation in temporal consistency, speed, and duration of wind across different sites. Baerwald et al. (2009) reported a 42.3% reduction in the amount of time turbines would have produced electricity. However, because of the technological limitations of the V80 turbines at that facility, cut-in speeds were altered 24 hours/day during the entire study. Arnett et al. (2011) reported the loss in power production resulting from the experimental treatments was low relative to annual energy production (i.e., 0.3–1%). Power loss for the 5.0 m/s treatment was 1/3 that of the 6.5 m/s treatment, reflecting the cubic effect of wind speed and power produced (Albadi and El-Saadany 2009). Until other studies report the financial costs of implementing operational mitigation, it will be difficult to determine the economic viability of this strategy.

Presently, our understanding of the sustainability of wind energy impacts on bats is limited by the lack of knowledge of population size, structure and dynamics (O'Shea et al. 2003). Until we have a better understanding of bat populations, our ability to determine whether the reduction in bat fatalities, from operational mitigation measures, is adequate to mitigate the adverse effects of wind energy development remains unknown. Gathering population data that is sufficient to address this issue is a priority, but such data are not expected to be available in the near future, particularly for migratory tree-roosting bats that constitute the highest proportion of bat fatalities. Because bats have low reproductive potential (i.e., reproducing once per year and typically only having 1-2 pups) and require high adult survivorship to avoid population declines, they are not able to recover quickly from large-scale impacts (Findley 1993, Barclay and Harder 2003). Given the magnitude and extent of bat fatalities throughout North America, we believe that wind operators should implement operational mitigation strategies, even in the absence of population data.

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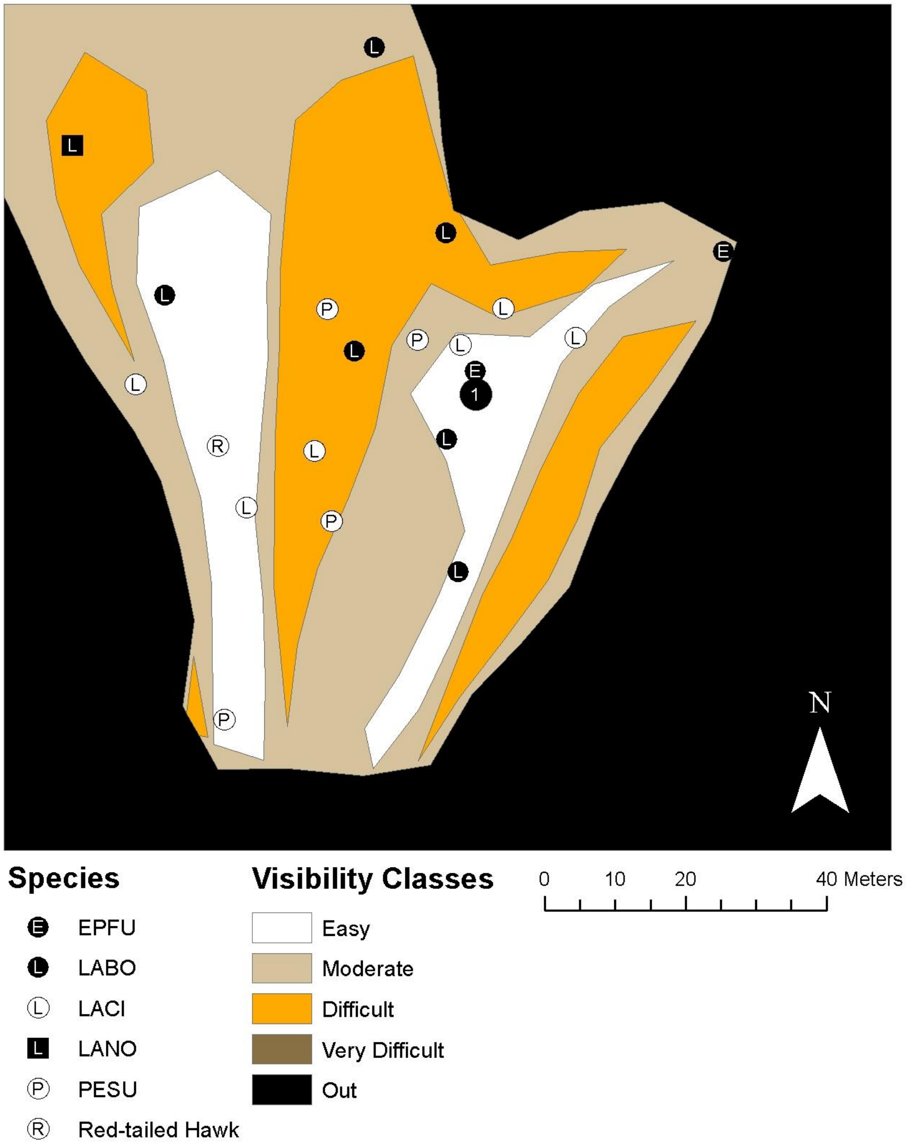
APPENDIX 1

MAPS OF TURBINE PLOTS, VISIBILITY CLASSES AND FATALITIES FROM 12 TURBINES SEARCHED DAILY AT THE PINNACLE WIND FACILITY, MINERAL COUNTY, WEST VIRGINIA, 2012

Turbine 1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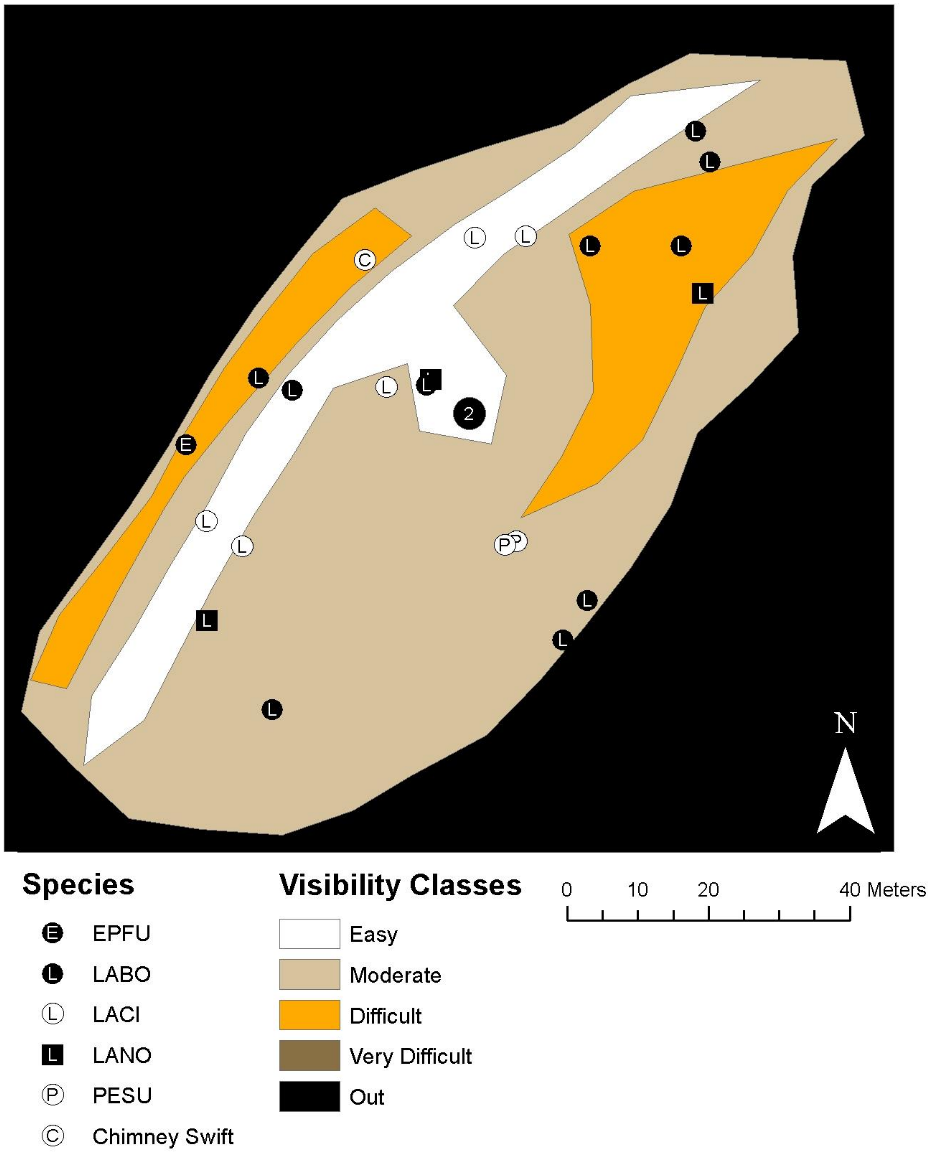
Turbine 2



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Chimney Swift
Visibility Classes
Easy
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Difficult
Very Difficult
Out
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Turbine 5


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Ⓛ LACI
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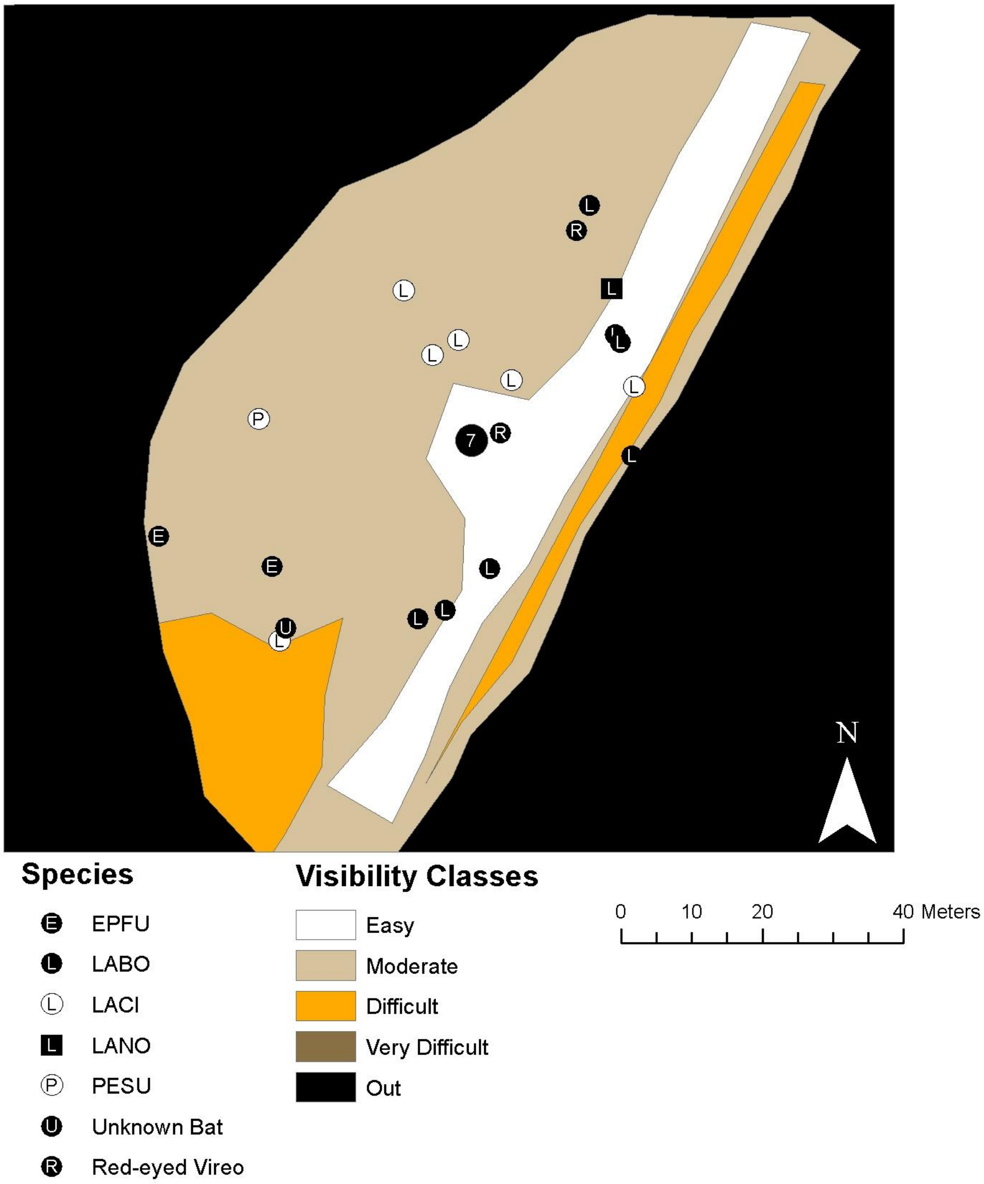
Turbine 7



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Turbine 9


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P PESU
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C Chimney Swift
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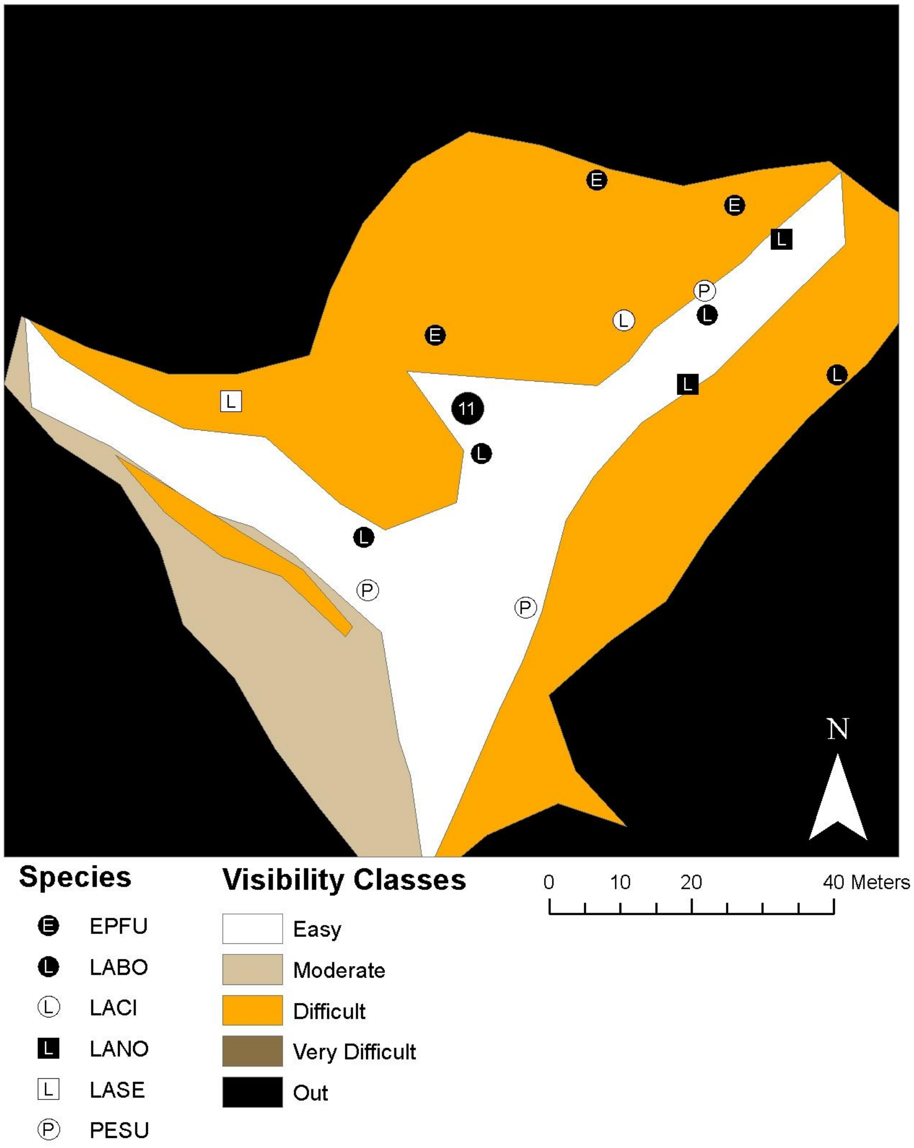
Turbine 11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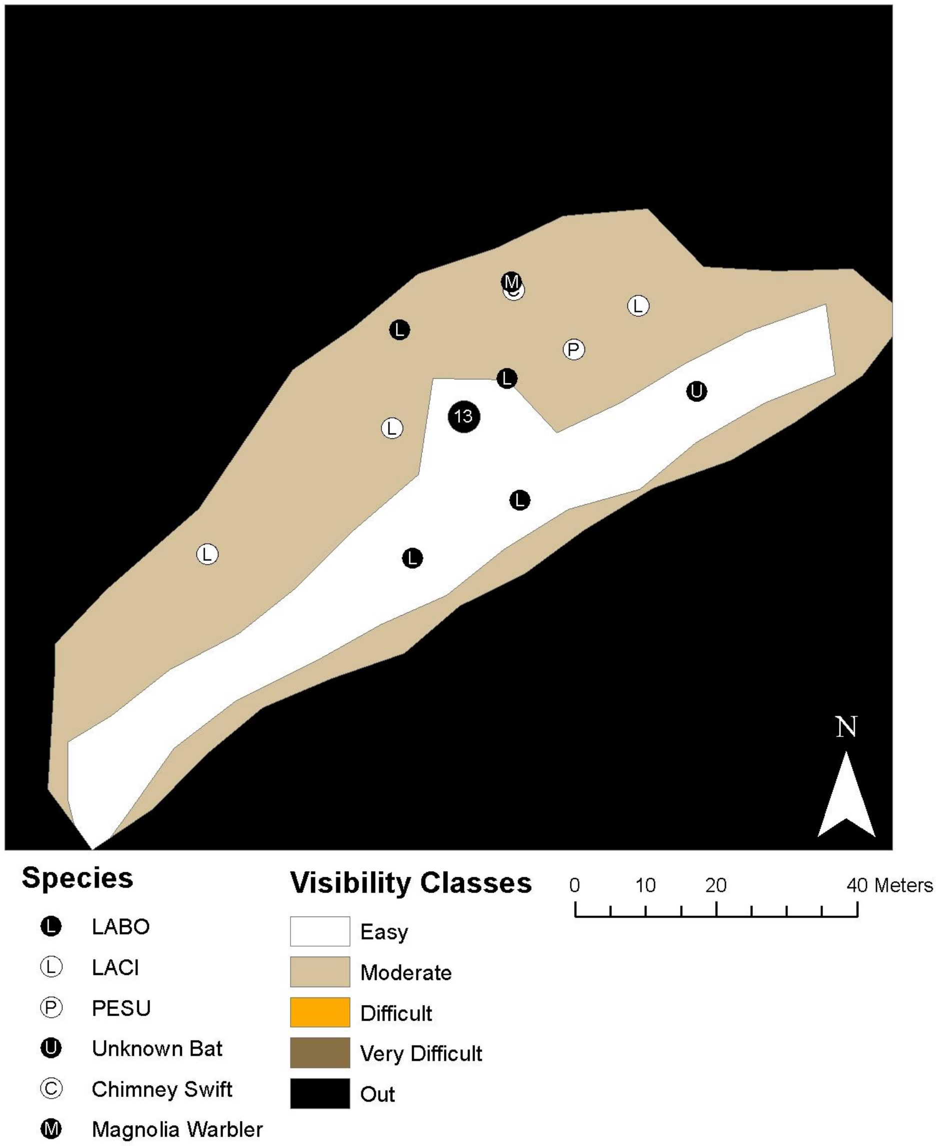
Turbine 13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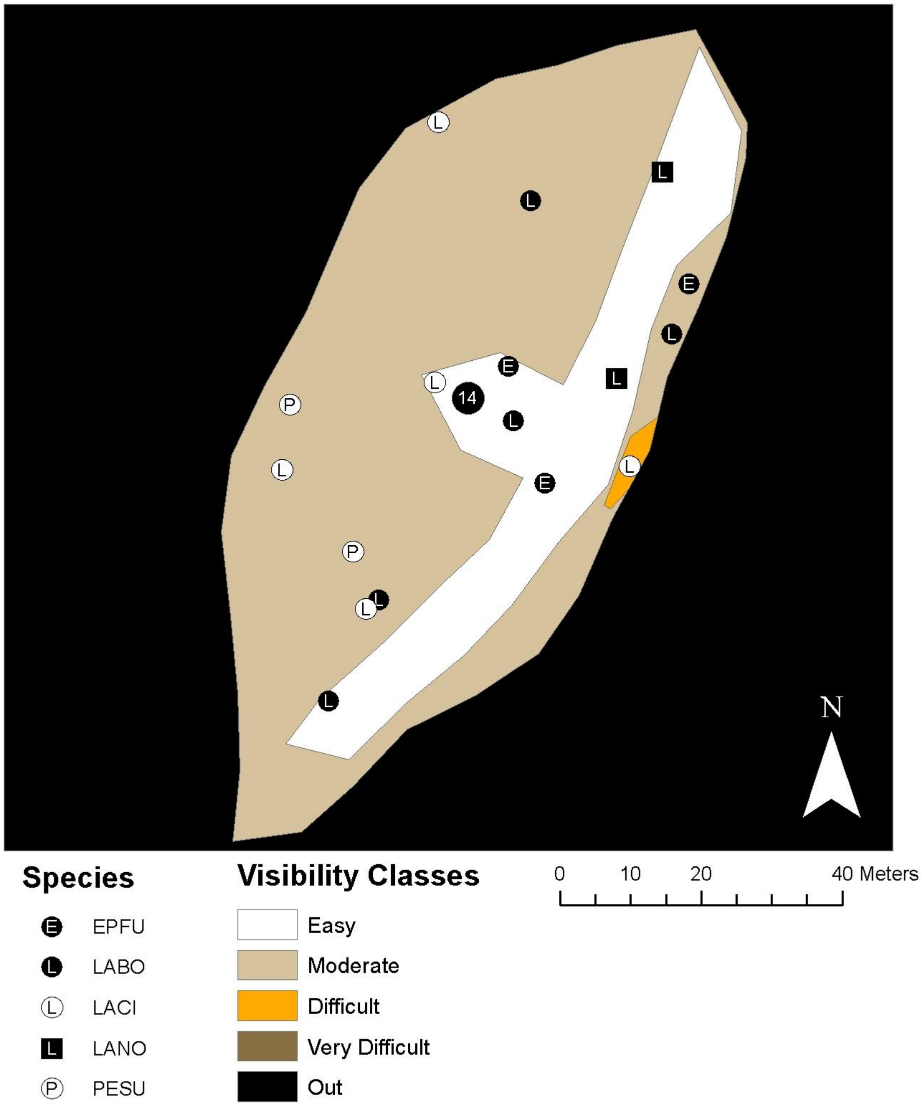
Turbine 14



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Visibility Classes
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Moderate
Difficult
Very Difficult
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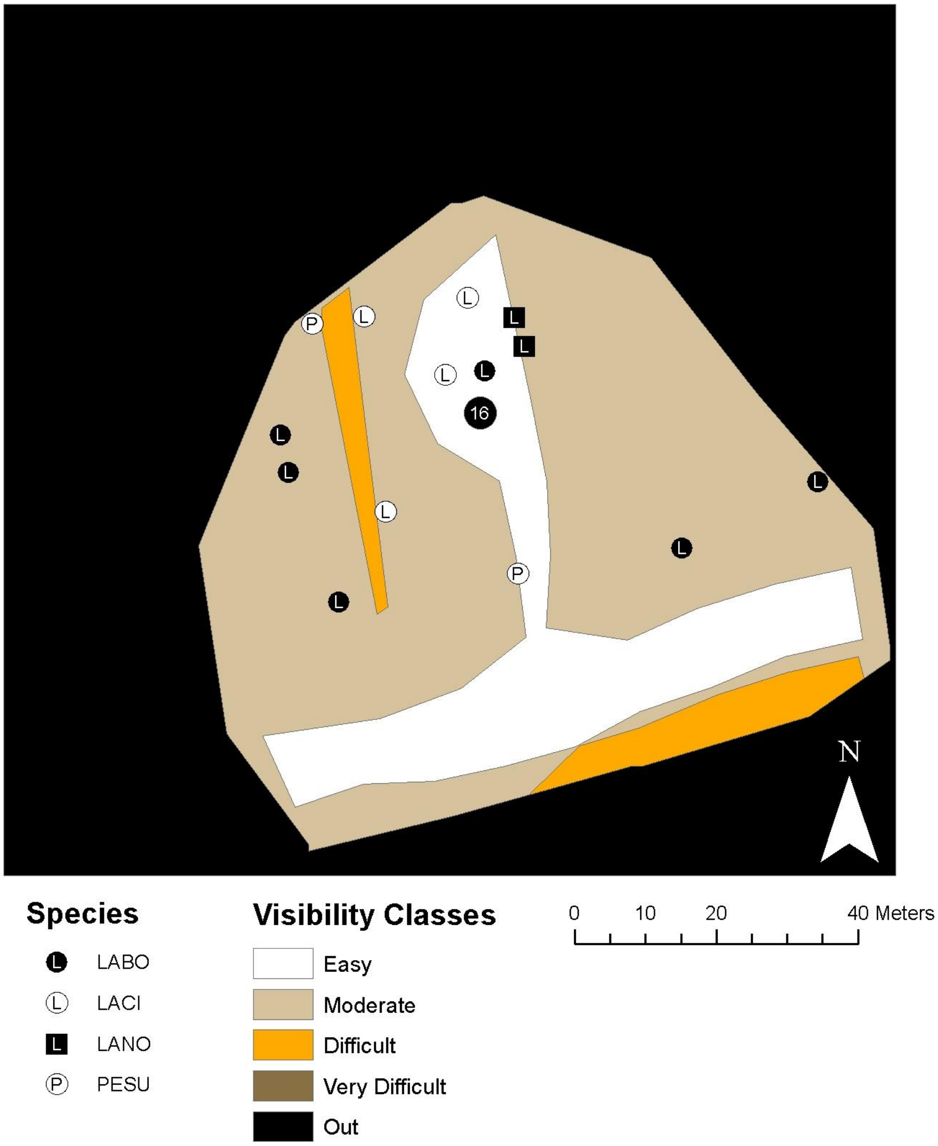
40 Meters

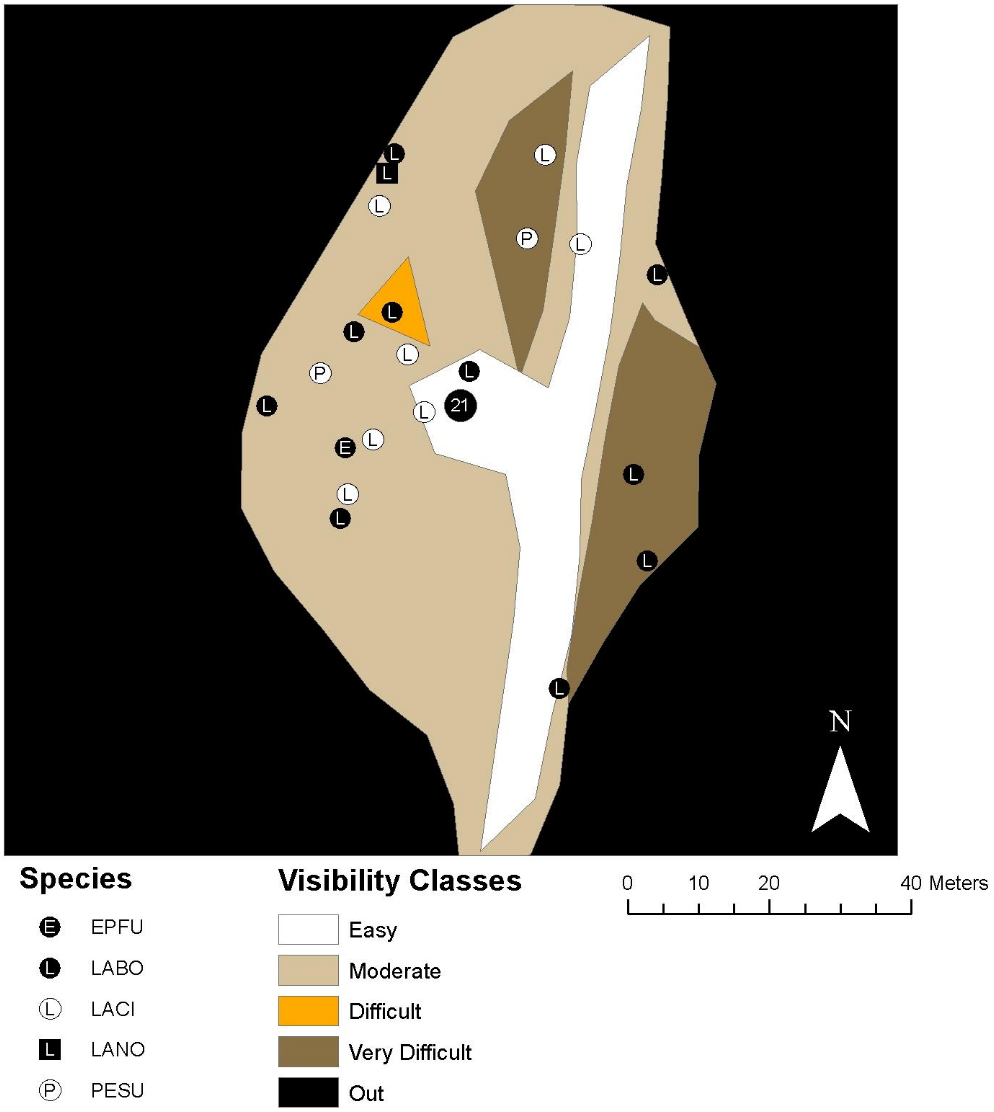
Turbine 16


L
P
L
L
L
L
L
16
L
L
L
L
P
L
L
N
Species
LABO
LACI
LANO
PESU
Visibility Classes
Easy
Moderate
Difficult
Very Difficult
Out
0
10
20
40 Meters

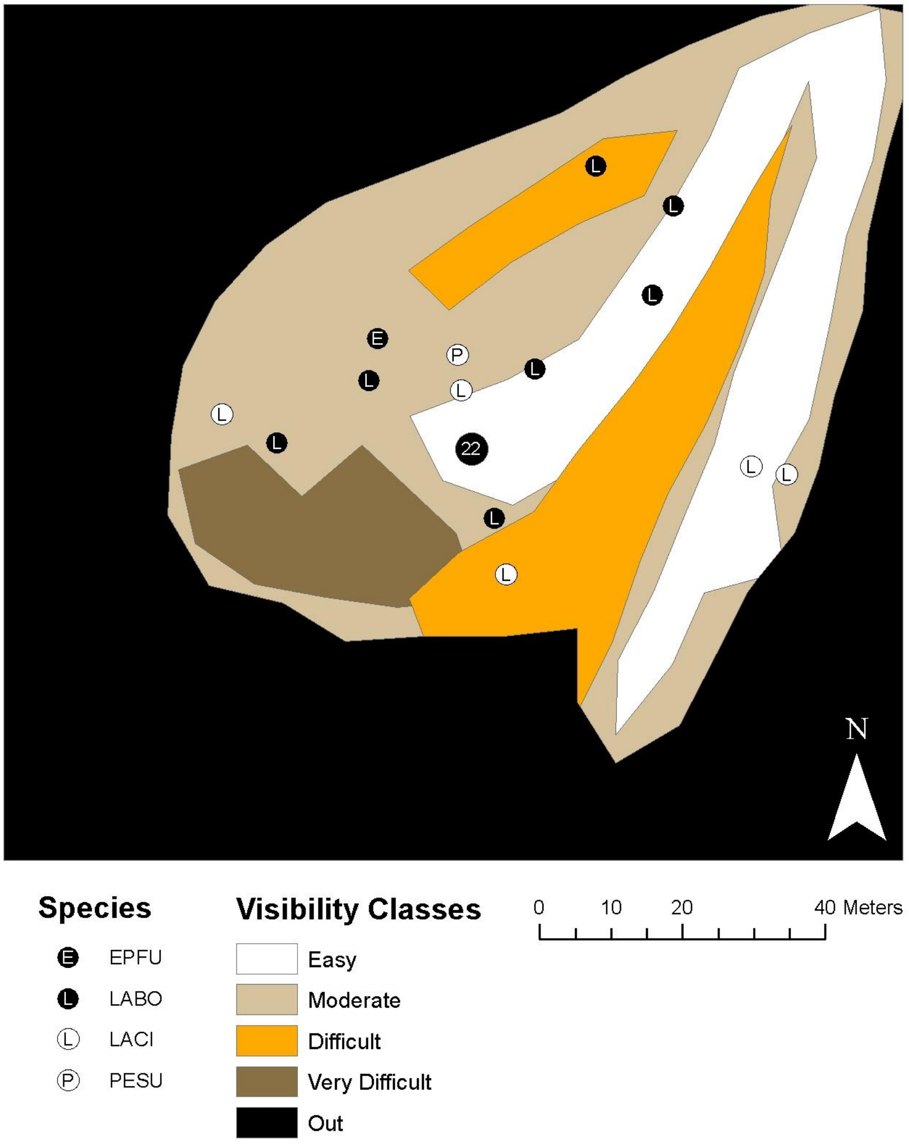
Turbine 19


L
L
L
O
L
R
19
L
L
L
L
P
N
Species
LABO
LACI
PESU
Oven Bird
Red-eyed Vireo
Visibility Classes
Easy
Moderate
Difficult
Very Difficult
Out
0
10
20
40 Meters

Turbine 21


21
N
Species
EPFU
LABO
LACI
LANO
PESU
Visibility Classes
Easy
Moderate
Difficult
Very Difficult
Out
0
10
20
40 Meters

Turbine 22


22
N
E
P
L
Species
EPFU
LABO
LACI
PESU
Visibility Classes
Easy
Moderate
Difficult
Very Difficult
Out
0
10
20
40 Meters