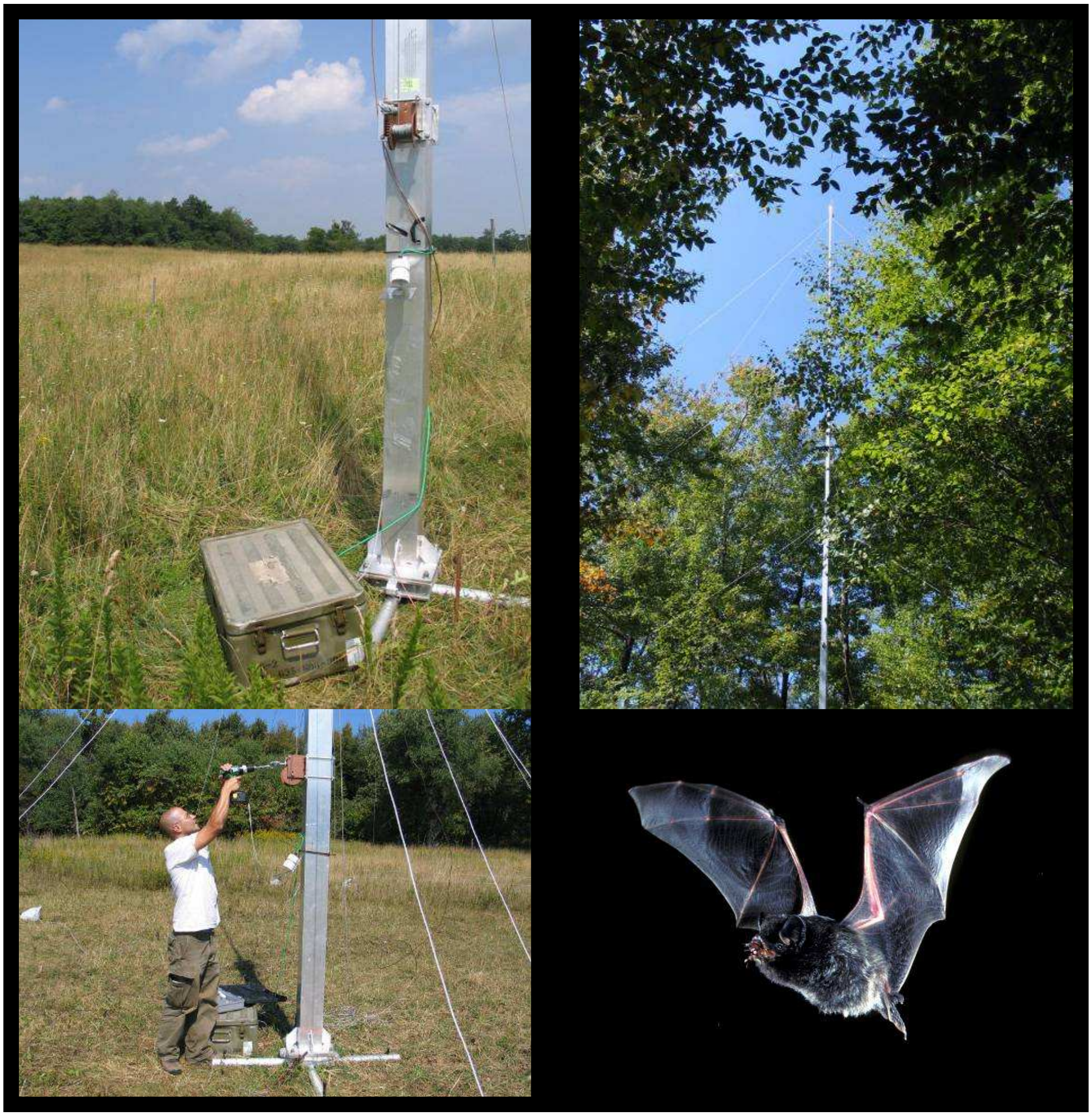
Patterns of pre-construction bat activity at a proposed wind facility in south-central Pennsylvania

2005 Annual Report



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EXECUTIVE SUMMARY

We initiated a 5-year study in mid-summer 2005 to determine patterns of bat activity and evaluate the use of acoustic monitoring to predict fatality of bats at a proposed wind energy facility in south-central Pennsylvania. The primary objectives of this study are to 1) determine level and patterns of activity of different species groups of bats using the proposed wind facility prior to and after construction of turbines; 2) correlate bat activity with weather and other environmental variables; and 3) determine if indices of pre-construction bat activity can be used to predict post-construction bat fatalities at proposed wind facilities.

We recorded echolocation calls of bats with Anabat II zero-crossing ultrasonic detectors programmed to record calls each day from one half-hour before sunset to one half-hour after sunrise each day of the study from 1 August to 1 November 2005. We used meteorological (met) towers and 22 m tall, portable, telescoping towers to vertically array detectors for acoustic sampling during this study. We recorded calls at proposed turbine locations from detectors deployed on 3 met towers (one detector at 1.5, 22, and 44 m high at each tower) and from 6 locations using portable towers (one detector at 1.5 and 22 m high at each tower) from a forested ridge and from 2 met towers and 4 portable tower locations on an open strip-mined ridge.

We recorded a total of 9,162 bat calls from all detectors and tower locations combined from 1 August through 1 November 2005. Bat activity was highly variable throughout the study period, but generally highest from mid-August through mid-September with brief peaks of high activity in October. Bat activity generally was highest immediately after sunset and declined through the night until just before sunrise the following morning. High (≥35 kHz, e.g., *Myotis* species) and low (<35 kHz, e.g., *Lasiurus* spp.) frequency-emitting echolocating bats tended to fly at different heights on the study area. While the two species groups had approximately equal activity levels at 22 m, activity rate of high frequency-emitting bats was estimated to be 9–59% higher than that of low frequency bats at 1.5 m. This trend was reversed at 44 m where it was estimated that activity rate of low frequency-emitting bats was 17–210% higher than that of high frequency bats. The height at which either species group tended to fly differed in the two habitats. Although activity rates for either species group at 44 m were approximately equal in forest and open habitats, it was estimated that activity rate in the forest habitat was 9–61% higher than in open habitat at 1.5 m. This trend was most extreme at 22 m, where it was estimated that activity rate in forest habitat was 99–229% higher than in open habitat.

The best model and eleven other models in the 95% candidate set all included linear effects of temperature and wind speed, quadratic effect of temperature and the interaction of temperature with height. Total bat activity increased with increasing temperature up to about 19–21^{o} C, after which activity began to decline. While bat activity was positively related to temperature, the effect differed at different heights. For every 1^{o} C increase in temperature, bat activity increased 7–13% at 1.5 m, 0–7% at 22 m, but was unaffected by temperature at 44 m. The optimum temperature for maximum activity was similar for the two species groups in both habitats. Wind speed was less than 6.5 m/s (23.4 km/h) on 80% of the nights and the highest wind speed recorded was 15.7 m/s (56.5 km/h); even at wind speeds above 6.5 m/s, there was still some bat activity in both species groups. The effect of wind speed was the same for both species groups in both habitats and at all three heights. For each 1 m/s (3.6 km/h) increase in wind speed, activity rate was estimated to decrease by 11–39%. Activity patterns of the two species groups were similar in both open and forest habitats at 44 m, but at 22 m was between 2 and 3 times higher over forests than in the open habitat.

This study was conducted at one proposed wind energy facility located on a forested ridge and an open, reclaimed ridge that had been previously strip-mined, so statistical inferences are limited to this site. However, we believe that our findings likely reflect patterns of bat activity on similar forested and open ridges with comparable vegetation composition and topography in this region. We caution that our study only encompasses the late summer-fall period and does not represent a full period when bats are known to be active (generally April through November). Analyses presented in this report are exploratory, in part because so little data exist upon which to develop a priori, confirmatory hypotheses and associated candidate models. The current analysis only estimates activity rates and differences in activity patterns of two species groups (high and low frequency), in forested and open habitat, and at three heights.

We began a second year of pre-construction acoustic monitoring in mid-April 2006 that will continue through the end of October 2006. Turbine construction for this site is tentatively scheduled for summer-fall 2007, after which we will gather two years of post-construction activity and fatality data from April through October in 2008 and 2009.

INTRODUCTION

Wind has been used to commercially produce energy in North America since the early 1970s and is one of the most rapidly growing sectors of the energy industry. Wind turbines are able to generate electricity without many of the negative environmental impacts associated with other energy sources (e.g., air and water pollution, greenhouse gas emissions associated with global warming and climate change), potentially benefiting birds, bats, and many other species. However, fatalities of birds and bats have been recorded at wind facilities worldwide, including in Australia (Hall and Richards 1972), North America (Erickson et al. 2002, Johnson et al. 2003, 2004, Fiedler 2004, Kerns and Kerlinger 2004, Arnett 2005), and northern Europe (Ahlen 2002, 2003). Bat fatality at wind facilities received little attention until 2003 when 1,400–4,000 bats were estimated to have been killed at the Mountaineer Wind Energy Center in West Virginia (Kerns and Kerlinger 2004). Documentation of continued high bat fatality at Mountaineer in 2004 (Arnett 2005) coupled with survey data from Tennessee indicating equal and higher kill rates than Mountaineer (Fiedler 2004; Tennessee Valley Authority, unpublished data) support the contention that forested ridges in the eastern U.S. are high risk sites for bat fatalities.

Interactions between bats and wind turbines are poorly understood. The combination of nocturnal habits, volancy, small size, and variation in resource dependence (i.e., species vary in roost, water, and food resource dependence), have made even a rudimentary understanding of how bats interface with their environment difficult to establish (Gannon et al. 2003). Post-construction monitoring has provided most of what little information has been gathered on bat fatalities at wind farms. While patterns of fatality of bats at wind facilities allow for some conjecture about risk factors for some species, information on use of the area encompassing a facility are needed to place bat fatality in an appropriate context (Fiedler 2004). Pre-construction surveys at wind facilities have been conducted and most commonly employ mist nets and acoustic detectors to assess local bat species presence and activity. However, using this information to predict bat fatality and, thus risk at a site has proved to be challenging. The ability to generate reliable risk assessments prior to construction of wind facilities is greatly hampered by the lack of baseline data on bat population distributions and densities throughout much of North America (O'Shea et al. 2003, Reynolds 2006) and migratory patterns and behavior of bats (Larkin 2006).

Acoustic monitoring allows researchers to detect and record calls of echolocating bats that can be used to assess relative activity and identify species or groups of species. Monitoring echolocation calls has limitations and acoustic detectors often are used in the field without a thorough understanding of these limitations, the underlying assumptions, or the use of standardized protocols (Hayes 2000, Sherwin et al. 2000, Weller and Zabel 2002, Gannon et al. 2003). Estimating amount of activity is relatively straightforward, but estimating abundance requires differentiation between multiple passes of a single bat and multiple bats making single passes, and is not usually possible. Echolocation calls are reliably distinguishable from other sounds (e.g., bird, arthropod, wind, mechanical), but ability to distinguish species of bats varies with taxon, location, type of equipment, and quality of recording, and may be challenging (Barclay 1999, Hayes 2000).

Understanding bat activity levels prior to construction of wind facilities could assist in identifying habitats and features that may pose high risk of fatality and aid with decision-making, including specific placement of turbines (Fiedler 2004, Reynolds 2006). Unfortunately, past and current efforts to acoustically monitor bat activity prior to construction of turbines may suffer from flaws in study design, including small sample sizes and poor temporal and spatial replication (Hayes 1997, 2000), pseudoreplication (Hurlbert 1984), and inappropriate inference because limitations and assumptions were not understood or clearly articulated (Hayes 2000, Sherwin et al. 2000, Gannon et al. 2003). Also, there is a lack of information and lack of agreement among stakeholders, biologists, and scientists regarding what constitute different levels of risk in relation to bat activity and potential fatality of bats at wind facilities. Perhaps most importantly, we currently are unaware of any study that has correlated pre-construction monitoring data with post-construction fatality, a fundamental link necessary for understanding potential risk of wind facilities to bats.

We initiated a 5-year study in late summer 2005 to evaluate whether indices of bat activity gathered before construction using acoustic detectors can predict post-construction fatality of bats at a proposed wind facility in south-central Pennsylvania. This project will occur in 2 phases. The first phase collected echolocation calls to develop indices of bat activity from August through October 2005 and will continue to collect these data from mid-April through October 2006 and 2007. The second phase will involve monitoring bat activity at the same sites after turbines are constructed, coupled with extensive fatality searches in 2008 and 2009. Here, we present results from the 2005 field season, discuss patterns and preliminary conclusions, and outline next steps for this project.

OVERALL PROJECT OBJECTIVES

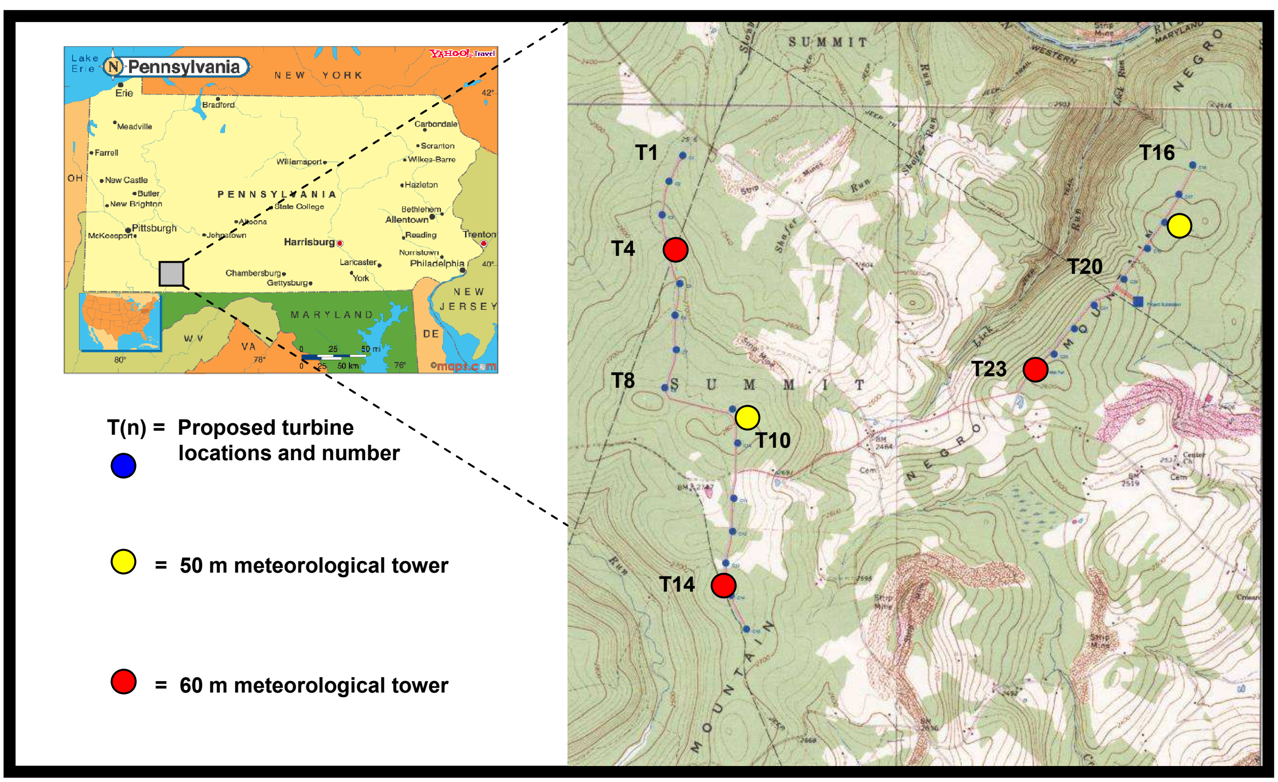
1. Determine activity of different bat species groups using the proposed wind farm in south-central Pennsylvania prior to and after construction.
2. Determine if indices of pre-construction bat activity can predict post-construction bat fatalities at turbine locations on a proposed wind farm in south-central Pennsylvania.
3. Evaluate temporal and spatial (both horizontal, i.e. sampling points across the turbine string, and vertically, i.e., multiple detectors at each sampling point at different heights) patterns of variability of bat species group activity at turbine locations and meteorological towers located across the wind facility.
4. Correlate bat activity prior to and after construction with weather and other environmental variables.
5. Evaluate patterns of post-construction bat fatality in relation to weather conditions, fog, and other environmental variables and assess the predictability of fatality based on these factors.
6. Evaluate study design, temporal and spatial variation, and sample size requirements and offer suggestions for standardizing protocols for future acoustic detector studies.

STUDY AREA and METHODS

Study Area

The study area is located in Somerset County in south-central Pennsylvania. Both facilities lie within the Appalachian mixed mesophytic forests ecoregion and encompass the moist broadleaf forests that cover the plateaus and rolling hills west of the Appalachian Mountains (Brown and Brown 1972, Strausbaugh and Core 1978). There are two proposed "strings" of turbines for the site (Figure 1). The western string has 15 proposed turbine locations and 3 meteorological towers that gathered weather data continuously at T4 (60 m tall), T10 (50 m tall), and T14 (60 m tall) (herein referred to as "forest" ridge/habitat; Figure 1). Eleven of the 15 proposed turbines in this string occur in relatively dense, second-growth deciduous hardwood forest with a canopy height generally ranging from 15–20 m; 3 of the 15 turbines in this string occur in open hay pasture near second-growth forest and one occurs in a stand of young (<10 years old) regenerating forest. Meteorological towers at T4 and T14 occur within an approximate 120 x 120 m cleared area surrounding by second growth forest. The tower located near T10 is in open hay pasture within 75 m of second growth forest (Figure 1). The eastern string has 8 proposed turbine locations and 2 meteorological towers located at T18 (50 m tall) and T23 (60 m tall) (herein referred to as "open" ridge/habitat; Figure 1). All turbines and meteorological towers in this string occur in open grassland reclaimed after strip mining for coal.

Figure 1. Location of the study area in Somerset County in south-central Pennsylvania, and locations of 5 meteorological towers and 23 proposed turbines at the proposed wind facility.



Acoustic Surveys

Monitoring bat activity. Indices of bat activity were derived from echolocation calls recorded with Anabat II zero-crossing ultrasonic detectors connected to a CF-ZCAIM storage unit (Titley Electronics Pty Ltd, Ballina, NSW Australia). Each detector system was synchronized and programmed to record calls each day from one half-hour before sunset to one half hour after hr after sunrise each day of the study.

We used all five meteorological towers and seven 22 m tall, portable, telescoping towers (Force 12 Inc., Paso Robles, California, USA) for acoustic sampling during this study. We chose this size of portable tower based on trade-offs between maximum height, portability, and cost. The height of meteorological towers allowed acoustic monitoring at a height that reached into the lower portion of the rotor-swept zone of turbines likely to be installed at this facility. Three acoustic detectors were vertically arranged at each of the 5 meteorological towers at 1.5, 22, and 44 m above the ground (Figure 2). The height of 44 m corresponds to the highest location detectors could be placed using a truck mounted with a crane and bucket (Figure 3). The 22 m height corresponds to the highest point on portable towers used during this study. We deployed microphones for each detector within water-proof casings (a.k.a. "bat-hats;" Figure 4; EMS Systems, Berkeley, California, USA) attached to electrical cable that extended to the ground, where detectors were placed in waterproof military surplus dry boxes (Figure 5). We used a pulley system mounted to the meteorological tower (see Figure 3) to allow retrieval of equipment. We subjectively chose to face all microphones in the direction of the prevailing winds at the site (270^{o}, due west) and assume data gathered in this direction is representative of bat activity at our monitoring locations. Echolocation calls and weather data were collected at meteorological towers for 93 consecutive nights from August 1 through November 1, 2005.

We randomly selected 6 proposed turbine locations on the forest ridge and 4 proposed turbine locations on the open ridge that did not have meteorological towers and deployed a portable tower at each for acoustic monitoring. We subjectively chose to place towers 40 m away (approximately one rotor blade length) from the proposed turbine location and in the direction of the prevailing wind (due west) in an attempt to establish the same sampling points which can be used during post-construction without interfering with turbines during operation. Two bat hats with microphones were placed on each portable tower facing due west at 1.5 and 22 m above the ground and detectors were placed in waterproof dry boxes on the ground (Figures 2 and 5). Five of these locations (3 on the forest ridge and 2 on the open ridge) were monitored for one week, and then towers were moved to the second set of 5 locations and sampled the following week. We attempted to rotate towers between the two sets of proposed turbine locations weekly from 11 August through 31 October, and collected 35 nights of acoustic monitoring for the first set of towers and 45 days for the second.

We also established 2 reference sites (one each on a forest and open ridge) to acoustically monitor bats at locations without turbines or meteorological towers. We used the same portable, telescoping towers and detector placement described above for randomly selected points. These data allow for a coarse comparison of annual variability of bat activity in similar habitats

Figure 2. Depiction of the vertical array of acoustic detectors used at portable (left) and meteorological (right) towers (figure modified from D. S. Reynolds).

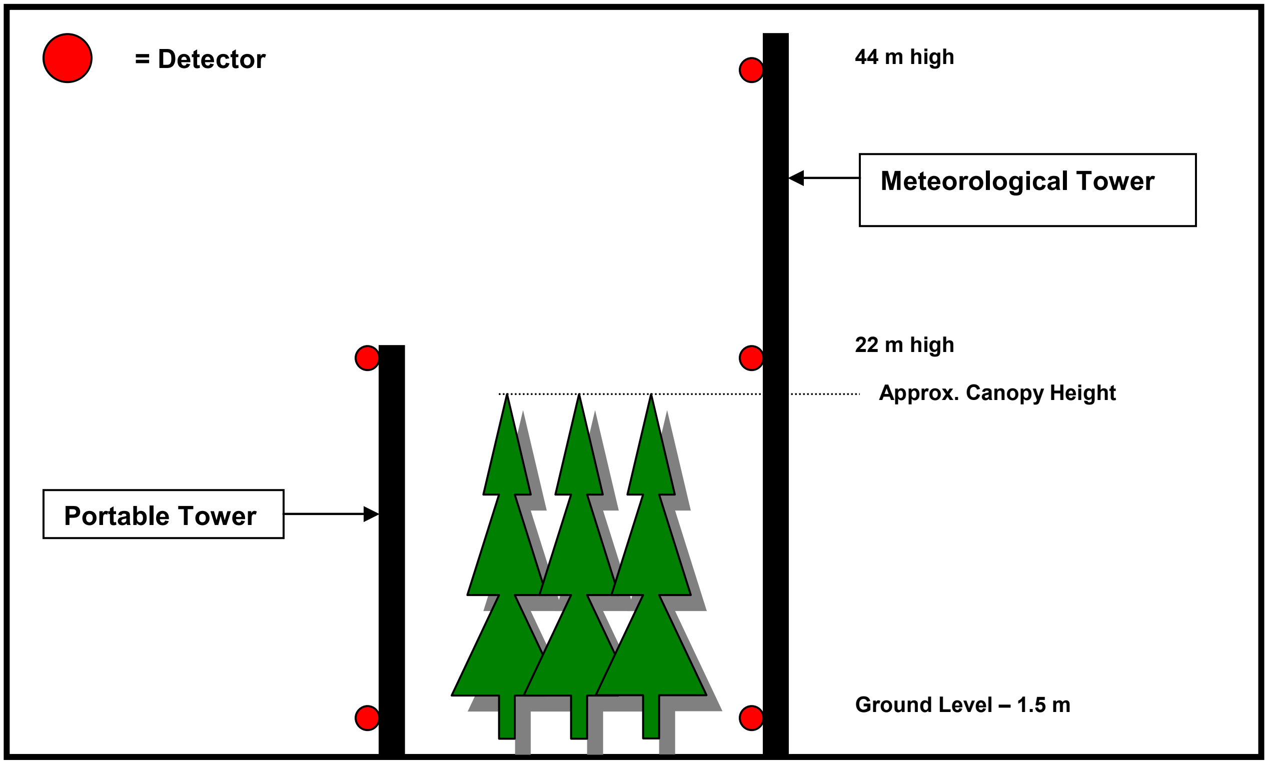


Figure 3. Pictures of a pulley system designed to hoist "bat hats" to 22 and 44 m heights on meteorological towers (A), mounting pulley systems with a boom truck (B), and a mounted pulley and bat hat system on a tower (C).

A. Pulley system for deploying "bat hats."

B. Boom truck used to mount pulley system

C. A mounted pulley system and bat hat at 22 m high.

Figure 4. Photographs of "bat hats" depicting the setup that was used at portable and meteorological towers for this study.

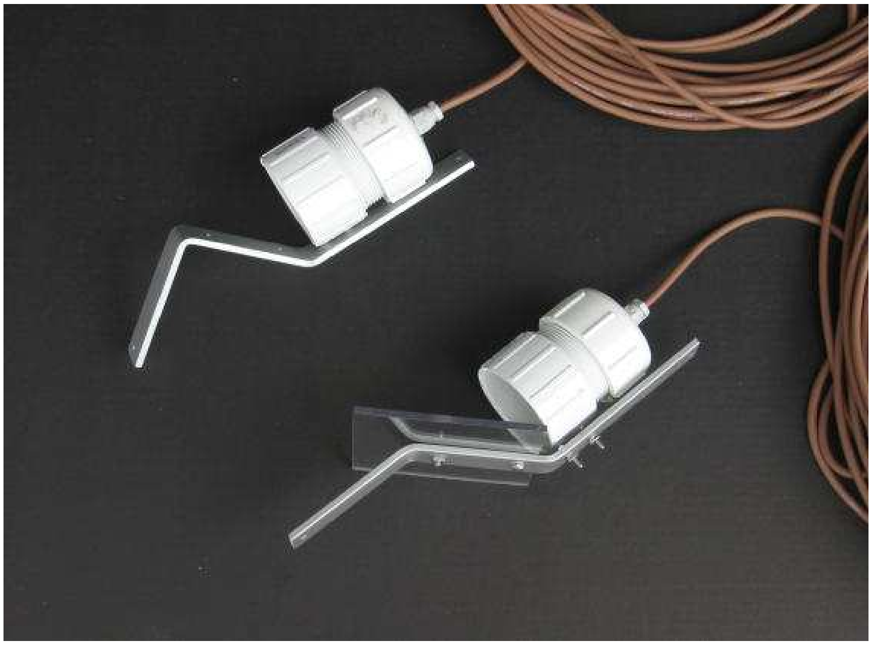


Figure 5. Military surplus dry boxes used to store acoustic detectors at ground-level during the study.

where no turbines will be located. Echolocation calls were gathered at reference sites for a total of 72 days from 21 August through 31 October. Appendix I lists all meteorological and portable towers and describes their basic habitat characteristics.

Detector calibration. We calibrated sensitivity of Anabat detectors according to Larson and Hayes (2000). Each week, we rotated detectors at a particular tower among the different heights to ensure no particular detector was consistently used at any height (C. Corben, pers. commun.; e.g., detectors for 44 m height will be switched to the 1.5 m, 22 m detector switched to the 44 m height, and 1.5 m detector to the 22 m height, and so on).

Definitions and Assumptions

Following Hayes (2000), Sherwin et al. (2000), and Gannon et al. (2003), we defined *a priori* that: 1) a "call" was considered a sequence with a duration greater than 10 ms and consisting of two or more individual calls (Thomas 1988, O'Farrell and Gannon 1999, Gannon et al. 2003); 2) calls were treated as independent (i.e., any sequence was considered a discrete event); and 3) replication was defined as multiple systems running simultaneously at multiple sites in two different habitats (ridges) within the sampling period. We assumed *a priori* that 1) high and low frequency echolocating bats were consistently recorded using frequencies > or <35 kHz, respectively, and correctly classified as one group or another; 2) high and low frequency echolocating bats were randomly distributed in vertical space; 3) temporal and spatial variation would be adequately accounted for through simultaneous sampling at all sites; and 4) amount of echolocation calls recorded reflects amount of use by bats.

Analyses

We downloaded and processed data from detectors throughout the sampling period. All non-bat ultrasonic detections were eliminated from the data sets prior to summary and analysis using filters in the Anabat analysis program Analook. These "cleaned" call data files were then sorted by tower and date for further analyses.

High – low call frequency determination. We divided echolocation calls into two groups based on minimum frequency of the call, in part because these groups may differ in their use of habitat and response to environmental factors. To accomplish this, 2 filters were constructed in the Anabat analysis program Analook for use in classifying echolocation calls of the file as being produced by either a high (>35 kHz minimum frequency) or low (<35 kHz in minimum frequency) echolocating bat. Both filters were derived from those developed by Britzke and Murray (2000), with a Smoothness value of 15 and a Bodyover of 80. Smoothness refers to the distance between successive points before they are not considered part of the same echolocation call, while Bodyover parameter refers to the minimum length of the body of echolocation calls. Both parameters serve to remove extraneous noise that is not associated with the echolocation call.

Use of the above parameters in the Analook filter resulted in the presence of only cleaned echolocation calls within the sequence. Next, the minimum frequency parameter was adjusted to separate the high and low echolocation sequences. For the low group filter the maximum frequency was 35 kHz, while the high frequency filter the minimum frequency parameter was set at 35 kHz. Each of these 2 filters then allowed for the correct assignment of each echolocation call sequence analyzed to be correctly assigned in the high or low species group. One filter was loaded into memory in the program Analook, and Scanfiles option was used to mark all sequences that had echolocation calls that met the filter criteria. The marked files were then moved into a directory labeled as high or low based on the filter that was used in the Scanfiles option. Next, the other filter was loaded and calls were marked and moved into the appropriate directory. All files that could not be assigned through use of the filtering process were visually examined and moved to the appropriate directory.

Once completed, all Anabat files were moved into either a high or low directory. The associated program Dataget allowed for extraction of information saved with each echolocation file (e.g., date, location, and the filename) to be saved into a text file. Dataget was run on files in each directory and a text file was loaded into Excel, where a column was then added to designate the filenames as either high or low (depending on the text file loaded). The same process was repeated with the other text file and results were combined so that there was a spreadsheet in Excel that contained 2 columns (filename and high/low designation). The original spreadsheet was then loaded into Excel and both spreadsheets were sorted by filename. This permitted the high/low classification to be added to the master spreadsheet for further analysis. Eleven call files could not be assigned a high/low frequency value and were thus excluded from further analyses.

Data summary methods. Meteorological stations associated with the project developer's wind resource assessment program existed at three locations on the forest ridge at proposed locations of turbines 4, 10, and 14, and at two locations on the open ridge at proposed locations of turbines 18 and 22. Meteorological data were collected every 10 min and averaged from 2 hours before sunset to 1 hour after sunrise to give nightly average wind speed and temperature. Wind speed was measured at 30 m and 50 m at all towers and at 60 m at two of the forest towers (turbines 4 and 14) and one of the open towers (turbine 22). Air temperature was measured at 3 m at all towers and at 50 m at two of the forest towers (turbines 4 and 14). Only air temperature measured at 3 m was used to calculate nightly average air temperature for each side (forest or open) because none of the meteorological towers in the open habitat measured temperature at 50 m. Wind speed at heights at which bat calls were measured (1.5 m, 22 m and 44 m) were interpolated from measured wind speeds at 30 m, 50 m and 60 m. Wind speed increased linearly with height, so interpolation was justified.

High and low frequency bat calls collected from forest and open habitats (i.e., ridges) at each of the three heights on each night were summed across the active towers to give a total number of calls in each of these 6 categories on each of the 93 nights of this study. Not all acoustic detectors functioned correctly on every night, and our models accounted for this by comparing the number of calls per tower. Our final data set had 1,116 observations (2 species groups * 2 habitats [ridges] * 3 heights * 93 nights). Each habitat and night had a unique value of average nightly temperature, and each habitat, night and height had a unique value of wind speed.

Modeling patterns of activity. This study was designed to estimate activity rates (number of calls/tower) of bats and differences in those rates based on three factors; species group (those with high and low frequency calls), habitat (forest vs open ridge), and height above the ground (1.5 m, 22 m, 44 m). We hypothesized that bats of different species groups might prefer one habitat over the other, might have a tendency to fly higher than the other, or that preferred flight height differed with habitat. Other studies have reported that activity rates can differ with temperature and wind speed (e.g., Reynolds 2006), but how these latter two factors would affect activity patterns of the two groups in our study area was unknown. To explore these relationships, we developed a fairly large set of plausible models describing the interaction of temperature and/or wind speed with each other and with each of the design factors (species group, height and habitat). Date and the quadratic effect of date were included in all models to account for the seasonal nature of bat activity that peaked in mid-August to mid-September. The full set of candidate models used for comparison is provided in Appendix I.

Although the data are counts (i.e. number of passes per night in each factor combination, and would naturally be modeled as poisson distributed) the observed values generally had much more variation than would be expected of poisson distributed data. Thus, data were modeled as overdispersed Poisson using a generalized linear model and the quasi-likelihood function with an offset equal to the $\log_e$ (the number of functioning towers available to measure the activity). The scale parameter was fixed at 2.92 for all models. We used Akaike's Information Criterion (AIC) to compare the models and identify the most parsimonious model, as determined by AIC differences that was among the best in the set of proposed models (Burnham and Anderson 2002). Model probabilities (Akaike weights [w_i]; probability that the *i*-th model is actually the best approximating model among all the candidate set, given the data) also were calculated. For the null model and all models in the 95% confidence set ($\sum w_i \geq 0.95$), we present the AIC differences, AIC between each model and the best approximating model, and considered any model <2.0 AIC units from the best model to be a competing model warranting discussion relative to the biological inferences (Burnham and Anderson 2002). All analyses were performed in SAS® (Version 8.2, SAS Institute 2000). Appendices II and III present a summary of all candidate models and descriptions of their structure and results from model selection analyses for all candidate models, respectively.

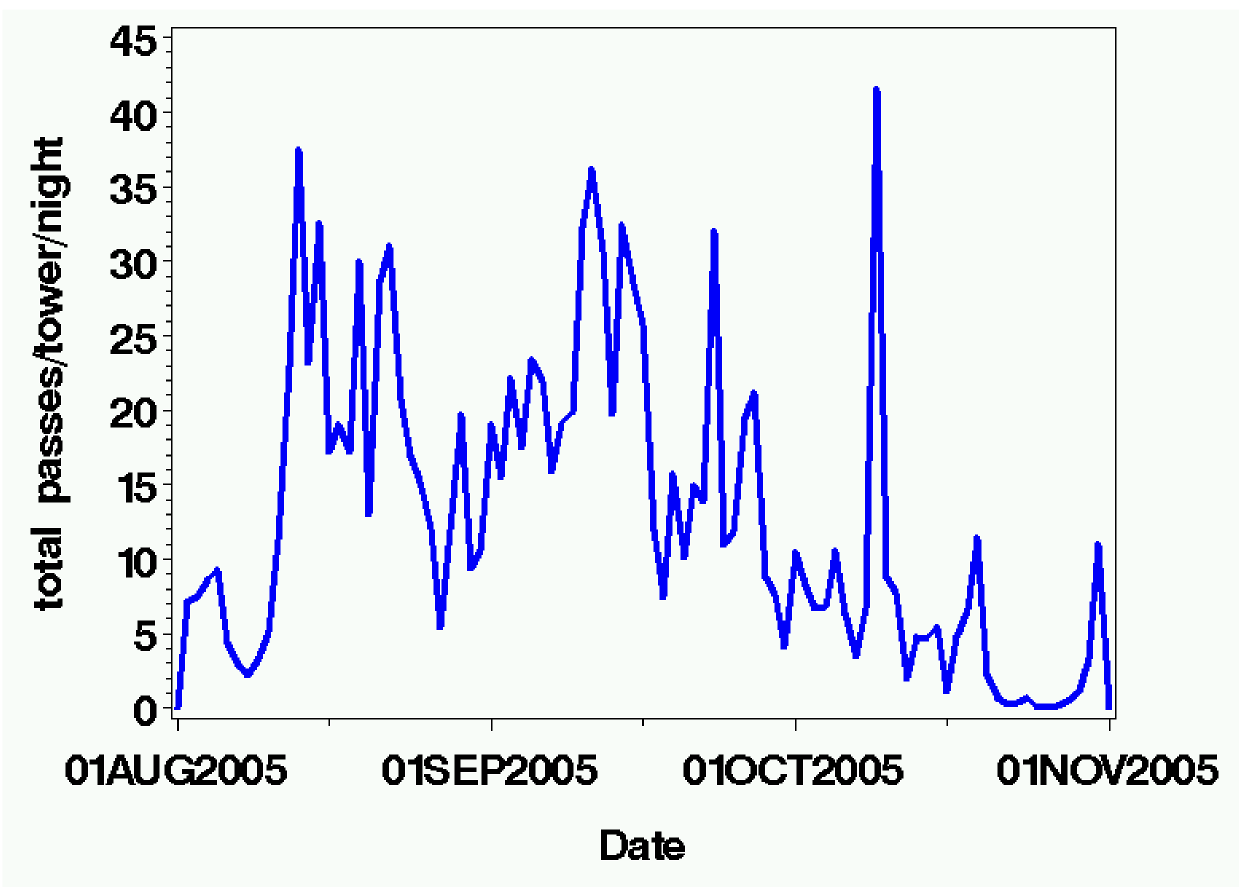
RESULTS

We recorded a total of 9,162 bat calls from all detectors and tower locations combined from 1 August through 1 November 2005. Bat activity was highly variable throughout the study period, but generally highest from mid-August through mid-September with brief peaks of high activity in October (Figure 6). Bat activity generally was higher immediately after sunset and declined through the night until just before sunrise the following morning (Figure 7).

High-Low Frequency Bat Activity

The two species groups we defined (see methods) tended to fly at different heights at the Casselman site (Figures 8 and 9, Table 1). Although the two species groups had approximately equal activity levels at 22 m, activity rate of high frequency bats was estimated to be 9–59% higher than that of low frequency bats at 1.5 m (Table 1). This trend was reversed at 44 m where it was estimated that activity rate of low frequency bats was 17–210% higher than that of high frequency bats. The height at which either species group tended to fly differed in the two habitats (Figures 8 and 9). Although activity rates for either species group at 44 m were approximately equal in forest and open habitats, it was estimated that activity rate in the forest habitat was 9–61% higher than in open habitat at 1.5 m. This trend was most extreme at 22 m, where it was estimated that activity rate in forest habitat was 99–229% higher than in open habitat.

Figure 6. Mean number of bat calls/night/tower from 1 August – 1 November 2005, south-central Pennsylvania.



Date

Figure 7. Histogram depicting total number of bat calls for all towers and detectors gathered from one-half hour before sunset and one-half hour after sunrise from 1 August to 1 November, 2005, south-central Pennsylvania.

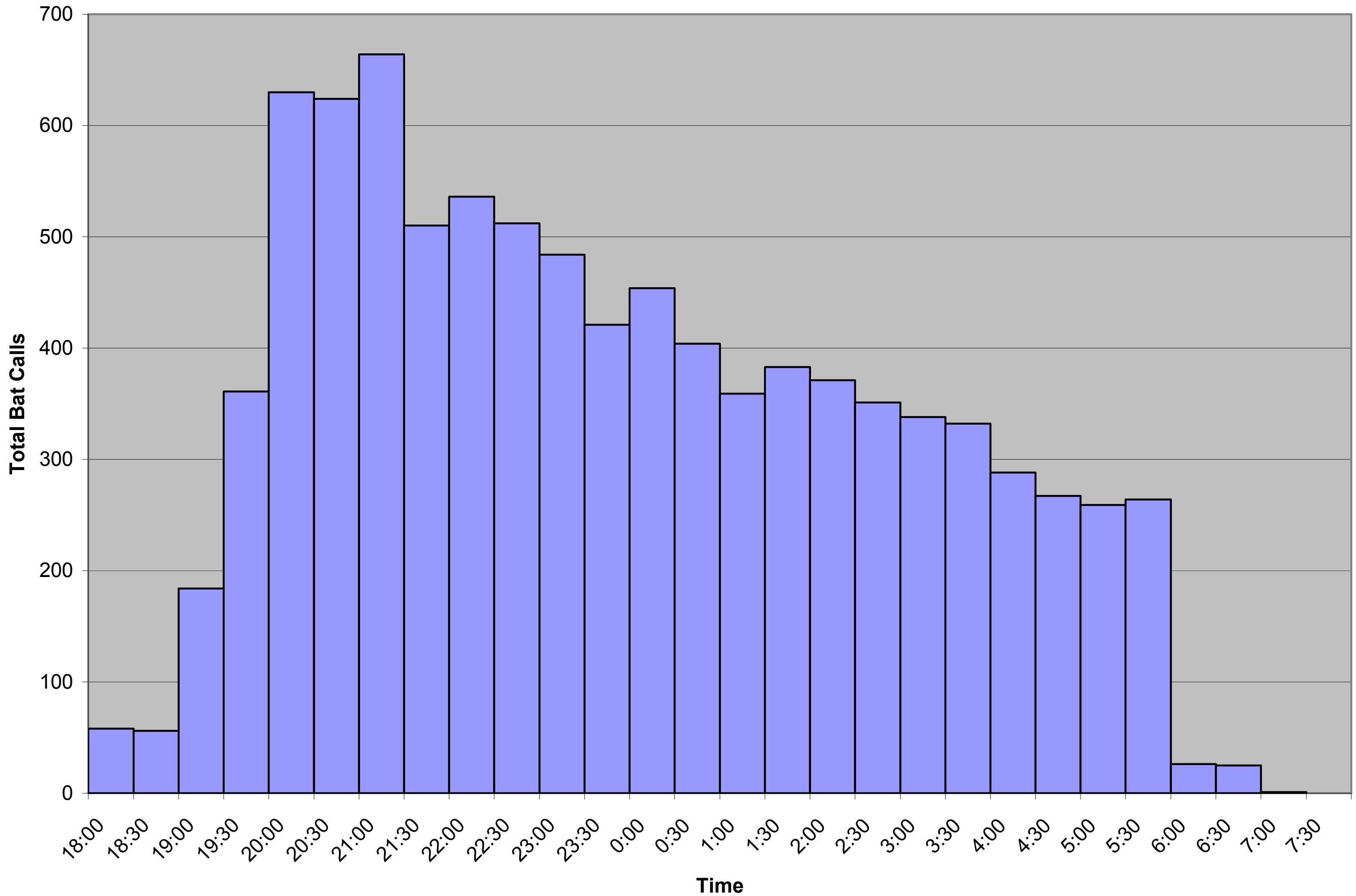


Figure 8. Nightly average number of calls at different vertical heights for low frequency (<35 kHz) echolocating bats in south-central Pennsylvania, 1 August – 1 November 2006 (FM = forest meteorological tower, FP = forest portable tower, OM = open meteorological tower, OP = open portable tower; the number for each tower follows the habitat/tower type).

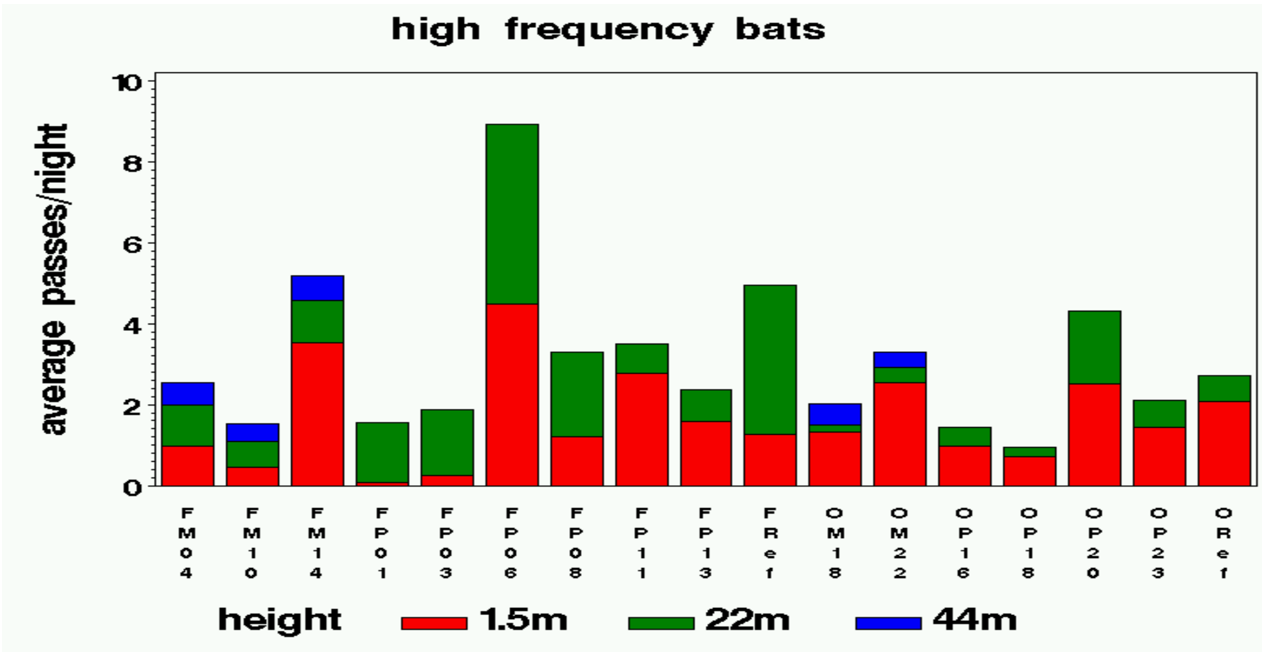


Figure 9. Nightly average number of calls at different vertical heights for high frequency (≥35 kHz) echolocating bats in south-central Pennsylvania, 1 August – 1 November 2006 (FM = forest meteorological tower, FP = forest portable tower, OM = open meteorological tower, OP = open portable tower; the number for each tower follows the habitat/tower type).

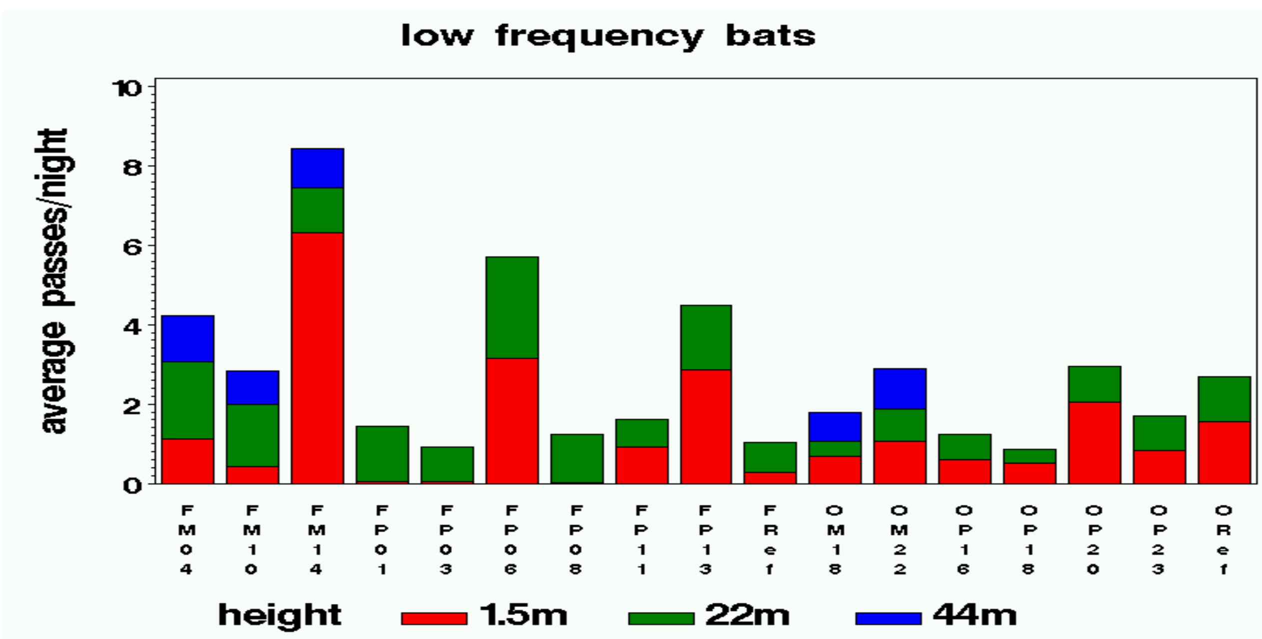


Table 1. Median relative increase (+, estimate and 95% CI > 1) or decrease (-, estimate and 95% CI < 1) in total bat activity for each condition described and lower and upper limits of the 95% confidence interval of this estimate. When 95% confidence limits on the estimate are < and > 1, the inference is no effect (0).

Condition	Median	95 CI lower	95 CI upper	Effect
high vs low freq, ht=1.5	1.31064	1.08479	1.58351	+
high vs low freq, ht=22	1.00668	0.7879	1.28477	0
high vs low freq, ht=44	0.52531	0.32246	0.85577	-
forest vs open, ht=1.5	1.32684	1.09407	1.60914	+
forest vs open, ht=22	2.55968	1.99333	3.28694	+
forest vs open, ht=44	1.48088	0.89106	2.46113	0
+1 m/s wind speed	0.73852	0.61370	0.88873	-
+1 degree C at ht=1.5	1.10495	1.07244	1.13845	+
+1 degree C at ht=22	1.03556	1.00392	1.06820	+
+1 degree C at ht=44	0.97814	0.92627	1.03292	0

Bat Activity in Relation to Weather Variables

There were 14 models with a cumulative Akaike weight of 95% and all of these included linear effects of temperature and wind speed and the interaction of temperature with height. The best model only had a 26% probability of being the best model, given the data, and three other models less than 2 QAIC units from the best model accounted for 62% of summed Akaike weights (Table 2). In addition to linear effects of nighttime temperature and wind speed and the interaction of temperature with height, the top four models included either the quadratic term for temperature (model #310), the quadratic term for wind speed (model #320), or the interaction of wind speed and temperature (model #305).

Total bat activity generally increased with increasing temperature (Figure 10) and the effect differed at different heights. For every 1^{o} C increase in temperature, bat activity increased 7–13% at 1.5 m, 0–7% at 22 m, but was unaffected by temperature at 44 m (Table 1). Wind speed was less than 6.5 m/s (23.4 km/h) on 80% of the nights and the highest wind speed recorded was 15.7 m/s (56.5 km/h); even at wind speeds above 6.5 m/s, there was still some bat activity (Figure 11) in both species groups. The effect of wind speed was the same for both species groups in both landscapes/habitats and at all three heights. For each 1 m/s (3.6 km/h) increase in wind speed, activity rate was estimated to decrease by 11–39% (Table 1). The interaction of temperature and height is depicted with an example in Figures 12a–d, where the estimated median number of bat calls/tower/night at different heights when wind speed is zero is modeled as a function of temperature. The relationship between temperature and height is similar at all wind speeds, but most easily represented at low wind speed when bat activity rates are highest. The effect of temperature, is most pronounced at 1.5 m above the ground for both landscapes/habitats and species groups.

Table 2. Difference in Akaike Information Criteria score between the ith and top-raked model (Δ_i), Akaike weights (w_i), and the sum of the Akaike weights ($\sum w_i$) of all models comprising ≥95% of the model weights, and the null model, used to explain relationships of bat activity in relation to weather variables in in south-central Pennsylvania, 1 August – 1 November 2006.

Model Rank	**Model #**	**Model Structure**	**ΔQAIC**	$\mathbf{w_i}$	$\sum \mathbf{w_i}$
1	302	temp ws temp*height	0.00	0.26	0.26
2	310	temp ws temp*height temp*temp	1.24	0.14	0.40
3	320	temp ws temp*height ws*ws	1.44	0.12	0.52
4	305	temp ws temp*height temp*ws	1.80	0.10	0.62
5	326	temp ws temp*height temp*temp ws*ws	2.62	0.07	0.69
6	323	temp ws temp*height temp*ws ws*ws	2.92	0.06	0.75
7	313	temp ws temp*height temp*ws temp*temp	3.04	0.06	0.81
8	304	temp ws temp*height ws*height	3.88	0.04	0.84
9	329	temp ws temp*height temp*ws temp*temp ws*ws	4.08	0.03	0.88
10	312	temp ws temp*height temp*temp ws*height	5.05	0.02	0.90
11	321	temp ws temp*height ws*ws ws*height	5.58	0.02	0.92
12	307	temp ws temp*height temp*ws ws*height	5.62	0.01	0.93
13	328	temp ws temp*height temp*temp ws*height ws*ws	6.78	0.01	0.94
14	315	temp ws temp*height temp*ws ws*height temp*temp	6.79	0.01	0.95
109	100	NULL	49.2	0.00	1.00

Figure 10. Total number of bat calls/night/tower by temperature (C) from 1 August – 1 November 2005, south-central Pennsylvania.

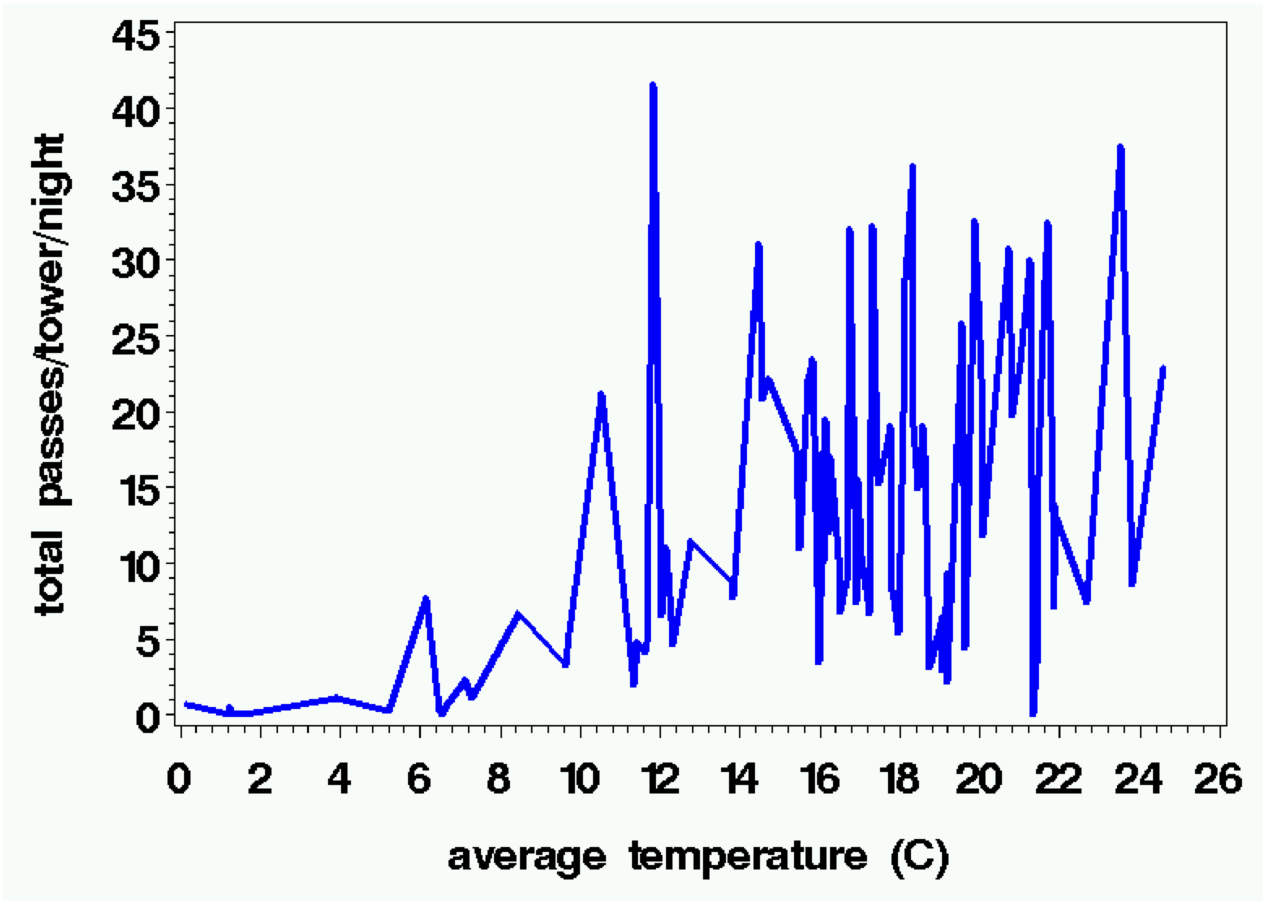


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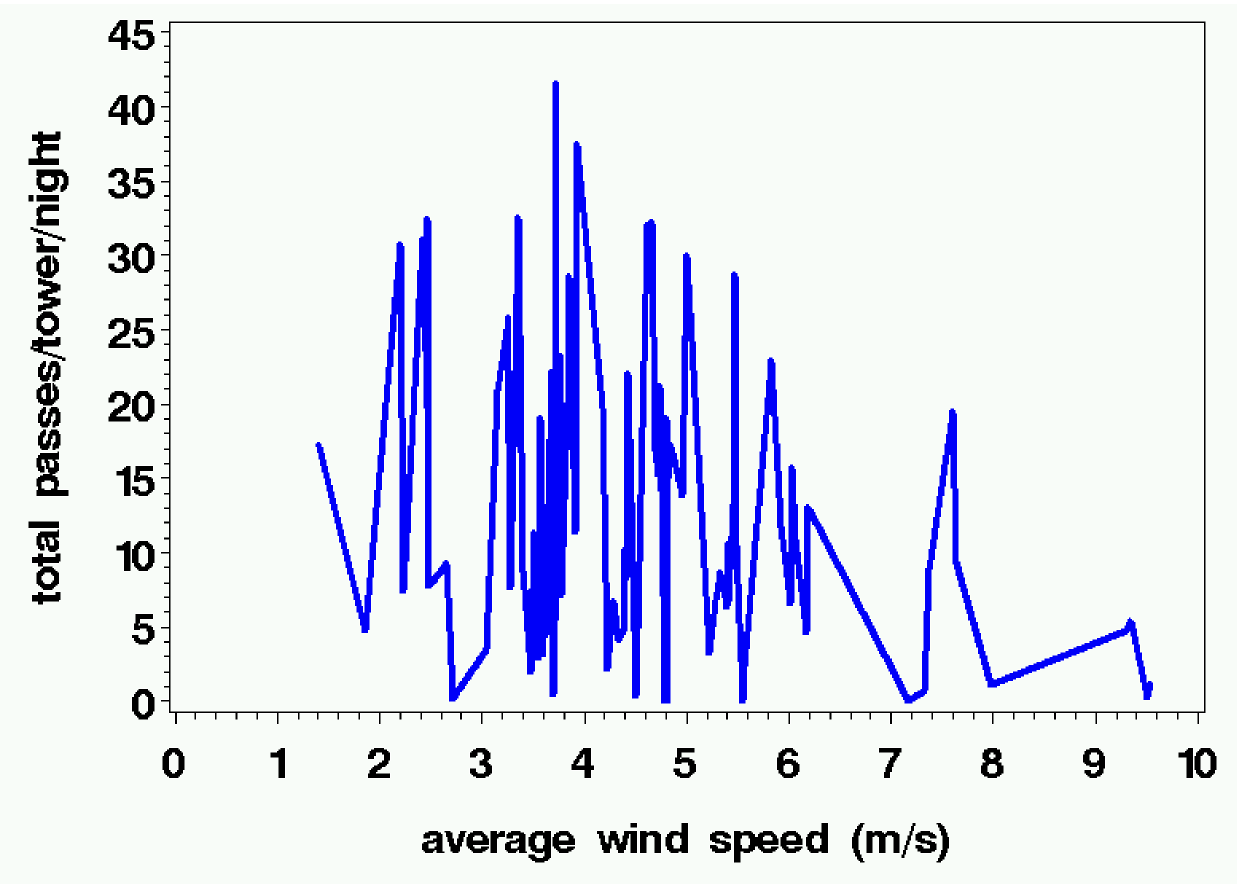
Figure 11. Total number of bat calls/night/tower by maximum wind speed (m/s) from 1 August – 1 November 2005, south-central Pennsylvania.



Figures 12a–d. Estimated median number of passes/tower/night by high and low frequency bats in forested and open landscapes when wind speed = 0 km/h at three heights (Solid Green = 1.5 m, Dashed green = 22 m, Dotted Blue = 44 m) as a function of temperature (C).

Figure 12a.

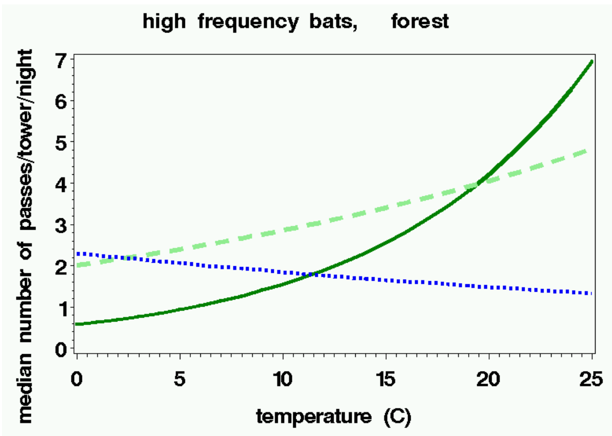


Figure 12b.

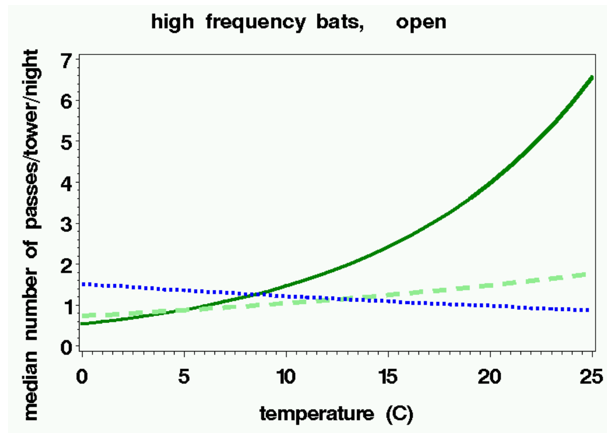


Figure 12c.

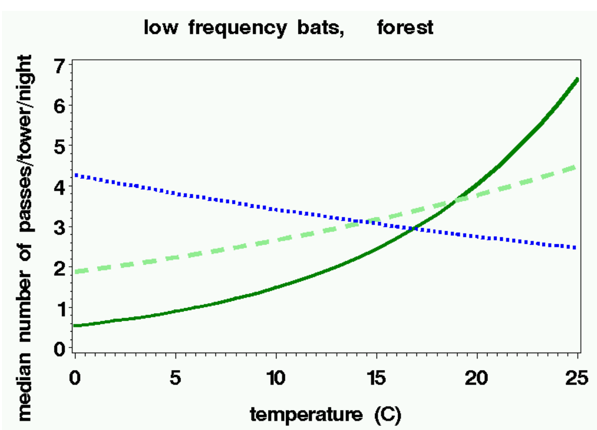
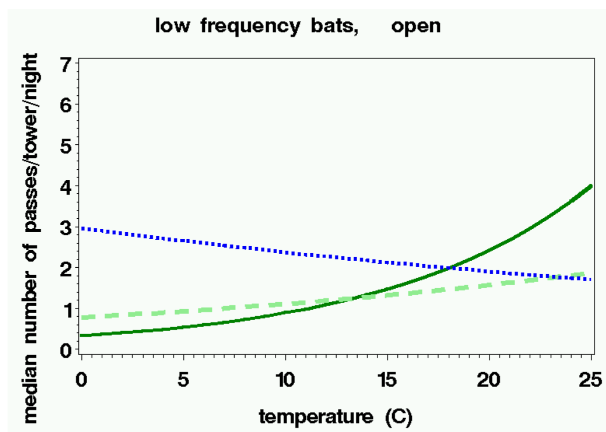


Figure 12d.



DISCUSSION

Energy forecasters predict that world power consumption will increase by 50% by 2025, and wind energy is expected to provide 5% (~117,000 MW) of the U.S. energy needs (NREL 2006). More than 2,400 MW of wind energy were installed in 2005 in the U.S., with a projected 3,000 MW installed in 2006 (AWEA 2006). With the rapid expansion of wind energy development coupled with serious concern over bat fatalities at wind facilities (Tuttle 2004), reliable techniques for assessing the impact of wind power generation on bats is essential. Unfortunately, pre-construction estimates of activity have not been correlated with post-construction fatality, and the ability of various techniques, including acoustic monitoring, to predict fatality and evaluate risk remains unknown. Ultimately, if clear relationships between pre-construction activity and post-construction fatality can be established, pre-construction assessments of activity could provide useful assessments of risk to bats prior to development of wind facilities (Fiedler 2004).

Acoustic detectors have been used during post-construction monitoring, offering some insight on the use of detectors to predict fatality. Fiedler (2004) found that bat activity levels generally were greater during nights when fresh killed bats were found during searches the next day compared to those days when no fresh bats were found. However, Fiedler also reported that the logistic regression model using bat activity as an explanatory variable for evaluating the likelihood of fatality performed poorly. She noted that three species (big brown bat, eastern pipistrelle, and silver-haired bat) were found proportionally less at turbine fatalities than were acoustically recorded, whereas two species (eastern red bat and hoary bat) were found proportionally more frequently, suggesting greater collision risk for the latter species than would be predicted with acoustic monitoring alone. Similarly, Gruver (2002) reported that while hoary bats represented 88.1% of turbine fatalities at Foote Creek Rim, Wyoming, they only made up 7.8% of acoustical recordings. Johnson et al. (2004) found no difference in the mean number of bat passes/detector night when detectors were located at turbines with ($\bar{x}$ = 2.4) and without ($\bar{x}$ = 2.1) fatalities found the following day in Minnesota. Jain (2005) found that specific towers in his study did not show a significant relationship between mortality and ultrasonic activity. These findings suggest that predicting bat fatality from post-construction activity indices, may not be possible for the species killed most frequently at wind facilities (see Johnson 2005). However, the aforementioned studies all noted that seasonal increases in bat activity closely coincided with the overall incidence of mortality at these sites. Given these observations and the mixed findings from Fiedler's work, future studies with more extensive and intensive investigation may identify stronger linkages between activity indices and fatality.

Temporal patterns of activity measured on our study area were similar to those gathered from other studies. We found that during the period of our study bat activity was generally highest from mid-August through mid-September and declined through October. In Iowa, Jain (2005) found that bat activity, measured by the number of calls per night, peaked in July (99.5 calls/detector-night) and August 2004 (56.44 calls/detector-night), declined in September (10.5 calls/detector-night), and had mostly ceased by October, when detection was curtailed. Fiedler (2004) reported that activity exhibited a seasonal peak between early August and mid-September during all three years of her study in Tennessee. Johnson et al. (2004) and Gruver (2002) reported similar patterns in Minnesota and Wyoming, respectively. Association between timing of high activity and overall incidence of bat fatality previously reported (see Fiedler 2004, Johnson et al. 2004, and Jain 2005 for examples) suggest that temporal patterns of activity may prove useful for predicting the timing of fatality events in the future, but more studies across a wide range of landscape and environmental conditions are warranted.

Structural variation among habitats is an important consideration when inferring patterns of activity from acoustic data. Different species of bats respond to and use habitats with varying structural complexity (often referred to as clutter) differently (see Hayes 2003, Barclay and Kurta 2006, and Lacki et al. 2006 for recent reviews). Differences in wing morphology and maneuverability, as well as use of different echolocation frequencies and duty-cycles, influence the ability of bats to negotiate clutter and allow sympatric species to exploit different habitats. In general, maneuverable species of bats with small bodies and low wing-loading (e.g., most species of *Myotis*) are able to use habitats with higher levels of clutter than can less maneuverable species of bats with large bodies and high wing-loading (e.g., hoary bat). Bats also frequently use edge habitat for commuting and foraging (e.g., Furlonger et al. 1987; Krusic et al. 1996, Grindal and Brigham 1999, Lacki et al. 2006). For example, the amount of bat activity in forests of British Columbia was higher along edges of clearcuts than either within the clearcut or within the uncut forest (Grindal and Brigham 1999). Silver-haired bats, a relatively large species, are more active in clearcuts than in intact patches, whereas little brown myotis forage most extensively along the forest edge and northern long-eared bats (*Myotis septentrionalis*) forage most frequently in intact forest (Patriquin and Barclay 2003).

We found little to no activity of low or high frequency bats at the 1.5 m height at portable tower sites FP1, 3, and 8 on the forested ridge, most likely because these detectors were under the canopy and surrounded by relatively dense vegetation (Appendix 1b). Conversely, we found extensive use by low and high frequency bats at portable tower FP6 on the forested ridge, likely because this site is located on the edge of a gas pipeline road (see Appendix Ic) which facilitated easy commuting and foraging by bats along this linear, open corridor. We also found higher levels of activity at the meteorological tower (FM14) located in a small clearcut and moderate levels at the other tower (FM4) located in a similar opening. Small forest gaps resulting from small-scale natural or anthropogenic disturbances can increase use by bats relative to adjacent undisturbed forest (Grindal and Brigham 1998, Hayes 2003, Hayes and Loeb 2006). Openings created by clearing forest around towers may result in higher levels of bat use. Grindal and Brigham (1998) reported that insect abundance in patch cuts and un-logged forests were similar, and suggested that differences in levels of activity may be a function of differences in amount of clutter.

Our findings were influenced, in part, by the location of sampling sites and the influence of vegetation structure adjacent to detectors. Weller and Zabel (2002) found that detectors oriented toward the direction with the fewest trees recorded 24–44% more detections of bats than those oriented in two other directions. Patriquin et al. (2003) found that while sound transmission varied among forest types (conifer, deciduous, and mixed), increases in vegetation density among open, thinned, and intact forest patches did not significantly reduce the ability to detect 40 kHz sound. They did find that 25 kHz sound was less detectable in intact patches of forest and best in thinned stands in all forest types they studied. We chose to sample consistently in the same direction, regardless of vegetation structure and possible biases induced by vegetation, rather than aiming microphones in a direction so as to maximize the number of bat detections (Weller and Zabel 2002). We also caution that clearing has not yet occurred at forested sites on our study area and use is expected to change considerably, particularly at the 1.5 m level, after forest harvest (Hayes and Loeb 2006). We hypothesize that our data gathered at FM4 and 14 are more likely to reflect bat activity levels when perturbations that are a standard part of wind facility construction in forests are completed.

Accounting for spatial variation is important when collecting acoustic data at turbines because different species of bats partition their use of habitats vertically, particularly in forests (e.g., Hayes and Gruver 2000, Jung et al. 1999, Kalcounis et al. 1999). Consequently, the assumption that activity data gathered below the rotor-swept area represents risk of bats in the rotor-swept area may be unjustified for some bat species and certain landscape and habitat conditions. Reynolds (2006) noted that large, migratory events of different species may be missed without sampling into the rotor-swept area. The few acoustic studies that have employed vertical arrays of detectors that reach into the rotor-swept zone appear to reflect an emerging pattern of more low frequency echolocating bats detected at higher altitudes and the reverse for high frequency bats (Reynolds 2006, S. Reynolds, St. Paul's School, unpublished data, this study). However, it remains to be determined if vertical acoustic sampling into the rotor-swept area increases predictability of fatality events for different species and groups of species of bats.

We found that bat activity generally increased with increasing temperature and decreased as wind speed increased. Other acoustic monitoring studies at existing and proposed wind facilities have reported similar results (e.g., Fiedler 2004, Redell et al. 2006, Reynolds 2006). Erickson and West (2002) reported that both regional patterns of climatic conditions as well as local weather conditions can predict activity of bats. Strong winds can influence insect abundance and activity, which in turn influences bat activity and bats are known to suppress their activity during periods of rain, low temperatures, and strong winds (Erkert 1982, Erickson and West 2002). In the Netherlands, Verboom and Spoelstra (1999) reported that pipistrelle bat foraging activity and commuting was concentrated on the leeward side and closer to tree lines as wind speed increased. These patterns generally corroborate recent studies of bat fatality and the relationships with weather. At Buffalo Mountain in Tennessee, Fiedler (2004) found a negative relationship between bat fatality and wind speed, wind speed difference, and temperature, and a positive relationship with wind direction. The positive relationship with wind direction indicated that the further wind direction was from southwest (the prevailing wind direction) the more likely a fatality event was to occur, perhaps due to more northerly winds associated with storm fronts and/or conditions that are conducive for bat migration (Fiedler 2004). Kerns et al. (2005) reported that the majority of bats killed at the Meyersdale, Pennsylvania and Mountaineer, West Virginia facilities occurred on low wind nights, and fatalities tended to increase just before and after the passage of storm fronts. These emerging patterns hold promise for improving our ability to assess risk and better predict factors influencing the timing of fatality events. Modeling the relationships between bat activity and weather variables will be an important component of future studies designed to assess risk of bat fatality at wind facilities.

SCOPE, LIMITATIONS, and NEXT STEPS

This study was conducted at one proposed wind energy facility located on a forested ridge and an open, reclaimed ridge that had been strip mined previously, and statistical inferences are limited to this site. However, we believe that our findings likely reflect patterns of bat activity on similar forested and open ridges with comparable vegetation composition and topography in this region. We caution that this portion of our study only encompasses the mid-summer-fall period and does not represent a full period when bats are active (generally April through November).

Our analyses are exploratory, in part because so little data exist upon which to develop a priori, confirmatory hypotheses and associated candidate models. We performed our analysis using weather data gathered only from metrological towers on site; future modeling will incorporate weather data gathered from meteorological towers supplemented with data gathered with a hand-held weather tracker (Kestrel 4000, Nielsen-Kellerman Co., Boothwyn, PA) and from weather stations in Johnstown, Pennsylvania and Morgantown, West Virginia to more precisely model weather and bat activity, particularly data gathered at portable towers.

The current analysis only estimates activity rates and differences in activity patterns of two species groups (high and low frequency), in forested and open habitat, and at three heights. We anticipate development of more species and species-specific group models in the future. Additionally, we will reanalyze all calls for the final report to determine the proportion of feeding "buzzes" as a means to evaluate foraging activity.

High variation in levels of activity has consequences with respect to sampling design and level of effort required to obtain accurate estimates of activity; as fewer nights are sampled, there is an increased probability of obtaining mean estimates of activity that differ greatly from those calculated from large datasets (Hayes 1997). Low-intensity sampling could result in under- or over-estimates of activity and the most precise and accurate estimates will likely come from intensive sampling efforts (Hayes 1997). Unfortunately, the cost of intensive sampling can often exceed the project budget (Fenton 2000). But if acoustic monitoring is to be used to predict bat fatality at wind facilities, accurate measures of activity and fatality, both before and after construction are critical. In our future analyses, we will evaluate the trade-offs of reduced sampling and hence, reduced costs, on the accuracy and precision of our estimates of bat activity and fatality, with the ultimate goal of optimizing sampling designs and data requirements for employing acoustic monitoring to predict bat fatality at wind facilities.

We began a second year of pre-construction acoustic monitoring in mid-April 2006 that will continue through the end of October 2006. Turbine construction for this site is tentatively scheduled for spring-summer 2007, after which we will gather two years of post-construction activity and fatality data.

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Appendix Ia. Description of landscape characteristics in the direction of microphones and the cone of acoustic detection for each detector height at each tower deployed in south-central Pennsylvania. (FM = forest meteorological tower, FP = forest portable tower, OM = open meteorological tower, OP = open portable tower; the number for each tower follows the habitat/tower type).

Tower Code	Detector Microphone Height (m)	Landscape/Habitat Characteristics in direction of each microphone/cone of detection
FM04	1.5 22 44	Open, within clear-cut area Open, above canopy Open, above canopy
FM10	1.5 22 44	Open, within hay pasture Open, above canopy Open, above canopy
FM14	1.5 22 44	Open, within clear-cut area Open, above canopy Open, above canopy
FP01	1.5 22	Under canopy facing into old logging skid road Open, at top of canopy height and above
FP03	1.5 22	Under canopy facing into moderate to heavy vegetation and trees Open, at top of canopy height and above
FP06	1.5 22	Under canopy on the edge of gas pipeline road, but facing into a thinned stand of saw-timber class trees Open, at top of canopy height and above on the edge of, but facing away from, gas pipeline road
FP08	1.5 22	Under canopy facing into moderate vegetation and trees Open, at top of canopy height and above

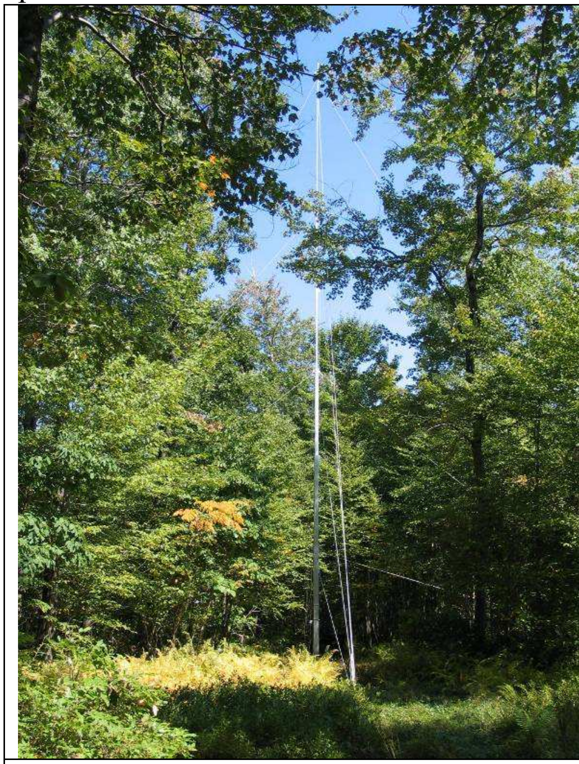
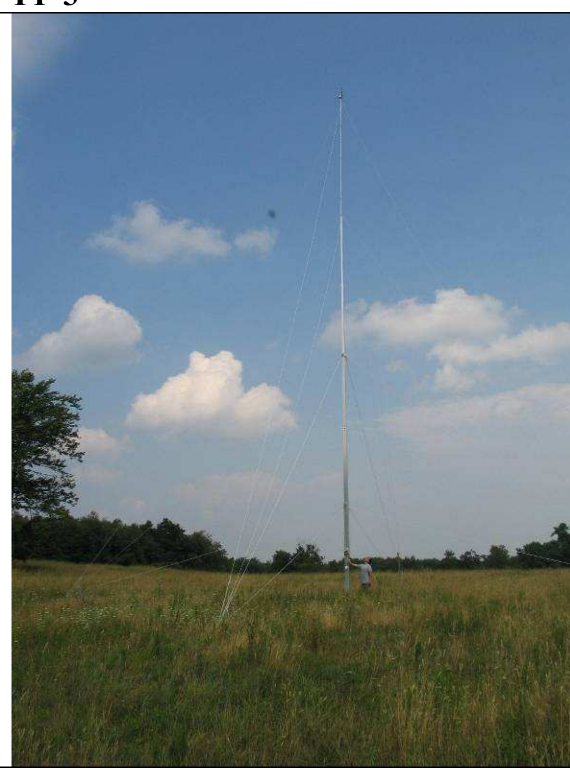
FP11	1.5 22	Open, in hay pasture within 10 m of edge of young, regenerating forest stand (below canopy) Open, in hay pasture within 10 m of edge of young, regenerating forest stand (above canopy)
FP13	1.5 22	Open, in hay pasture within 50 m of edge of unthinned stand of saw-timber sized trees (below canopy) Open, in hay pasture within 50 m of edge of unthinned stand of saw-timber sized trees (above canopy)
OP16, 18, 20, 23, ref.	1.5 22	Open, in reclaimed grassland on strip mine Open, in reclaimed grassland on strip mine

Appendix Ib. Percent vegetation cover at different heights from the ground estimated in three circular plots centered on portable towers located in un-cut forest.

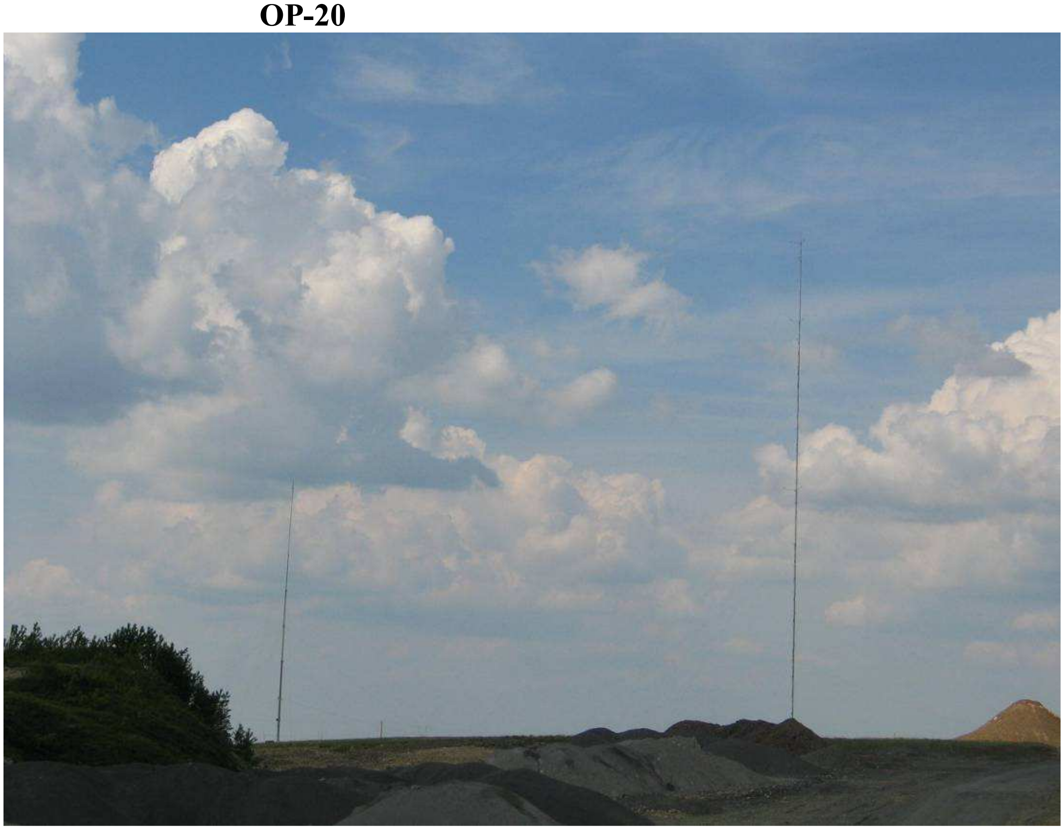
		% Vegetation Cover at Different Heights From Ground [a]		
Tower	**Distance from Tower**	**Low (0.2-2m)**	**Middle (2-8m)**	**High (8-20m)**
FP1	0-5m	16	13	14
	5-20m	33	55	50
	20-40m	35	56	24
FP3	0-5m	50	14	48
	5-20m	83	54	68
	20-40m	91	73	51
FP6	0-5m	19	9	30
	5-20m	85	21	28
	20-40m	91	29	44
FP8	0-5m	26	20	61
	5-20m	85	33	58
	20-40m	85	28	63
FPREF	0-5m	39	9	21
	5-20m	75	49	60
	20-40m	63	45	69

a – Low = ground cover and low shrub/tree cover; Middle = tall shrubs and small trees in the mid-canopy layer; High = overstory canopy.

Appendix Ic. Photos depicting vegetation characteristics associated with sampling sites at portable tower locations in south-central Pennsylvania.

	
FP-1	**FP-3**
	
FP-6	**FP-13**

OP-20



A portable (left) and meteorological tower located on the open, strip-mined ridge

Appendix II. Description of 109 models used to evaluate bat activity in relation to weather variables. All models included the design factors (species group [high or low frequency], habitat [forest or open ridge], and height [1.5, 22, or 44 m]) and all 2- and 3-way interactions of these factors. Additionally, the following models were included in the candidate set. Models 100 through 112 model temperature and wind speed as having the same effect regardless of species group, habitat or height. Models 201 through 232 allow the effects of temperature and/or wind speed to vary by species group. Models 301 through 332 parallel models 201 through 232, but allow the effects of temperature and/or wind speed to vary by height rather than species group. Finally, models 401 through 432 also parallel models 201 through 232, but allow the effects of temperature and/or wind speed to vary by habitat rather than species group.

Model #	Description	Variables
100	Null model, no effect of temp or wind speed	
101	linear effect of temperature	temp
102	linear effect of wind speed	ws
103	linear effect of temperature and wind speed	temp ws
104	linear effect of temperature and wind speed and interaction of the two	temp ws temp*ws
105	linear and quadratic effect of temperature	temp temp*temp
106	linear and quadratic effect of wind speed	ws ws*ws
107	linear effect of temperature and wind speed and quadratic effect of temperature	temp temp*temp ws
108	linear effect of temperature and wind speed with interaction of the two, and quadratic effect of temperature	temp temp*temp ws temp*ws
109	linear effect of temperature and wind speed and quadratic effect of wind speed	ws ws*ws temp
110	linear effect of temperature and wind speed with interaction of the two, and quadratic effect of wind speed	ws ws*ws temp temp*ws
111	linear and quadratic effect of temperature and wind speed	temp temp*temp ws ws*ws

112	linear and quadratic effect of temperature and wind speed, and interaction of the two	temp temp*temp ws ws*ws temp*ws
201	linear effect of temperature differs between the two species groups	temp temp*group
202	linear effect of temperature and wind speed, but the linear effect of temperature differs between the two species groups	temp ws temp*group
203	linear effect of temperature and wind speed, but the linear effect of wind speed differs between the two species groups	temp ws ws*group
204	linear effect of temperature and wind speed, but the linear effect of each differs between the two species groups	temp ws temp*group ws*group
205	linear effect of temperature and wind speed, with interaction of the two, but the linear effect of temperature differs between the two species groups	temp ws temp*ws temp*group
206	linear effect of temperature and wind speed, with interaction of the two, but the linear effect of wind speed differs between the two species groups	temp ws temp*ws ws*group
207	linear effect of temperature and wind speed, with interaction of the two, but the linear effect of both temperature and wind speed differs between the two species groups	temp ws temp*ws temp*group ws*group
208	linear effect of temperature and wind speed, with interaction of the two, all of which differ between the two species groups	temp ws temp*ws temp*group ws*group temp*ws*group
209	linear and quadratic effect of temperature and the linear effect differs between the two species groups	temp temp*temp temp*group

210	linear effect of temperature and wind speed and quadratic effect of temperature and the linear effect of temperature differs between the two species groups	temp temp*temp ws temp*group
211	linear effect of temperature and wind speed and quadratic effect of temperature and the linear effect of wind speed differs between the two species groups	temp temp*temp ws ws*group
212	linear effect of temperature and wind speed and quadratic effect of temperature and the linear effects of both temperature and wind speed differ between the two species groups	temp temp*temp ws temp*group ws*group
213	linear effect of temperature and wind speed, with interaction of the two, and quadratic effect of temperature and the linear effect of temperature differs between the two species groups	temp temp*temp ws temp*ws temp*group
214	linear effect of temperature and wind speed, with interaction of the two, and quadratic effect of temperature and the linear effect of wind speed differs between the two species groups	temp temp*temp ws temp*ws ws*group
215	linear effect of temperature and wind speed, with interaction of the two, and quadratic effect of temperature and the linear effects of both temperature and wind speed differ between the two species groups	temp temp*temp ws temp*ws temp*group ws*group
216	linear effect of temperature and wind speed, with interaction of the two, all of which differ between the two species groups, and quadratic effect of temperature	temp temp*temp ws temp*ws temp*group ws*group temp*ws*group
217	linear effect of wind speed differs between the two species groups	ws ws*group

218	linear and quadratic effect of wind speed and the linear effect of wind speed differs between the two species groups	ws ws*ws ws*group
219	linear effect of wind speed and temperature and quadratic effect of wind speed and the linear effect of wind speed differs between the two species groups	ws ws*ws temp ws*group
220	linear effect of wind speed and temperature and quadratic effect of wind speed and the linear effect of temperature differs between the two species groups	ws ws*ws temp temp*group
221	linear effect of wind speed and temperature and quadratic effect of wind speed and the linear effects of both wind speed and temperature differ between the two species groups	ws ws*ws temp ws*group temp*group
222	linear effect of wind speed and temperature, with interaction of the two, and quadratic effect of wind speed and the linear effect of wind speed differs between the two species groups	ws ws*ws temp ws*temp ws*group
223	linear effect of wind speed and temperature, with interaction of the two, and quadratic effect of wind speed and the linear effect of temperature differs between the two species groups	ws ws*ws temp ws*temp temp*group
224	linear effect of wind speed and temperature, with interaction of the two, and quadratic effect of wind speed and the linear effects of both wind speed and temperature differ between the two species groups	ws ws*ws temp ws*temp ws*group temp*group

225	linear effect of wind speed and temperature, with interaction of the two, all of which differ between the two species groups, and quadratic effect of wind speed	ws ws*ws temp ws*temp ws*group temp*group ws*temp*group
226	linear and quadratic effect of wind speed and temperature, and the linear effect of temperature differs between the two species	temp temp*temp ws ws*ws temp*group
227	linear and quadratic effect of wind speed and temperature, and the linear effect of wind speed differs between the two species	temp temp*temp ws ws*ws ws*group
228	linear and quadratic effect of wind speed and temperature, and the linear effects of both temperature and wind speed differ between the two species	temp temp*temp ws ws*ws temp*group ws*group
229	linear and quadratic effect of temperature and wind speed, and interaction of the two	temp temp*temp ws ws*ws temp*ws
230	linear and quadratic effect of temperature and wind speed, and interaction of the two, and the linear effect of temperature differs between the two species.	temp temp*temp ws ws*ws temp*ws temp*group
231	linear and quadratic effect of temperature and wind speed, and interaction of the two, and the linear effect of wind speed differs between the two species.	temp temp*temp ws ws*ws temp*ws ws*group
232	linear and quadratic effect of temperature and wind speed, and interaction of the two, and the linear effects of both temperature and wind speed differ between the two species.	temp temp*temp ws ws*ws temp*ws temp*group ws*group
233	linear and quadratic effect of temperature and wind speed, and interaction of the two differs between the two species.	temp temp*temp ws ws*ws temp*ws temp*group ws*group temp*ws*group

Appendix III. Results of model selection for all possible candidate models. Model # = number assigned by us to track individual models, Model = list of variables included in the model, k = number of estimated parameters, LL = log likelihood of the model, QAIC = AIC based on quasi likelihood,) = difference in QAIC of the model relative to the best model in the set, weight = Akaike weight associated with the model, cumwt = cumulative weight from the current model and all better models, relwt = weight of evidence in favor of the best model relative to the current model.

Model#	k	Model	Log Likelihood	QAICc	Delta	Weight	Cumulative Weight	Relative Weight
302	18	temp ws temp*height	1408.06	-2779.49	0.0000	0.25591	0.25591	1.00
310	19	temp ws temp*temp temp*height	1408.47	-2778.25	1.2390	0.13774	0.39365	1.86
320	19	temp ws ws*ws temp*height	1408.38	-2778.06	1.4365	0.12478	0.51843	2.05
305	19	temp ws temp*ws temp*height	1408.20	-2777.70	1.7971	0.10420	0.62263	2.46
326	20	temp ws temp*temp temp*height ws*ws	1408.82	-2776.88	2.6186	0.06910	0.69173	3.70
323	20	temp ws temp*ws temp*height ws*ws	1408.67	-2776.58	2.9186	0.05947	0.75120	4.30
313	20	temp ws temp*ws temp*temp temp*height	1408.61	-2776.45	3.0428	0.05589	0.80710	4.58
304	20	temp ws temp*height ws*height	1408.19	-2775.61	3.8796	0.03678	0.84388	6.96
329	21	temp ws temp*ws temp*height temp*temp ws*ws	1409.13	-2775.41	4.0792	0.03329	0.87717	7.69
312	21	temp ws temp*temp temp*height ws*height	1408.64	-2774.44	5.0543	0.02044	0.89761	12.52
321	21	temp ws ws*ws temp*height ws*height	1408.38	-2773.91	5.5803	0.01572	0.91333	16.28
307	21	temp ws temp*ws temp*height ws*height	1408.36	-2773.87	5.6211	0.01540	0.92873	16.62
328	22	temp ws temp*temp temp*height ws*height ws*ws	1408.82	-2772.72	6.7760	0.00864	0.93737	29.61
315	22	temp ws temp*ws temp*height ws*height temp*temp	1408.82	-2772.71	6.7877	0.00859	0.94596	29.78
324	22	temp ws temp*ws temp*height ws*ws ws*height	1408.69	-2772.45	7.0483	0.00754	0.95351	33.92
331	23	temp ws temp*ws temp*height ws*height temp*temp ws*ws	1409.14	-2771.26	8.2344	0.00417	0.95768	61.39
301	17	temp temp*height	1402.75	-2770.93	8.5590	0.00354	0.96122	72.21
206	18	temp ws temp*ws ws*hilow	1403.67	-2770.71	8.7833	0.00317	0.96439	80.77
308	23	temp ws temp*ws temp*height ws*height temp*ws*height	1408.66	-2770.31	9.1804	0.00260	0.96699	98.52
309	18	temp temp*temp temp*height	1403.42	-2770.22	9.2779	0.00247	0.96946	103.43
222	19	temp ws temp*ws ws*ws ws*hilow	1404.36	-2770.04	9.4586	0.00226	0.97172	113.22
109	17	temp ws temp*ws	1402.24	-2769.92	9.5715	0.00214	0.97386	119.79
208	20	temp ws temp*ws temp*hilow ws*hilow temp*ws*hilow	1405.25	-2769.73	9.7636	0.00194	0.97580	131.87
111	18	temp ws temp*ws ws*ws	1403.08	-2769.54	9.9502	0.00177	0.97757	144.76
225	21	temp ws temp*ws ws*ws ws*hilow temp*hilow ws*temp*hilow	1406.06	-2769.28	10.2142	0.00155	0.97911	165.19

316	24	temp ws temp*ws temp*height temp*temp ws*height temp*ws*heigth	1409.16	-2769.22	10.2777	0.00150	0.98062	170.52
214	19	temp ws temp*ws temp*temp ws*hilow	1403.82	-2768.95	10.5433	0.00131	0.98193	194.74
325	24	temp ws temp*ws temp*height ws*ws ws*height ws*temp*height	1408.97	-2768.83	10.6610	0.00124	0.98317	206.54
207	19	temp ws temp*ws temp*hilow ws*hilow	1403.67	-2768.65	10.8391	0.00113	0.98430	225.78
230	20	temp ws temp*ws temp*temp ws*ws ws*hilow	1404.57	-2768.36	11.1301	0.00098	0.98528	261.13
406	18	temp ws temp*ws ws*side	1402.40	-2768.18	11.3093	0.00090	0.98618	285.61
110	18	temp ws temp*ws temp*temp	1402.39	-2768.15	11.3450	0.00088	0.98706	290.76
216	21	temp ws temp*ws temp*temp temp*hilow ws*hilow temp*ws*hilow	1405.44	-2768.03	11.4638	0.00083	0.98789	308.56
205	18	temp ws temp*ws temp*hilow	1402.30	-2767.98	11.5120	0.00081	0.98870	316.08
224	20	temp ws temp*ws ws*ws ws*hilow temp*hilow	1404.37	-2767.98	11.5161	0.00081	0.98951	316.74
405	18	temp ws temp*ws temp*side	1402.29	-2767.95	11.5445	0.00080	0.99030	321.26
112	19	temp ws temp*ws temp*temp ws*ws	1403.28	-2767.87	11.6268	0.00076	0.99107	334.75
332	25	temp ws temp*ws temp*temp ws*ws temp*height ws*height temp*ws*height	1409.45	-2767.71	11.7834	0.00071	0.99177	362.01
232	22	temp ws temp*ws temp*temp ws*ws temp*hilow ws*hilow temp*ws*hilow	1406.31	-2767.70	11.7984	0.00070	0.99248	364.74
223	19	temp ws temp*ws ws*ws temp*hilow	1403.15	-2767.60	11.8932	0.00067	0.99314	382.45
423	19	ws ws*ws temp ws*temp temp*side	1403.13	-2767.57	11.9278	0.00066	0.99380	389.12
422	19	ws ws*ws temp ws*temp ws*side	1403.09	-2767.49	12.0049	0.00063	0.99443	404.42
215	20	temp ws temp*ws temp*temp temp*hilow ws*hilow	1403.83	-2766.89	12.6029	0.00047	0.99490	545.37
414	19	temp temp*temp ws temp*ws ws*side	1402.56	-2766.43	13.0684	0.00037	0.99528	688.28
231	21	temp ws temp*ws temp*temp ws*ws temp*hilow ws*hilow	1404.57	-2766.30	13.1915	0.00035	0.99563	731.97
213	19	temp ws temp*ws temp*temp temp*hilow	1402.45	-2766.21	13.2867	0.00033	0.99596	767.67
407	19	temp ws temp*ws temp*side ws*side	1402.43	-2766.17	13.3215	0.00033	0.99629	781.15
413	19	temp temp*temp ws temp*ws temp*side	1402.43	-2766.16	13.3352	0.00033	0.99661	786.52
306	19	temp ws temp*ws ws*height	1402.33	-2765.97	13.5212	0.00030	0.99691	863.17
229	20	temp ws temp*ws temp*temp ws*ws temp*hilow	1403.35	-2765.92	13.5709	0.00029	0.99720	884.87
322	20	temp ws temp*ws ws*height ws*ws	1403.33	-2765.90	13.5959	0.00029	0.99748	896.03
429	20	ws ws*ws temp temp*temp temp*ws temp*side	1403.32	-2765.87	13.6257	0.00028	0.99776	909.46
430	20	ws ws*ws temp temp*temp temp*ws ws*side	1403.29	-2765.81	13.6840	0.00027	0.99804	936.35
424	20	ws ws*ws temp ws*temp ws*side temp*side	1403.13	-2765.50	13.9944	0.00023	0.99827	1000.00
203	17	temp ws ws*hilow	1399.61	-2764.66	14.8345	0.00015	0.99843	1000.00
408	20	temp ws temp*ws temp*side ws*side temp*ws*side	1402.71	-2764.65	14.8454	0.00015	0.99858	1000.00
415	20	temp temp*temp ws temp*ws temp*side ws*side	1402.58	-2764.40	15.0967	0.00013	0.99871	1000.00
314	20	temp ws temp*ws temp*temp ws*height	1402.50	-2764.23	15.2651	0.00012	0.99884	1000.00

330	21	temp ws temp*ws ws*height temp*temp ws*ws	1403.51	-2764.17	15.3238	0.00012	0.99896	1000.00
425	21	ws ws*ws temp ws*temp ws*side temp*side ws*temp*side	1403.44	-2764.04	15.4554	0.00011	0.99907	1000.00
431	21	ws ws*ws temp temp*temp temp*ws temp*side ws*side	1403.32	-2763.80	15.6946	0.00010	0.99917	1000.00
103	16	temp ws	1398.12	-2763.74	15.7509	0.00010	0.99927	1000.00
219	18	temp ws ws*ws ws*hilow	1399.77	-2762.91	16.5793	0.00006	0.99933	1000.00
416	21	temp temp*temp ws temp*ws temp*side ws*side temp*ws*side	1402.88	-2762.91	16.5877	0.00006	0.99940	1000.00
211	18	temp ws temp*temp ws*hilow	1399.66	-2762.69	16.8003	0.00006	0.99945	1000.00
204	18	temp ws temp*hilow ws*hilow	1399.62	-2762.62	16.8758	0.00006	0.99951	1000.00
432	22	ws ws*ws temp temp*temp temp*ws temp*side ws*side temp*ws*side	1403.65	-2762.38	17.1128	0.00005	0.99956	1000.00
106	17	temp ws ws*ws	1398.35	-2762.15	17.3479	0.00004	0.99960	1000.00
403	17	temp ws ws*side	1398.19	-2761.83	17.6613	0.00004	0.99964	1000.00
107	17	temp ws temp*temp	1398.16	-2761.77	17.7218	0.00004	0.99968	1000.00
202	17	temp ws temp*hilow	1398.15	-2761.74	17.7568	0.00004	0.99971	1000.00
402	17	temp ws temp*side	1398.13	-2761.69	17.7993	0.00003	0.99975	1000.00
227	19	temp ws temp*temp ws*ws ws*hilow	1399.82	-2760.95	18.5400	0.00002	0.99977	1000.00
221	19	temp ws ws*ws ws*hilow temp*hilow	1399.78	-2760.87	18.6228	0.00002	0.99979	1000.00
212	19	temp ws temp*temp temp*hilow ws*hilow	1399.67	-2760.65	18.8453	0.00002	0.99981	1000.00
108	18	temp ws temp*temp ws*ws	1398.40	-2760.18	19.3120	0.00002	0.99983	1000.00
220	18	temp ws ws*ws temp*hilow	1398.38	-2760.14	19.3570	0.00002	0.99985	1000.00
419	18	ws ws*ws temp ws*side	1398.36	-2760.10	19.3900	0.00002	0.99986	1000.00
420	18	ws ws*ws temp temp*side	1398.36	-2760.10	19.3953	0.00002	0.99988	1000.00
411	18	temp temp*temp ws ws*side	1398.24	-2759.86	19.6327	0.00001	0.99989	1000.00
404	18	temp ws temp*side ws*side	1398.20	-2759.78	19.7158	0.00001	0.99991	1000.00
303	18	temp ws ws*height	1398.20	-2759.78	19.7176	0.00001	0.99992	1000.00
210	18	temp ws temp*temp temp*hilow	1398.19	-2759.76	19.7309	0.00001	0.99993	1000.00
410	18	temp temp*temp ws temp*side	1398.17	-2759.72	19.7769	0.00001	0.99995	1000.00
228	20	temp ws temp*temp ws*ws temp*hilow ws*hilow	1399.84	-2758.91	20.5871	0.00001	0.99995	1000.00
226	19	temp ws temp*temp ws*ws temp*hilow	1398.43	-2758.17	21.3243	0.00001	0.99996	1000.00
427	19	ws ws*ws temp temp*temp ws*side	1398.41	-2758.14	21.3573	0.00001	0.99997	1000.00
426	19	ws ws*ws temp temp*temp temp*side	1398.41	-2758.13	21.3669	0.00001	0.99997	1000.00
319	19	temp ws ws*ws ws*height	1398.38	-2758.06	21.4334	0.00001	0.99998	1000.00
421	19	ws ws*ws temp ws*side temp*side	1398.37	-2758.05	21.4427	0.00001	0.99998	1000.00
311	19	temp ws temp*temp ws*height	1398.25	-2757.81	21.6838	0.00001	0.99999	1000.00
412	19	temp temp*temp ws temp*side ws*side	1398.25	-2757.80	21.6938	0.00000	0.99999	1000.00
327	20	temp ws temp*temp ws*height ws*ws	1398.42	-2756.08	23.4123	0.00000	0.99999	1000.00
428	20	ws ws*ws temp temp*temp temp*side ws*side	1398.42	-2756.08	23.4174	0.00000	1.00000	1000.00

101	15	temp	1392.71	-2754.99	24.5042	0.00000	1.00000	1000.00
104	16	temp temp*temp	1392.89	-2753.28	26.2158	0.00000	1.00000	1000.00
201	16	temp temp*hilow	1392.74	-2752.99	26.5074	0.00000	1.00000	1000.00
401	16	temp temp*side	1392.74	-2752.98	26.5149	0.00000	1.00000	1000.00
209	17	temp temp*temp temp*hilow	1392.91	-2751.27	28.2217	0.00000	1.00000	1000.00
409	17	temp temp*temp temp*side	1392.90	-2751.25	28.2426	0.00000	1.00000	1000.00
217	16	ws ws*hilow	1384.96	-2737.43	42.0615	0.00000	1.00000	1000.00
102	15	ws	1383.46	-2736.48	43.0162	0.00000	1.00000	1000.00
218	17	ws ws*ws ws*hilow	1385.28	-2736.00	43.4978	0.00000	1.00000	1000.00
105	16	ws ws*ws	1383.86	-2735.23	44.2614	0.00000	1.00000	1000.00
417	16	ws ws*side	1383.70	-2734.90	44.5957	0.00000	1.00000	1000.00
418	17	ws ws*ws ws*side	1383.95	-2733.33	46.1611	0.00000	1.00000	1000.00
317	17	ws ws*height	1383.56	-2732.57	46.9235	0.00000	1.00000	1000.00
318	18	ws ws*ws ws*height	1383.94	-2731.25	48.2436	0.00000	1.00000	1000.00
100	14	NULL	1379.35	-2730.31	49.1817	0.00000	1.00000	1000.00

Appendix IV. Likelihood ratio statistics for analysis of variance for design factors in the best model of the set.

Source	**DF**	**Chi-Square**	**Pr > ChiSq**
date	1	26.52	<.0001
date*date	1	147.65	<.0001
height	2	11.24	0.0036
hi - low	1	1.58	0.2092
height*hi-low	2	13.18	0.0014
group	1	28.82	<.0001
height*group	2	17.21	0.0002
hi-low*group	1	0.21	0.6483
height*hi-low*group	2	3.75	0.1534
temperature	1	8.47	0.0036
wind speed	1	10.63	0.0011
temperature*height	2	19.88	<.0001