Patterns of pre-construction bat activity at the proposed Hoosac Wind Energy Project, Massachusetts, 2006–2007

Final Project Report

Cris D. Hein, Edward B. Arnett, and Michael R. Schirmacher
Bat Conservation International

Manuela M. P. Huso
EcoStats, LLC

D. Scott Reynolds
Northeast Ecological Services

Final Project Report Prepared for the
BATS AND WIND ENERGY COOPERATIVE

May 2011

REPORT CITATION

Hein, C. D., E. B. Arnett, M. R. Schirmacher, M. M. P. Huso, and D. S. Reynolds. 2011. Patterns of pre-construction bat activity at the proposed Hoosac wind energy project, Massachusetts, 2006–2007. A final project report submitted to the Bats and Wind Energy Cooperative. Bat Conservation International. Austin, Texas, USA.

ACKNOWLEDGEMENTS

This study was conducted under the auspices of the Bats and Wind Energy Cooperative (BWEC). We thank the American Wind Energy Association (AWEA), Bat Conservation International (BCI), the National Renewable Energy Laboratory-Department of Energy (NREL), and the US Fish and Wildlife Service (USFWS). Tom Gray and John Anderson (AWEA), Christy Johnson-Hughes and Alex Hoar (USFWS), Bob Thresher and Karin Sinclair (NREL), and Ed Arnett and Merlin Tuttle (BCI) provided oversight for the BWEC on this project. We thank the Massachusetts Technology Collaborative (MTC) and Iberdrola Renewables (IBR) for funding this study, and the numerous donors to BCI, member companies of AWEA, and the National Fish and Wildlife Foundation, for additional support. At IBR, we thank Andy Linehan (deceased), Scott McDonald, and Kristen Goland for logistical support. Jack Waggett assisted with installation of detector systems on meteorological towers and helped with field logistics. We thank Tom Kunz, Paul Cryan, Scott Darling, and Tim Sullivan for their review of this report and members of the BWEC Scientific Advisory and Technical Advisory Committees for their support.

EXECUTIVE SUMMARY

We initiated a multi-year, pre-construction study in summer 2006 to investigate patterns of bat activity at the proposed Hoosac Wind Energy Project (HWEP) in northwestern Massachusetts. The primary objectives of this study were to: 1) determine levels and patterns of activity of different phonic groups of bats using the proposed HWEP prior to construction; 2) correlate bat activity with weather and other environmental variables; and, 3) combine results from this study with those from similar efforts to determine if indices of pre-construction bat activity can be used to predict post-construction bat fatalities at proposed wind facilities. We report results from two years of pre-construction data collection.

We recorded echolocation calls of bats with Anabat II zero-crossing ultrasonic detectors, programmed to record calls beginning ½-hour prior to sunset and ending ½-hour after sunrise each day of the study from 27 July–11 November 2006, and 1 June–31 October 2007. We used 5 meteorological towers to position acoustic microphones at 10, 31.5, and 39.2 m above ground level (agl). We identified 2 broad phonic groups, high frequency bats frequency (≥ 33 kHz, mostly *Myotis* spp., red bats [*Lasiurus borealis*] and tri-colored bats [*Perimyotis subflavus*]), low frequency bats (<33 kHz, hoary bats [*Lasiurus cinereus*], big brown bats [*Eptesicus fuscus*], and silver-haired bats [*Lasionycteris noctivagans*]). We also identified a third phonic group, hoary bats, because this species is vulnerable to wind development and because their echolocation sequences are relatively easy to distinguish among other low frequency bats. In 2006, we recorded a total of 2,424 and 1,364 high frequency and low frequency bat passes, respectively. Hoary bats comprised 30% ($n = 410$) of low frequency passes. In 2007, we recorded a total of 7,739 and 2,063 high frequency and low frequency passes, respectively. Hoary bats comprised 13% ($n = 267$) of low frequency passes.

Seasonally, bat activity was highest between mid-July and mid-August for all phonic groups. However, timing and intensity of peak activity differed between years. Flight altitude was consistent between years, but differed among phonic groups. We detected high frequency bats more frequently at 10 m. Although activity by low frequency bats was more evenly distributed among the three heights, the majority of passes were recorded from higher altitudes (i.e., 31 m and 39 m agl). We also detected hoary bat passes more frequently at higher altitudes.

Our models incorporated location, temperature and several wind speed measurements. Temperature and location were consistently the most important factors in our models. We found a positive relationship with bat activity and temperature, particularly at temperatures >12° C. In general, both the probability of activity and estimated number of calls from each phonic group increased as much as 39% for every 1° C increase in temperature. Bat activity was highest at Bakke 2 followed by Crum 1, Crum 2 and Bakke 1. However, location alone explained only 2–8% of the variation in activity. While some measure of wind speed often was important, it never explained more than an additional 3.6% of the variation in activity. The HWEP has higher mean nightly wind speeds than other sites where comparable data have been gathered, which may explain why the relationship between activity and wind was not as strong as previously documented.

As this study was conducted at a single proposed wind energy facility located on forested ridges in northwestern Massachusetts the statistical inferences are limited to this site. To improve statistical power and determine whether our findings reflect patterns of bat activity on similar forested ridges with comparable vegetation composition and topography, additional studies are required at sites with similar characteristics in the region. Despite acoustic and meteorological equipment malfunctions, we were able to quantify the spatial (vertical and horizontal) and temporal (seasonal and yearly) activity patterns of bats. These data may provide useful information for predicting when, where, and which bats may be most at risk of interacting with wind turbines at the HWEP. Moreover, specific timings and locations of peak activity may further refine the use of curtailment as a mitigation option.

INTRODUCTION

As energy demands increase worldwide, many countries are seeking ways to reduce fossil fuel consumption and generate alternative energy sources. Wind is one of the fastest growing forms of renewable energy and has been produced commercially in North America for nearly 4 decades (Pasqualetti et al. 2004, National Research Council 2007). In recent years, the United States has led the world in wind generating capacity, including ~10,000 Megawatts (MW) of new capacity in 2009 (AWEA 2010a). Currently, Massachusetts ranks 31^{st} in the US for installed capacity at 15 MW and 27^{th} for capacity added (9 MW) in 2009 (AWEA 2010b). Although wind generated energy reduces carbon and other greenhouse gas emissions associated with global warming, it is not entirely environmentally neutral because wildlife and habitat can be directly or indirectly impacted by development.

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

Nine species of bats are known or believed to occur in Massachusetts (Massachusetts Department of Fish and Game [MDFG] 2010). Of these, the Indiana bat (*Myotis sodalis*) and the eastern small-footed bat (*M. leibii*) are listed by the MDFG as endangered and a species of concern, respectively. However, because of the impacts of White-nose Syndrome, the MDFG has proposed listing for the little brown myotis (*M. lucifugus*), northern long-eared myotis (*M. septentrionalis*), and the tri-colored bat (*Perimyotis subflavus*). The Indiana bat, once documented in Berkshire, Hampden and Worcester Counties (west-central Massachusetts), is now thought to be extirpated from Massachusetts, and eastern small-footed bats only have been documented from Berkshire and Hampden Counties (MDFG 2010). The remaining 4 species, big brown bat (*Eptesicus fuscus*), eastern red bat (*Lasiurus borealis*), hoary bat (*Lasiurus cinereus*), and silver-haired bat (*Lasionycteris noctivagans*) are not granted special conservation status in the state, but several, collectively known as migratory tree-roosting bats (eastern red bat, hoary bat, and silver-haired bat), are of increasing concern with respect to wind development because fatalities are comprised predominantly of these four species (Arnett et al. 2008).

Although several hypotheses (i.e., roost, landscape, acoustic or visual attraction) explaining possible bat/turbine interactions exist, none have been confirmed (Arnett 2005, Barclay et al. 2007, Cryan and Brown 2007, Kunz et al. 2007a). Resolution of these different hypotheses requires additional data on population estimates, migratory pathways, and flight behaviors. However, the combination of nocturnal habits, volancy, size, and variation in resource dependence (i.e., species vary in roost, water, and food requirements), makes even rudimentary understanding of how bats interface with their environment difficult to establish (Gannon et al. 2003). Available post-construction monitoring data from a few wind facilities have provided a baseline for bat behaviors and fatalities (Arnett et al. 2008, Horn et al. 2008). Our current understanding of bat fatality at wind developments allows for some conjecture about risk factors for certain species, but further information on nightly and seasonal activity patterns encompassing a facility or region is still necessary to place bat fatalities in an appropriate context (Fiedler 2004). Pre-construction acoustic surveys at wind facilities often are conducted to assess local bat species presence and activity. However, using this information to quantify potential bat fatalities is unproven. Furthermore, the ability to generate reliable risk assessments during early planning phases (i.e., prior to site selection and construction) often is hampered by lack of baseline data on distributions, densities, migratory patterns, and behavior of bats (O'Shea et al. 2003, Larkin 2006, Reynolds 2006, Cryan and Brown 2007) throughout much of North America. Thus, extensive planning (e.g., study design, survey intensity) for pre-construction acoustic studies at future wind developments is essential (EIA 2007, Kunz et al. 2007a, 2007b).

Acoustic monitoring allows researchers to detect and record echolocating bats to investigate relative activity and identify species or species groups (Kunz et al. 2007b). Understanding bat activity levels and patterns prior to construction of wind facilities may assist in identifying landscapes and conditions which may pose high risk of fatality and aid with decision-making, such as specific placement of turbines (Fiedler 2004, Reynolds 2006). Acoustic monitoring also provides insight into nightly and seasonal activity patterns of bats, which will help refine the timing and extent of potential mitigation strategies (e.g., curtailment). Unfortunately, lack of information and agreement among stakeholders and scientists exists regarding whether bat activity is an appropriate metric for establishing risk to bats at wind energy facilities. Although several studies, collectively, have shown a positive correlation ($r = 0.79$) between total number of bat calls/night and estimated fatalities/turbine/year (see Kunz et al. 2007b), confounding factors associated with these studies limit our ability to make inferences and develop a fundamental link necessary for understanding potential risk of wind facilities on bats.

OBJECTIVES

Iberdrola Renewables (IBR), which operated under PPM Energy at initiation of the study, proposes to develop the Hoosac Wind Energy Project (HWEP) in northwestern Massachusetts. In 2006, we initiated a multi-year, pre-construction study to evaluate the spatial and temporal activity patterns of bats. The first phase collected echolocation passes to develop indices of temporal and spatial activity patterns from July through November 2006 and June through October 2007. The second phase, which will occur after the site is operational, will involve post-construction fatality monitoring from mid-April through November for 2 consecutive years. Here, we present results from the 2006 and 2007 field seasons, discuss bat activity patterns, and outline future study efforts for this project. Specifically, our objectives for this report were to: 1) collect baseline information on activity levels for different phonic groups using the HWEP in northwestern Massachusetts, 2) examine spatial and temporal patterns of bat activity with acoustic detectors positioned on 5 meteorological (met) towers at 3 heights, and 3) combine our results with those of similar studies to evaluate if indices of pre-construction bat activity can be used to predict relative risk of post-construction bat fatalities at a site. This report focuses on objectives 1 and 2; results from this study will be combined with several similar ongoing efforts in the region to address Objective 3.

STUDY AREA

The proposed HWEP is located in Berkshire and Franklin Counties in northwestern Massachusetts (Fig. 1). The area is situated along the northern Appalachian Mountains in the Hoosac Range. Elevation at the HWEP ranges from 720–870 m. The region is characterized by forest mountain ridges and steep gorges. The vegetation community is classified as acidic talus forest woodland and is comprised predominately of various oaks (*Quercus* spp.), American Beech (*Fagus grandifolia*), Eastern Hemlock (*Tsuga canadensis*), and White Pine (*Pinus strobus*).

Two turbine strings are proposed for this site; the eastern and western strings consist of 9 and 11 turbines, respectively. Five 40 m met towers are distributed across the HWEP, with 2 (Bakke 1 and Bakke 2) associated with the western string and 3 (Crum 1, Crum 2, and Crum 3) with the eastern string. This distribution allowed us to capture variation associated with habitat features across the HWEP.

METHODS

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

EQUIPMENT

We used 15 Anabat II broadband acoustic detectors coupled with CF-ZCAIM storage units (Titley Electronics, Ballina, New South Wales, Australia) with an approximate detection range of 20 m (actual range is dependent on temperature, humidity, and frequency and intensity of echolocation call). We positioned detector microphones at 3 heights (10, 31.5, and 39.2 m above ground level [agl]) on 5 met towers to record echolocation call sequences, or bat passes (Fig. 2). This spatial arrangement allowed us to sample bat activity within the lower portion of the Rotor-Swept Area (RSA) and across the proposed HWEP. We subjectively chose the direction of each microphone on each met tower to maximize recordings of echolocation calls (Weller and Zabel 2002) based on our perception of how bats presumably used the surrounding habitat (Table 1). Prior to sampling, we calibrated each Anabat unit (sensitivity set to ~6) to minimize variability in reception among detectors (Larson and Hayes 2000). We programmed each detector to record data beginning ½-hour prior to sunset and ending ½-hour after sunrise for each night of the study (US Naval Observatory Astronomical Applications Department, http://aa.usno.navy.mil/data/docs/RS_OneYear.php). We housed microphones in waterproof "bat-hats" (EME Systems, Berkeley, California, USA) attached to electrical cables extending to ground level, where detectors were placed in waterproof boxes (Figs. 3, 4). We used a photovoltaic system to provide continuous solar power to all detectors.

ANALYSIS

We visited each tower approximately every 4 weeks to exchange compact flash (CF) cards. We downloaded and analyzed data using Anabat CFC Read (version 4.2a) and Analook (version 4.9j) software, respectively. Prior to analysis, we removed extraneous noise from our data using customized filters derived from Britzke and Murray (2000).

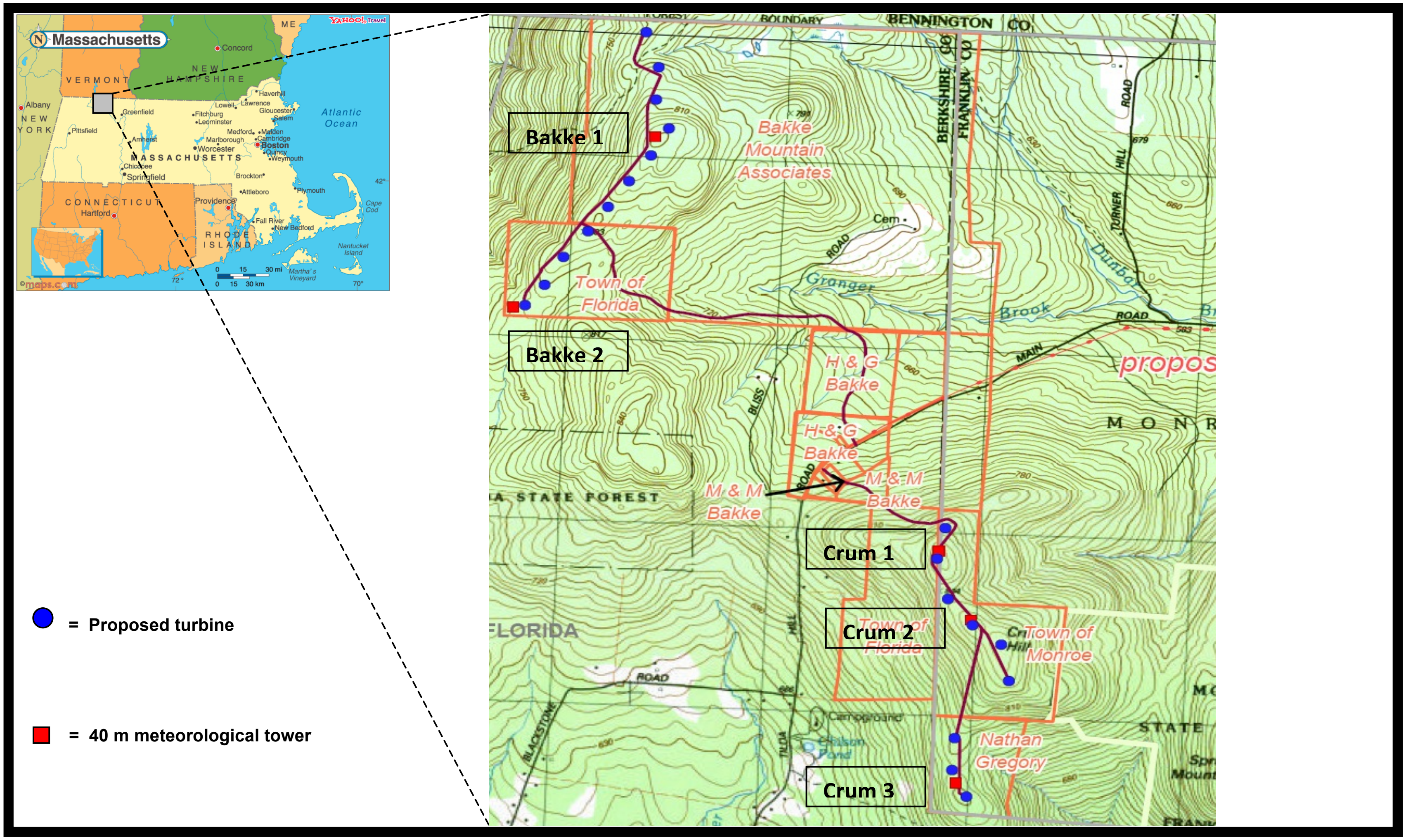

Figure 1. Map of the proposed Hoosac Wind Energy Project, Berkshire and Franklin Counties, Massachusetts, and locations of proposed turbine

Phonic group identification

We divided bat passes into 2 phonic groups based on minimum frequency of the echolocation sequence, in part because bats using these frequencies may differ in their use of habitat and in their response to environmental factors. To accomplish this, we constructed 2 filters to classify bat passes as being produced by either high frequency bats (≥33 kHz average minimum frequency; e.g., *Myotis* spp., tri-colored, or eastern red) or low frequency bats (<33 kHz average minimum frequency; e.g., big brown, silver-haired, or hoary).

Table 1. Height and direction of acoustic detector microphones on each meteorological (met) tower located at the proposed Hoosac Wind Energy Project, Massachusetts, 2006–2007.

Met Tower	Height (m)	Azimuth (cardinal direction)
Bakke 1	10.0	60 (northeast)
	31.5	310 (northwest)
	39.2	115 (southeast)
Bakke 2	10.0	180 (south)
	31.5	270 (west)
	39.2	0 (north)
Crum 1	10.0	135 (southeast)
	31.5	0 (north)
	39.2	180 (south)
Crum 2	10.0	125 (southeast)
	31.5	180 (south)
	39.2	0 (north)
Crum 3	10.0	150 (southeast)
	31.5	0 (north)
	39.2	90 (east)

Both filters were derived from those developed by Britzke and Murray (2000), with a Smoothness = 15 and a Bodyover = 80. We adjusted frequency parameters to separate high and low echolocation sequences. For the low group filter, we set the maximum frequency at 33 kHz, and for the high group filter, we set the minimum frequency at 33 kHz. We visually scanned all files not assigned by the filters and placed them into the appropriate high or low group. We also identified a third phonic group, hoary bats-a subset of the low frequency group, using a customized filter, with a Smoothness = 12, Bodyover = 110, MinFmin = 14, MaxFmin = 21, and CallNum = 1. We selected hoary bats because this species is vulnerable to wind development and because their echolocation sequences are relatively easy to distinguish among other low frequency bats.

Temperature and wind speed

We used civil sunrise and sunset data from the US Naval Observatory Astronomical Applications Department (http://aa.usno.navy.mil/data/docs/RS_OneYear.php) to define our crepuscular and nocturnal sampling period or "night". We monitored bat activity each night between ½-hour before sunset to ½-hour after sunrise. This sampling schedule provided coverage during times when bats presumably were most active (Hayes 1997). We adjusted met tower dates to "effective dates" such that all morning hours within each night were assigned the previous calendar date value. We summarized data for each "effective date" and checked for missing observations or anomalous or unreasonable values. Average temperature and wind speed were recorded at 10 minute intervals on each met tower. Wind speed was measured at 40 m agl in 2 directions on each tower and ambient temperature was measured at 3 m agl. We averaged wind speed data collected from 2 directions. At each met tower, we calculated 5 summary statistics for each night: average temperature (Temp) = mean over all 10 minute averages, average wind speed (WS) = mean over all 10 minute averages, proportion of 10-minute intervals during which average wind speed was greater than 3.5 m/s (PctG3.5), >5 m/s (PctG5), and >6.5 m/s (PctG6.5). We merged the total number of calls recorded by each phonic group with weather data for each location and night.

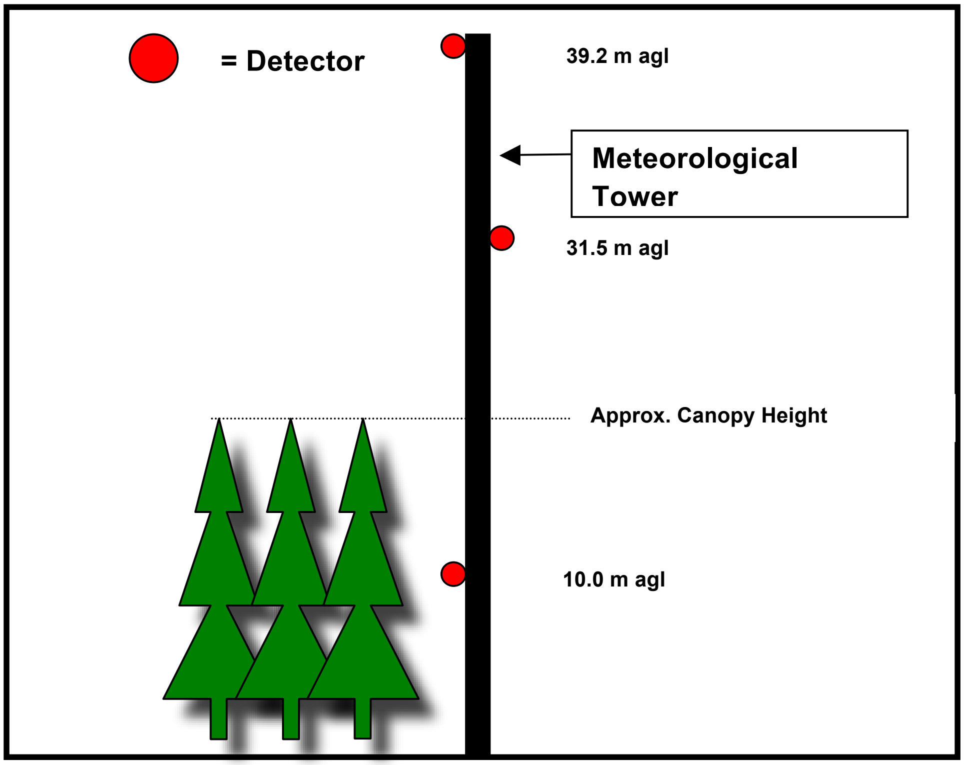

Figure 2. Depiction of the vertical array of acoustic detectors used at meteorological towers (modified from Reynolds 2006).

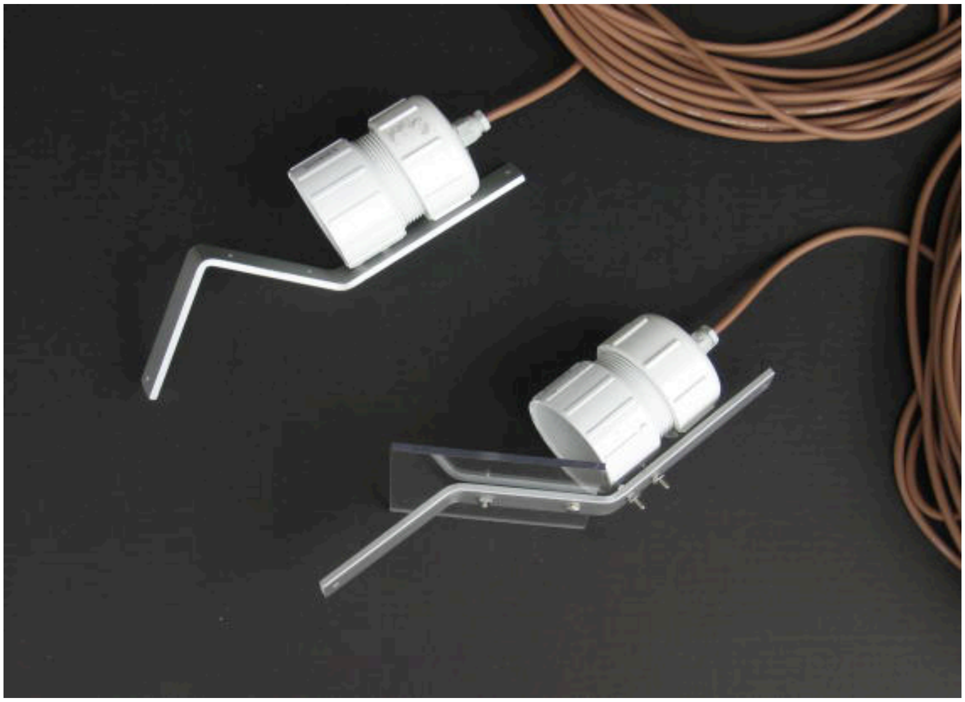

Figure 3. Examples of different bat-hat mounting systems used to deploy acoustic microphones at multiple heights on meteorological towers.

Figure 4. Waterproof boxes used to store acoustic detectors and solar battery, and a 30 watt solar panel mounted to a meteorological tower. Photo not taken at HWEP. (photo by D. S. Reynolds.)

Because of acoustic or meteorological equipment malfunctions, the full range of study dates was not available for analysis. Therefore, we used dates when all detectors were available for each analysis to maximize coincident data recordings among all met towers.

We designed our analysis to examine the relationship of bat activity for 3 phonic groups to various measures of temperature and wind speed. Because our response variable, counts (i.e., number of bat passes/night) from each location and height, contains numerous zeros (i.e., nights with no bat activity recorded) our data naturally conforms to the sequential hypotheses: 1) which variables relate to the probability of activity occurring on any given night/height/location; and 2) given that activity occurs, which variables are associated with level of activity? To examine these 2 questions simultaneously, we used hurdle models (Zuur et al. 2009) which divide the response into 2 parts, the zero counts and the non-zero counts. In the first part, the probability of activity is modeled as a binomial (binary) response and can be related to explanatory covariates such as height, wind speed, or temperature. In the second part, (the count part), the activity rate can be modeled as a truncated Poisson or negative binomial response and also can be related to explanatory covariates. We modeled activity as a truncated negative binomial response to accommodate variation in bat passes/night that exceeds that assumed from a Poisson distribution. We included design factors (i.e., location and height) in all models to account for the correlation of observations within these factors. We included temperature in all models as a surrogate for changing seasonal effects. This reduced residual autocorrelation to <0.09, so no further models of temporal autocorrelation were incorporated.

To explore how height, wind, and temperature might affect the probability of activity and the activity rate of bats in the 3 phonic groups, we established a set of 77 candidate models, including one null (no explanatory variables), 4 baseline models, and 72 plausible wind models (Appendix 1). The null model included no covariates for either the binomial part (probability of activity) or the count part (activity rate) of the hurdle model. The 4 baseline models differed in the factors included in each part of the hurdle model (i.e., height, location, and temperature), excluding wind speed. The first baseline model (location model) included only location effects in both parts. The second baseline model (count design model) included location and the interaction with temperature and height only in the count part of the model. The third baseline model (probability design model) included the same design factors as in the count design model, but only as covariates for the binomial part of the model. The fourth baseline model (full design model) included all design factors as covariates in both parts. Additional models (wind models) built upon the forth baseline model and included covariates of nightly wind speed. To construct the suite of candidate wind models, we first incorporated WS both separately and simultaneously in the binomial and count parts of the hurdle model. Next, we maintained WS in the binomial part, and considered each wind speed measurement (i.e., PctG6.5, PctG5, or PctG3.5), and interactions between wind speed and either height or temperature for the count part of the hurdle model. We repeated this process, but maintained WS in the count part and varied wind speed measurements and interactions in the binomial part. The same process was used for PctG3.5, PctG5 and PctG6.5, thus we considered measures of wind speed for both parts of the hurdle model simultaneously. This method of candidate model construction allowed us to first relate higher wind speed thresholds to the probability of bat activity, and then given activity, examine relationships between the amount of activity and wind speed measurements up to and including the higher threshold.

We used Akaike's Information Criterion (AIC) to perform 3 separate model selection analyses (Burnham and Anderson 2002), one for each of the 3 phonic groups (i.e., high frequency, low frequency, and the low-frequency subset-hoary bats) to evaluate and select the most-parsimonious model given the data and set of candidate models. We established a confidence set of models (i.e., highly competing models) by including only those models within 2 AIC units of the best approximating model. We calculated Nagelkerke's pseudo-R^2 (Rp^2) as a rough indicator of model strength. We compared Rp^2 values of the location model and the full design model with the null model. We also compared additional Rp^2

values of the best approximating model with the full design model. We report results for all base models and all models within 4 AIC units of the best approximating model. If clear evidence indicated a specific wind model was better than the full design model, we interpreted the most parsimonious, highly competing wind model.

We evaluated the probability and count of activity at each tower at a specific height, given mean temperature and wind speed. For high frequency bats we used 10 m as our reference height, and for low frequency and hoary bats we used 39 m as our reference height. We compared changes in probability and counts at different heights. We also examined the effects of changing temperature and wind speed on bat activity. We calculated parameter estimates, standard errors and effects for coefficients in each phonic group and year. We evaluated the ecological importance of each variable by computing 95% confidence intervals for each coefficient and interpreted the values within these intervals (Gerard et al. 1998). Odds ratios whose 95% confidence interval included 1 were considered relatively imprecise and provided little information regarding bat activity.

RESULTS

In 2006, we conducted bat acoustic monitoring for 108 nights between 27 July and 11 November 2006 from 4 towers at 3 heights for a total of 1,296 potential detector-nights (# detectors * # towers * # nights). Acoustic data from Crum 3 were excluded from our analyses because temperature data were not collected at this tower. Malfunctions in acoustic and meteorological equipment further reduced our dataset. Thus, we were able to use coincident data (i.e., nights with all detectors and weather equipment operational) for 828 detector-nights (69 nights * 4 towers * 3 heights). In 2007, we monitored bat activity for 153 nights between 1 June and 31 October from 4 towers at 3 heights for a total of 1,836 potential detector nights. The Bakke 1 met tower was not available for acoustic monitoring during the 2007 study period. Acoustic data from Crum 3 were excluded from our analyses because temperature data were not collected at this tower. Malfunctions in acoustic and meteorological equipment further reduced our dataset. Thus, we were able to use 1,251 detector-nights (139 nights * 3 towers *3 heights).

In 2007, we recorded 2 anomalous nights of low frequency bat activity (n = 122 and 186 passes), resulting in high variation in the count model. Because the next highest number of passes recorded = 53, we removed these two outliers from our analysis. We also removed 1 anomalous night of hoary bat activity from each year (2006: n = 18 passes, no other night had >8 passes; 2007: n = 27 passes, no other night had >11 passes). In addition, because we recorded so few hoary bat calls at 10 m detectors (12% of nights), we only analyzed our data for this group from 31.5 m and 39.2 m. For 2007 hoary bat data, variance estimates using the negative binomial distribution to model counts were unacceptably high, resulting in low precision on the dispersion parameter. Therefore, we modeled the count part of the model using a Poisson distributed random variable.

Bat activity was highly variable among phonic groups, within a season and between years (Fig. 5). In 2006, high frequency bats were more active in early August, with activity decreasing and remaining low through November. In contrast, high frequency bat activity remained high from late July through August in 2007. Low frequency bats were most active in late September in 2006, but had the highest peak in activity in late July 2007. Hoary bat activity peaked in early August and mid-August in 2006 and 2007, respectively.

We detected high frequency bats most frequently at 10 m. Although low frequency bats passes were more evenly distributed among altitudes, the majority of passes were recorded from ≥31 m (Fig. 6). We also detected hoary bats more often at higher altitudes. Bat activity for all 3 phonic groups was negatively and positively related to wind speed and temperature, respectively (Figs. 7 and 8). Changes in activity in relation to weather were more pronounced at 10 m, particularly for high frequency bats, with activity sharply decreasing at ~10 m/s and increasing at ~13° C in 2006. We observed similar trends in 2007.

MODEL ANALYSIS

Fall 2006

In fall 2006, mean wind speed and temperature were 7.5 m/s (range = 2.3–27.0 m/s) and 12.6° C (range = -3.3–25.2° C), respectively (Table 2). The absolute correlation of temperature with any measure of wind speed was ≤0.12. On average, the proportion of the night during which wind speed ≥3.5 m/s (PctG3.5) was 91% and ranged from near 12% to 100%. The PctG5 and PctG6.5 averaged 75% (range = ~0–100%) and 54% (range = ~0–100%), respectively.

We recorded a total of 2,424 high frequency (max = 258 passes, Crum 2, 10 m), 1,364 low frequency (max = 85 passes, Bakke 2, 39 m), and 410 hoary (max = 18, Bakke 2, 31 m) bat passes (Table 3). Among towers, mean activity for high frequency bats ranged from 0.6 (Bakke 1) to 5.09 (Crum 2) passes/night. Activity of low frequency bats ranged from 0.85 (Bakke 1) to 3.37 (Bakke 2) passes/night. For hoary bats, mean activity ranged from 0.27 (Bakke 1) to 0.89 (Bakke 2). We detected high frequency bats more often at 10 m. Low frequency bat passes were more evenly distributed, but the majority of passes were recorded at altitudes ≥31 m. We detected hoary bats more frequently at higher altitudes. On nights when bats were recorded at a station (i.e., excluding nights with zero activity), mean activity was2.3–4.0 times the average for high frequency bats, 2.3–3.3 times for low frequency bats, and 3.3–6.3 times for hoary bats. Although we recorded zero bat passes on the majority of nights, we detected at least 1 high frequency bat pass on 65%, 28% and 21% of detector-nights, 1 low frequency bat pass on 38%, 49% and 64%, and 1 hoary bat pass on 12%, 33%, and 34% of detector-nights at 10 m, 3.51 m and 39.2 m, respectively (Table 4).

High Frequency Bats

The best approximating model for high frequency bat activity, with a 10% probability, was based on the full design model and incorporated PctG5 in the probability part of the hurdle model (Appendix 2). This model was 1.25 times more likely than the next best approximating model which contained the same parameters plus PctG6.5 in the count part of the hurdle model. The confidence set (within 2 AIC units) of models included the top 9 models with a sum of Akaike weights of 0.563 indicating a 56.3% chance that 1 of these models was the best approximating model given the data and set of candidate models. The location model was 44 AIC units better than the null model, accounting for approximately 7% of variation in activity at the site, while the full design model was 623 AIC units better than the null model, accounting for approximately 60% of variation. Although the full design model was not included in the confidence set of models, it was 3.8 AIC units away from the best approximating model, and only accounted for an additional 0.3% of the variation in activity. Therefore, the best fitting model was no more likely than the full design model, thus no coefficients for slope were estimated.

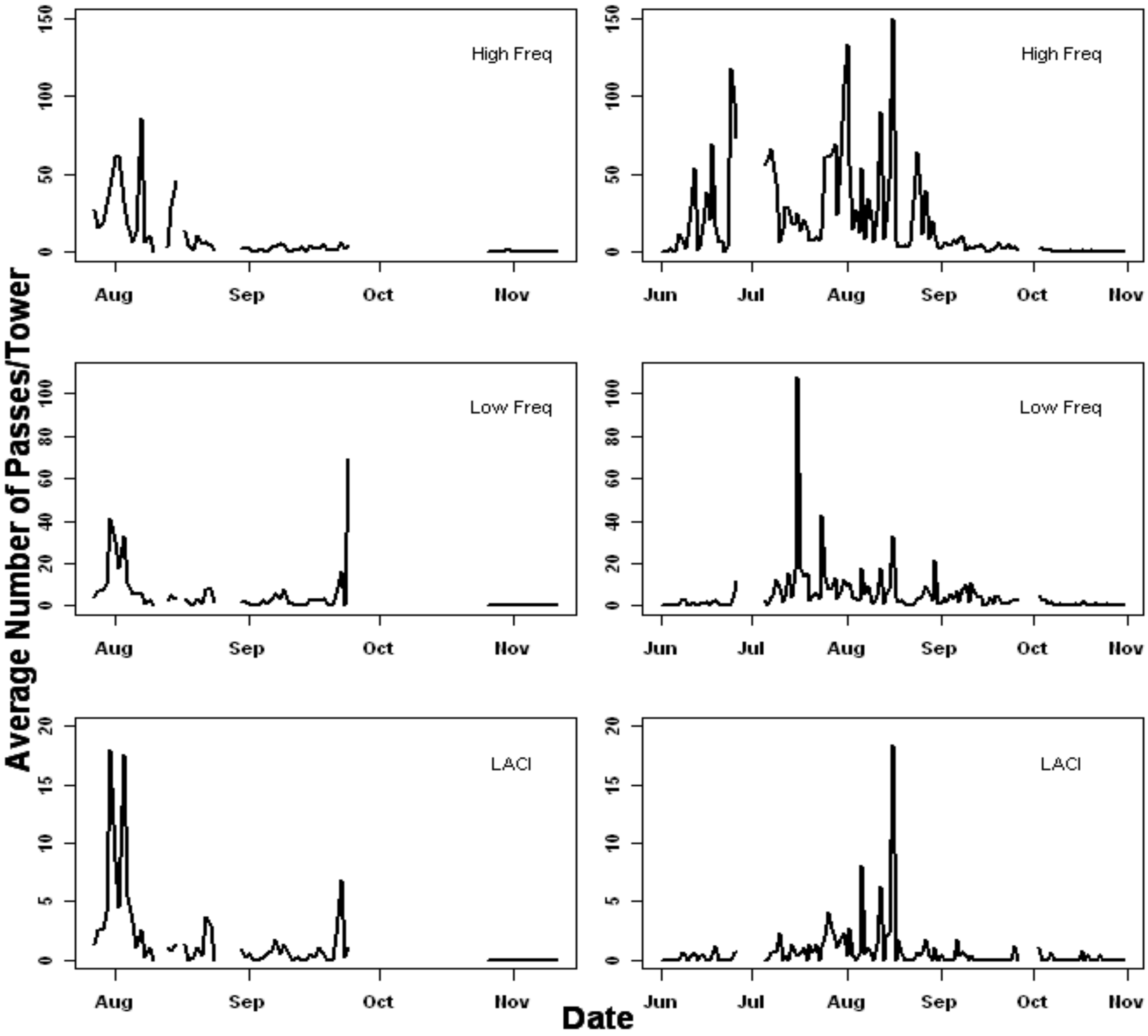

Figure 5. Mean bat passes/tower for each phonic group at the HWEP, 2006 (left) and 2007 (right). Gaps indicate dates when acoustic data were not available.

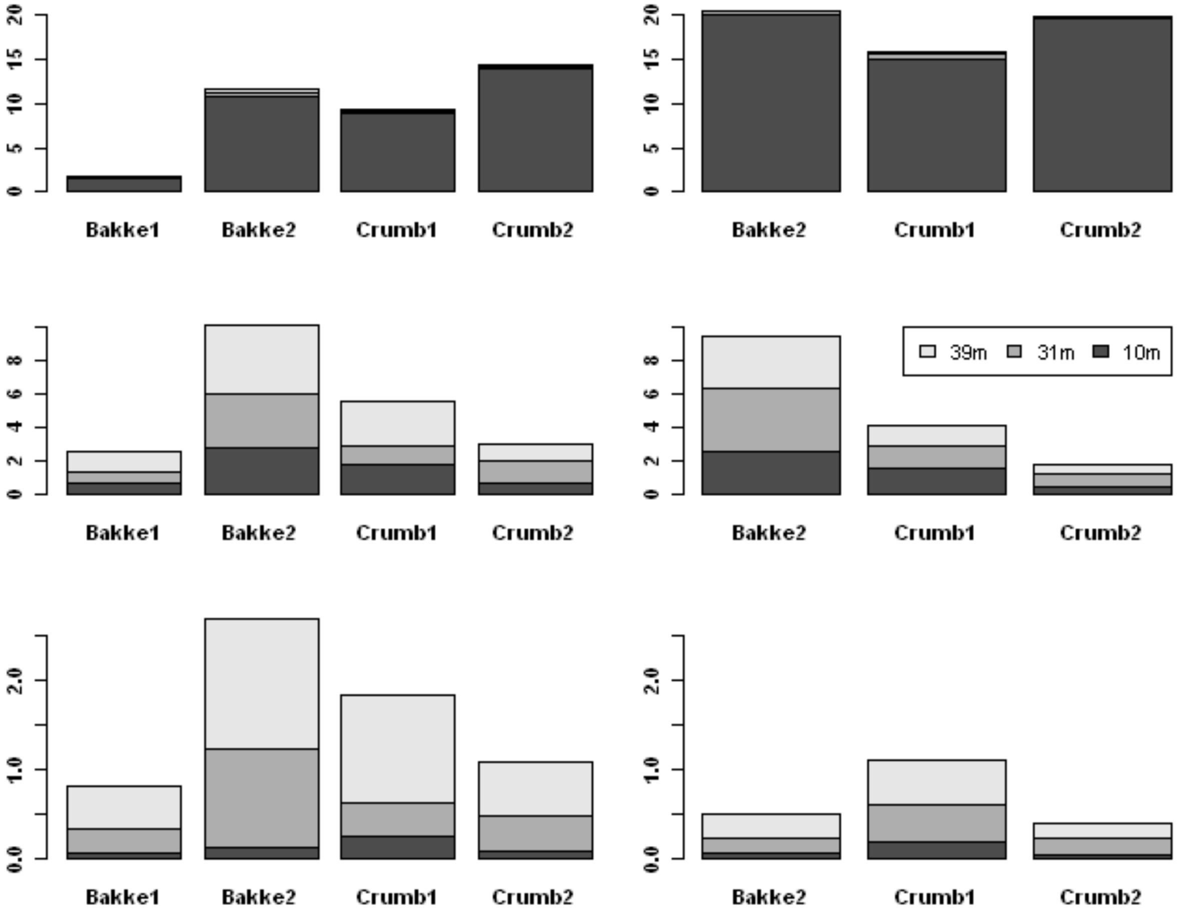

Figure 6. Mean bat passes/night at each tower and height for high frequency bats (≥33 kHz), low frequency, and hoary bats (<33 kHz) at the HWEP, 2006 (left) and 2007 (right).

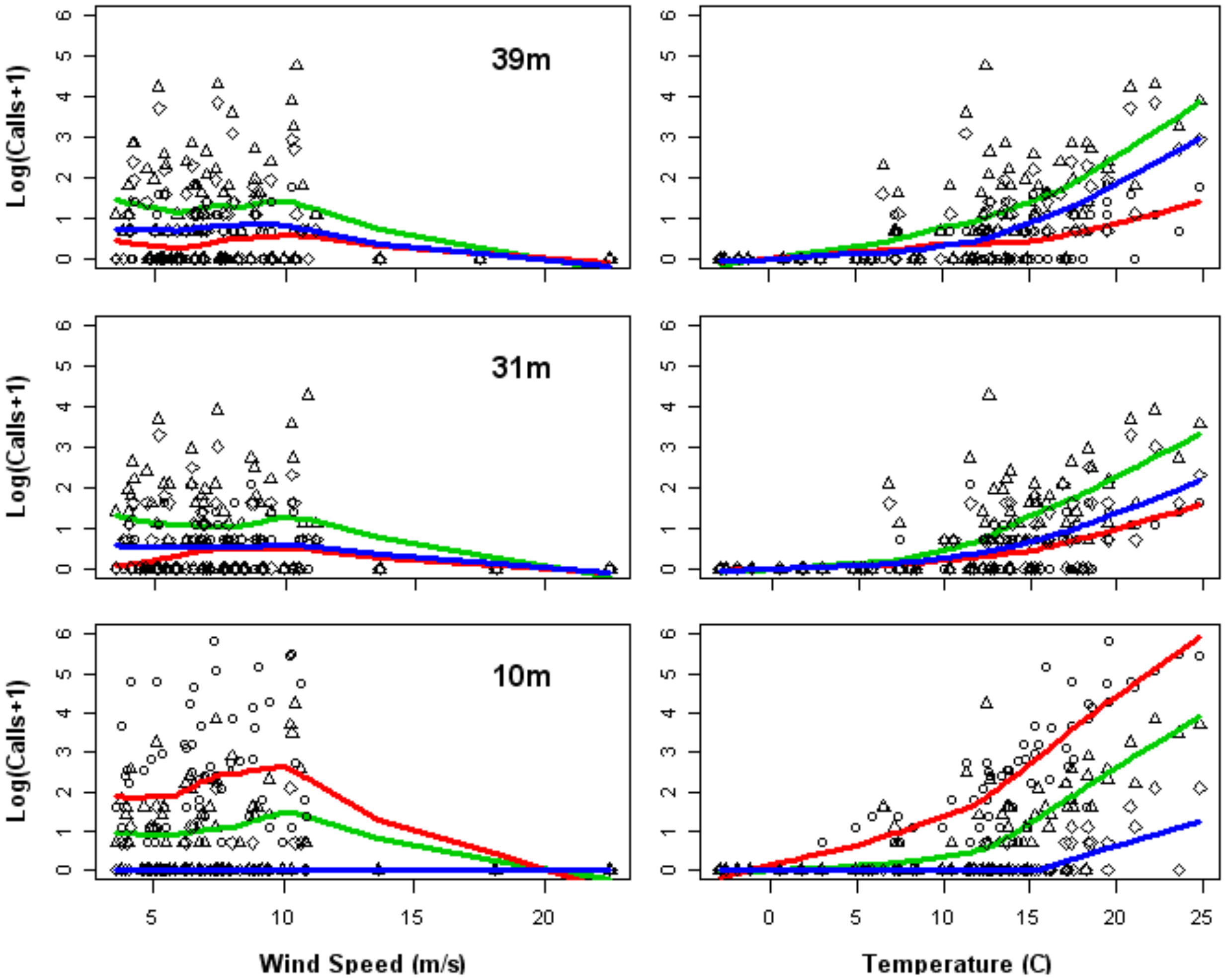

Figure 7. Log$_e$ (number of bat passes) at each height related to wind speed (left) and temperature (right) for high frequency (○), low frequency (◊) and LACI (Δ) at the HWEP, 2006. Red, green and blue lines are the loess fits for high frequency, low frequency, and hoary bats, respectively

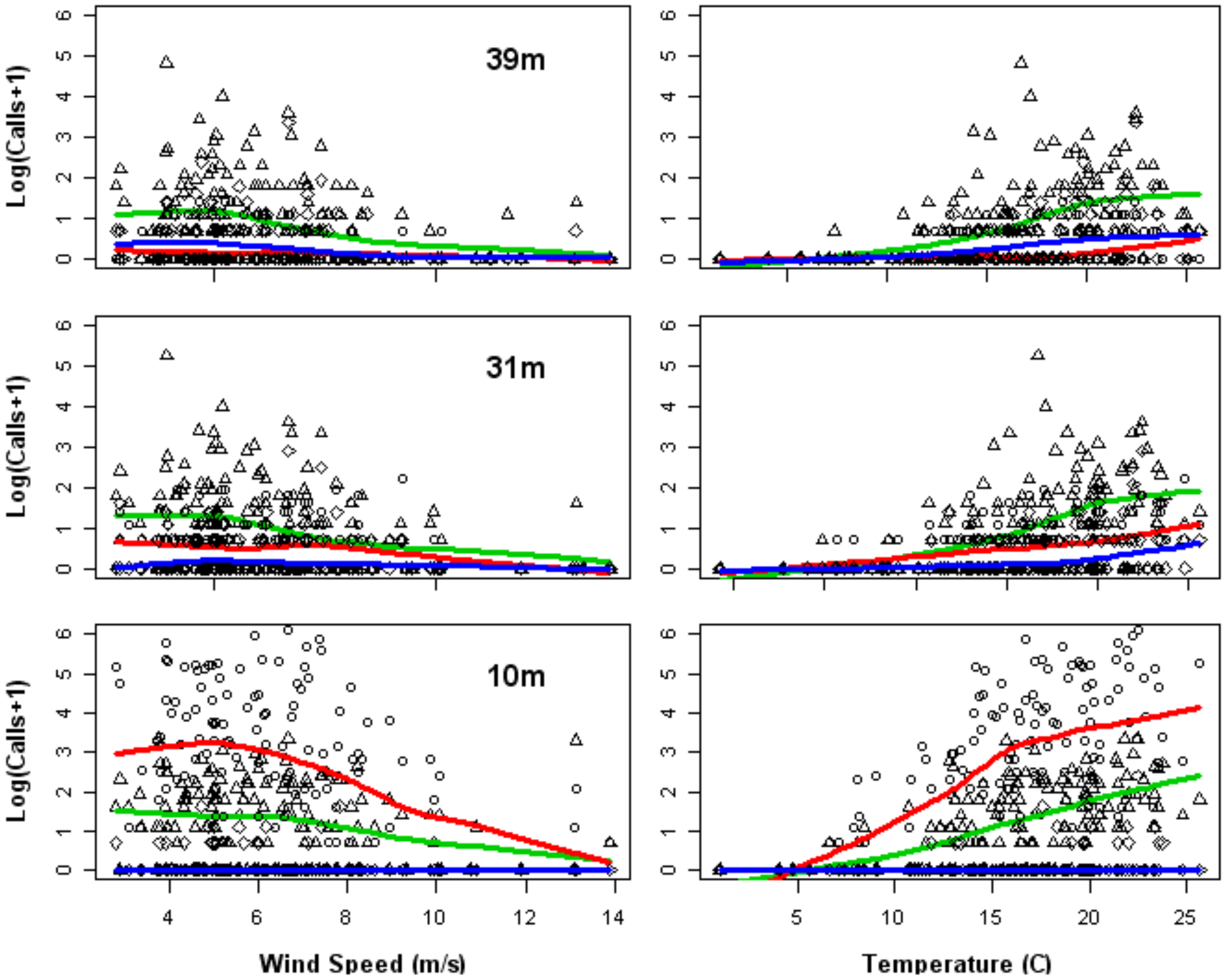

Figure 8. Log$_e$ (number of bat passes) at each height related to wind speed (left) and temperature (right) for high frequency (○), low frequency (◊) and LACI (Δ) at the HWEP, 2007. Red, green and blue lines are the loess fits for high frequency, low frequency, and hoary bats, respectively.

Low Frequency Bats

The best approximating model for low frequency bat activity, with a probability of 57.6%, was based on the full design model and incorporated the interaction between mean temperature and mean wind speed in both parts of the hurdle model (Appendix 2). This model was 5.0 times more likely than the next best approximating model which contained the same parameters plus the interaction between height and mean wind speed in both parts of the hurdle model. The confidence set of models only included the top model. The location model was 40 AIC units better than the null model, accounting for approximately 7% of variation in activity at the site, while the full design model was 262 AIC units better than the null model, accounting for approximately 34% of variation. The best fitting model was roughly 31 AIC units better than the full design model, accounting for an additional 3.6% of the variation in activity beyond the full design model.

On a night with average wind speed and temperature, the probability of activity at the Crum 1, 39 m detector was 42.6% (Table 5). Given similar conditions, the probability of activity at Crum 2, Bakke 1 and Bakke 2 were 27.1%, 29.4%, and 57.4%, respectively. The probability of activity decreased with decreasing altitude and was 0.06–2.65 times more likely at 39 m than at10 m. For every 1° C increase in temperature, the probability of bat activity increased 17–34%. The probability of bat activity was positively related to decreasing wind speed, with odds of activity increasing by 2–18% for every 1 m/s decrease in wind speed. We found little evidence of change in the probability of activity with temperature increases at lower altitudes (i.e., 31 m and 10 m agl).

The expected number of passes, on nights with mean temperature and wind speed, at Crum 1, 39 m was 1.97 passes/night (Table 5). We found the highest count at Bakke 2 with 3.57 passes/night and lower counts at Crum 2 (1.00 passes/night) and Bakke 1 (0.85 passes/night). The expected number of calls decreased with decreasing altitude and was 1.25–4.22 times more likely at 39 m than at 10 m. For every 1° C increase in temperature, the expected number of passes increased 2–15%. Activity increased with increasing wind speed, with 23–49% increase in counts for every 1 m/s increase in wind speed. We found little evidence of change in mean passes/night with temperature increases at lower altitudes.

Hoary bats

The best approximating model for hoary bat activity, with a probability of 20.1%, was based on the full design model and incorporated mean wind speed in the binomial part of the model (Appendix 2). This model was 1.5 times more likely than the next best approximating model that contained the same parameters plus mean wind speed in the count part of the model. The confidence set of models included the top 8 models with a sum of Akaike weights of 0.608. The location model was 16 AIC units better than the null model, accounting for approximately 6.2% of variation in activity at the site, while the full design model was 128 AIC units better than the null model, accounting for approximately 32% of variation. The best fitting model was roughly 8 AIC units better than the full design model, accounting for an additional 1.7% of the variation in activity beyond the full design model.

On a night with average wind speed and temperature, the probability of activity at the Crum 1, 39 m detector was 21.5% (Table 5). Given similar conditions, the probability of activity at Crum 2, Bakke 1 and Bakke 2 was 11.3%, 37.1%, and 19.4%, respectively. For every 1° C increase in temperature, the probability of activity increased 18–39%. The probability of bat activity was positively related to decreasing wind speed, with odds of activity increasing by 5–31% for every 1 m/s decrease in wind speed. We found little evidence of change in the probability of activity at 31 m and with temperature increases at 31 m.

The expected number of passes, on nights with average temperature and wind speed, at Crum 1, 39 m was 0.29 passes/night (Table 5). We found the highest count at Crum 2 with 0.32 passes/night and lower counts at Bakke 2 (0.29 passes/night) and Bakke 1 (0.11 passes/night). For every 1° C increase in temperature, the expected number of passes increased 8–28%. We found little evidence of change in mean passes/night with other coefficients.

Table 2. Mean, standard deviation (SD), minimum and maximum for temperature (° C), wind speed (m/s), and proportion of night with wind speed >3.5 m/s (PctG3.5), >5 m/s (PctG5), and >6.5 m/s (PctG6.5) from each of 4 meteorological towers at the HWEP, Massachusetts, 2006.

Tower	Variable	Mean	SD	Minimum	Maximum
Bakke 1	Temperature	12.25	6.34	-3.27	24.79
	Wind Speed	8.57	3.80	3.48	27.04
	PctG3.5	0.94	0.12	0.45	1.0
	PctG5	0.84	0.22	0.11	1.0
	PctG6.5	0.68	0.33	0.00	1.0
Bakke 2	Temperature	12.38	6.25	-2.78	24.91
	Wind Speed	6.31	2.81	2.25	20.02
	PctG3.5	0.85	0.22	0.12	1.00
	PctG5	0.66	0.30	0.00	1.00
	PctG6.5	0.39	0.33	0.00	1.00
Crum 1	Temperature	12.35	6.43	-3.21	24.36
	Wind Speed	7.13	3.05	3.19	21.05
	PctG3.5	0.90	0.15	0.38	1.0
	PctG5	0.70	0.29	0.02	1.0
	PctG6.5	0.48	0.35	0.00	1.0
Crum 2	Temperature	13.31	6.14	-2.61	25.24
	Wind Speed	7.98	3.09	2.88	22.07
	PctG3.5	0.95	0.11	0.36	1.0
	PctG5	0.83	0.24	0.05	1.0
	PctG6.5	0.63	0.35	0.00	1.0
All towers	Temperature	12.57	6.29	-3.27	25.24
	Wind Speed	7.51	3.33	2.25	27.04
	PctG3.5	0.91	0.16	0.12	1.0
	PctG5	0.76	0.28	0.00	1.0
	PctG6.5	0.55	0.36	0.00	1.0

Table 3. Summary of bat activity, by phonic group, recorded from 4 towers and 3 heights at the HWEP, Massachusetts, 2006.

Phonic group	Tower/height	Mean passes/night	Mean passes/night (given activity)[a]	Maximum number of passes	% of nights with zero bat passes
High	Bakke 1				
	10 m	1.60	2.82	9	43
	31 m	0.07	1.00	1	93
	39 m	0.13	1.13	2	88
	Overall	0.60	2.38	9	75
	Bakke 2				
	10 m	10.90	14.68	142	26
	31 m	0.44	1.43	3	69
	39 m	0.32	1.38	3	75
	Overall	3.91	9.10	142	57
	Crum 1				
	10 m	9.00	15.27	79	41
	31 m	0.12	1.00	1	88
	39 m	0.29	1.31	3	76
	Overall	3.19	10.13	79	68
	Crum 2				
	10 m	13.90	21.98	258	37
	31 m	0.34	1.46	6	77
	39 m	0.12	1.14	2	90
	Overall	5.09	15.43	258	67
Low	Bakke 1				
	10 m	0.65	2.81	11	77
	31 m	0.65	2.05	5	68
	39 m	1.25	3.44	18	64
	Overall	0.85	2.79	18	70
	Bakke 2				
	10 m	2.83	5.74	47	51
	31 m	3.16	5.51	66	43
	39 m	4.12	7.37	85	44
	Overall	3.37	6.22	85	46
	Crum 1				
	10 m	1.77	4.50	13	61
	31 m	1.12	3.35	19	67
	39 m	2.69	4.88	25	45
	Overall	1.89	4.39	25	57
	Crum 2				
	10 m	0.69	2.47	12	72
	31 m	1.34	3.13	17	57
	39 m	0.96	3.20	17	70
	Overall	0.97	2.95	17	67

Table 3. Continued.

Phonic group	Tower/height	Mean passes/night	Mean passes/night (given activity)	Maximum number of passes	% of nights with zero bat passes
Hoary	Bakke 1				
	10 m	0.06	1.33	2	96
	31 m	0.28	1.36	2	80
	39 m	0.48	2.06	8	77
	Overall	0.27	1.70	8	84
	Bakke 2				
	10 m	0.12	1.33	2	91
	31 m	1.12	2.71	18	59
	39 m	1.46	3.41	15	57
	Overall	0.89	2.90	18	69
	Crum 1				
	10 m	0.25	2.00	6	88
	31 m	0.37	2.38	7	84
	39 m	1.21	3.04	13	60
	Overall	0.62	2.71	13	77
	Crum 2				
	10 m	0.07	1.25	2	94
	31 m	0.41	2.56	8	84
	39 m	0.60	3.33	13	82
	Overall		2.72	13	87

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

Table 4. Number of detector-nights in which high frequency, low frequency and hoary bats were detected/not detected at each of 3 heights for all towers combined at the HWEP, Massachusetts, 2006.

Phonic Group	Number of Detections	Detector Height		
		10 m	31 m	39 m
High	0	96	199	218
	1	36	36	35
	2	24	6	6
	3	25	2	3
	4	10	0	0
	>4	71	1	0
	Non-zero[a]	166	45	44
	Missing[b]	14	32	14
Low	0	171	142	147
	1	30	38	44
	2	19	26	19
	3	10	16	13
	4	9	5	14
	>4	23	17	25
	Non-zero[a]	91	102	115
	Missing[b]	14	32	14
Hoary	0	242	185	182
	1	13	33	45
	2	6	10	12
	3	0	9	7
	4	0	1	1
	>4	1	6	15
	Non-zero[a]	20	59	80
	Missing[b]	14	32	14

[a] Number of detector-nights with at least 1 bat pass detected.

[b] Number of detector-nights data were not collected because of equipment malfunctions.

Table 5. Model parameter estimates, standard error (SE), parameter effects, and 95% confidence limits for probability and count models of bat activity at the HWEP, Massachusetts, 2006. Tower effects estimate the probability of activity (Probability) or estimated number of calls (Count) on a night with mean temperature and wind speed at 39 m. Additional parameter effects are interpreted as odds ratios.

Phonic group/Model	Coefficient	Estimate	SE	Effect	Lower 95% CL	Upper 95% CL
Low						
Probability[a]	Crum 1	-0.299	0.225	0.426	0.323	0.536
	Crum 2	-0.990	0.222	0.271	0.194	0.365
	Bakke 2	0.299	0.219	0.574	0.468	0.674
	Bakke 1	-0.876	0.218	0.294	0.214	0.390
	10 m	-0.519	0.233	0.595	0.377	0.940
	31 m	-0.242	0.234	0.785	0.496	1.241
	T	0.222	0.034	1.249	1.168	1.335
	WS	-0.094	0.038	0.910	0.845	0.980
	10 m*T	0.031	0.050	1.032	0.935	1.138
	31 m*T	0.044	0.051	10.44	0.945	1.155
	T *WS	0.002	0.008	1.002	0.987	1.017
Count[b]	Crum 1	0.682	0.347	1.977	1.001	3.906
	Crum 2	0.004	0.384	1.004	0.473	2.131
	Bakke 2	1.272	0.329	3.569	1.872	6.806
	Bakke 1	-0.160	0.377	0.852	0.407	1.783
	10 m	-0.832	0.310	0.435	0.237	0.799
	31 m	-0.509	0.296	0.602	0.337	1.075
	T	0.080	0.031	1.083	1.019	1.151
	WS	0.304	0.050	1.355	1.228	1.494
	10 m*T	0.074	0.050	1.077	0.977	1.187
	31 m*T	0.006	0.047	1.006	0.918	1.103
	T *WS	-0.035	0.008	0.965	0.949	0.981
	Log (theta)[c]	0.308				

Table 5. Continued.

Phonic group/Model	Coefficient	Estimate	SE	Effect	Lower 95% CL	Upper 95% CL
Hoary						
Probability[a]	Crum 1	-1.297	0.284	0.215	0.135	0.323
	Crum 2	-2.064	0.310	0.113	0.065	0.189
	Bakke 2	-0.528	0.266	0.371	0.259	0.498
	Bakke 1	-1.423	0.275	0.194	0.123	0.292
	31 m	-0.363	0.273	0.696	0.407	1.188
	T	0.247	0.040	1.280	1.184	1.385
	WS	-0.165	0.054	0.848	0.762	0.944
	31 m*T	-0.042	0.055	0.959	0.862	1.068
Count[b]	Intercept	-1.230	1.624	0.292	0.012	7.052
	Crum 2	-1.141	1.636	0.319	0.013	7.894
	Bakke 2	-1.253	1.643	0.286	0.011	7.158
	Bakke 1	-2.190	1.727	0.112	0.004	3.302
	31 m	-0.819	0.504	0.441	0.164	1.184
	T	0.159	0.044	1.172	1.076	1.276
	31 m*T	0.015	0.078	1.015	0.871	1.183
	Log (theta)[c]	0.126				

[a] Zero Hurdle Model: Binomial with Logit Link

[b] Count Model: Truncated Negative Binomial with Log Link.

[c] Theta estimates the extra variation of the count distribution.

Fall 2007

In fall 2007, mean wind speed and temperature were 6.3 m/s (range = 2.4–16.5 m/s) and 16.3° C (range = -1.3°–33.3° C), respectively (Table 6). The absolute correlation of temperature with any measure of wind speed was ≤0.06. On average, the proportion of the night during which wind speed ≥3.5 m/s was 86% (range = ~4–100%). The PctG5 and PctG6.5 averaged 65% (range = ~0–100%) and 42% (range = ~0–100%), respectively.

We recorded a total of 7,739 high frequency (max = 308 passes, Bakke 2, 10 m), 2,063 low frequency (max = 186 passes, Bakke 2, 39 m), and 267 hoary (max = 27, Crum 1, 39 m) bat passes (Table 7). Among towers, mean activity for high frequency bats ranged from 5.3 (Crum 1) to 7.13 (Bakke 2) passes/night. Activity of low frequency bats ranged from 0.6 (Crum 2) to 2.37 (Bakke 2) passes/night. For hoary bats, mean activity ranged from 0.13 (Crum 2) to 0.37 (Crum 1). We detected high frequency bats more often at 10 m, but low frequency bat passes were more evenly distributed. We detected hoary bats more frequently at higher altitudes. On nights when bats were recorded at a station (i.e., excluding nights with zero activity), mean activity was2.5–3.5 times the average for high frequency bats,1.9–3.7 times for low frequency bats, and 5.6–10.2 for hoary bats. Although we recorded zero passes on the majority of nights, we detected at least 1 high frequency bat pass on 71%, 25% and 13% of detector-nights, 1 low frequency bat pass on 45%, 41% and 36% of detector-nights, and 1 hoary bat pass on 12%, 21%, and 22% at 10 m, 31 m and 39 m, respectively (Table 8).

Table 6. Mean, standard deviation (SD), minimum and maximum for temperature (° C), wind speed (m/s), and proportion of night with wind speed >3.5 m/s (PctG3.5), >5 m/s (Pct G5), and >6.5 m/s (PctG6.5) from each of 4 meteorological towers at the HWEP, Massachusetts, 2007.

Tower	Variable	Mean	SD	Minimum	Maximum
Bakke 2	Temperature	14.53	4.54	-0.28	22.62
	Wind Speed	5.44	2.11	2.17	13.99
	PctG3.5	0.79	0.23	0.04	1.0
	PctG5	0.52	0.35	0.00	1.0
	PctG6.5	0.27	0.33	0.00	1.0
Crum 1	Temperature	13.96	6.03	-1.30	21.74
	Wind Speed	6.32	2.39	2.21	16.52
	PctG3.5	0.86	0.15	0.15	1.0
	PctG5	0.64	0.27	0.00	1.0
	PctG6.5	0.40	0.36	0.00	1.0
Crum 2	Temperature	20.57	6.03	4.63	33.26
	Wind Speed	7.24	2.39	2.75	14.79
	PctG3.5	0.92	0.15	0.28	1.00
	PctG5	0.80	0.27	0.00	1.00
	PctG6.5	0.60	0.36	0.00	1.00
All towers	Temperature	16.26	5.90	-1.30	33.26
	Wind Speed	6.32	2.42	2.17	16.52
	PctG3.5	0.86	0.20	0.04	1.00
	PctG5	0.65	0.34	0.00	1.00
	PctG6.5	0.42	0.37	0.00	1.00

Table 7. Summary of bat activity, by phonic group, recorded from 4 towers and 3 heights at the HWEP, Massachusetts, 2007.

Phonic group	Tower/height	Mean passes/night	Mean passes/night (given activity)[a]	Maximum number of passes	% of nights with zero bat passes
High	Bakke 2				
	10 m	20.11	24.96	308	19
	31 m	0.34	1.42	4	76
	39 m	0.14	1.00	1	86
	Overall	7.13	17.65	308	60
	Crum 1				
	10 m	15.11	20.39	158	26
	31 m	0.56	1.50	4	63
	39 m	0.24	1.26	3	81
	Overall	5.30	12.15	158	56
	Crum 2				
	10 m	19.59	32.41	269	40
	31 m	0.28	1.78	5	84
	39 m	0.08	1.10	2	93
	Overall	6.97	24.48	269	72
Low	Bakke 2				
	10 m	2.56	4.14	14	38
	31 m	3.74	7.88	186	53
	39 m	3.10	6.45	122	52
	Overall	3.13	5.95	53	47
	Crum 1				
	10 m	1.55	3.03	22	49
	31 m	1.39	2.84	23	51
	39 m	1.22	2.82	31	57
	Overall	1.38	2.90	31	52
	Crum 2				
	10 m	0.49	2.13	1	77
	31 m	0.79	2.28	16	65
	39 m	0.55	2.31	21	76
	Overall	0.60	2.24	21	73

Table 7. Continued.

Phonic group	Tower/height	Mean passes/night	Mean passes/night (given activity)[a]	Maximum number of passes	% of nights with zero bat passes
Hoary	Bakke 2				
	10 m	0.06	1.00	1	94
	31 m	0.18	1.71	6	90
	39 m	0.26	1.39	5	82
	Overall	0.16	1.42	6	84
	Crum 1				
	10 m	0.18	2.27	10	92
	31 m	0.41	1.97	11	79
	39 m	0.52	2.12	27	76
	Overall	0.37	2.08	27	82
	Crum 2				
	10 m	0.04	1.00	1	96
	31 m	0.19	1.29	4	85
	39 m	0.16	1.47	3	89
	Overall	0.13	1.32	4	90

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

Table 8. Number of detector-nights in which high frequency, low frequency and hoary bats were detected/not detected at each of 3 heights for all towers combined at the HWEP, Massachusetts, 2007.

Phonic Group	Number of Detections	Detector Height		
		10 m	31 m	39 m
High	0	116	288	344
	1	43	65	47
	2	28	27	6
	3	18	7	1
	4	17	3	0
	>4	190	1	0
	Non-zero[a]	296	103	54
	Missing[b]	5	26	19
Low	0	24	218	246
	1	63	68	69
	2	42	40	29
	3	20	27	20
	4	20	10	11
	>4	43	27	22
	Non-zero[a]	188	172	151
	Missing[b]	5	27	20
Hoary	0	388	331	326
	1	21	44	52
	2	0	7	14
	3	1	4	3
	4	1	2	0
	>4	1	3	3
	Non-zero[a]	24	60	72
	Missing[b]	5	26	19

[a] Refers to the number of detector- nights with at least 1 bat pass recorded.

[b] Refers to the number of detector-nights data were not collected because of equipment malfunctions.

High Frequency Bats

The best approximating model for high frequency bat activity, with a 14.4% probability, was based on the full design model and incorporated PctG5 in the binomial part of the model (Appendix 2). This model was 1.1 times more likely than the next best approximating model which also was based on the full design model, but incorporated the interaction between height and wind speed in both binomial and count parts of the model. The confidence set of models included the top 8 models with a sum of Akaike weights of 0.599. The location model was 24.3 AIC units better than the null model, accounting for approximately 3% of variation in activity at the site, while the full design model was 808.8 AIC units better than the null model, accounting for approximately 51% of variation in activity. The best fitting model was roughly 8.5 AIC units better than the full design model, accounting for an additional 0.4% of variation in activity beyond the full design model.

On a night with mean wind speed and temperature, the probability of activity at Crum 1, 10 m detector was 87% (Table 9). The probability of activity was similar at Bakke 2 (81%), but was lower at Crum 2 (50%). The probability of activity increased with decreasing altitude and was 7.4–15.2 and 16.4–37.0 times higher at 10 m than at 31 m and 39 m, respectively. For every 1° C increase in temperature, the probability of activity increased 12–23%. The probability of bat activity was positively related to decreasing wind speed, with odds of activity increasing by 4–19% for every 1 m/s increase in wind speed. We found little evidence of change in the probability of activity with temperature increases at higher altitudes.

The expected number of passes, on nights with average temperature and wind speed, at Crum 1, 10 m was 13.1 passes/night (Table 9). We found the highest count at Bakke 2 (14.9 passes/night) and the lowest count at Crum 2 (5.8 passes/night). The expected number of passes increased with decreasing altitude and was 32.3–83.3 and 83.3–500.0 times higher at 10 m than at 31 m and 39 m, respectively. For every 1° C increase in temperature, the expected number of passes increased 19–33%. The expected number of passes was positively related to decreasing wind speed, with odds of activity increasing by 5–24% for every 1 m/s increase in wind speed. We found little evidence of change in mean passes/night at Crum 1 or with temperature increases at higher altitudes.

Low Frequency Bats

The best approximating model for low frequency bat activity, with a 16.1% probability, was based on the full design model and incorporated PctG5 in the binomial part of the model (Appendix 2). This model was 1.3 times more likely than the next best approximating model which contained the same variable, but also incorporated PctG5 in the count part of the model. The confidence set of models included the top 6 models with a sum of Akaike weights of 0.559. The location model was 82.5 AIC units better than the null model, accounting for approximately 8% of variation in activity at the site, while the full design model was 318.5 AIC units better than the null model, accounting for approximately 26.3% of variation in activity. The best fitting model was roughly 17.3 AIC units better than the full design model, accounting for an additional 1.3% of the variation in activity beyond the full design model.

Given the proportion of the night with wind speed >5 m/s = 50% and mean temperature, the probability of activity at the Crum 1, 39 m detector was 55% (Table 9). The probability of activity was similar at Bakke 2 (55%), but lower at Crum 2 (11%). The probability of activity increased with decreasing altitude and was 1.1–2.1 times more likely at 10 m. For every 1° C increase in temperature, the probability of bat activity at our reference detector increased 18–30%. The probability of bat activity was positively related to PctG5, with activity 1.7–3.8 times more likely for every 10% decrease in the proportion of night with wind speed >5 m/s. We found little evidence of change in the probability of activity with temperature increases at higher altitudes.

Table 9. Model parameter estimates, standard error (SE), parameter effects, and 95% confidence limits for probability and count models of bat activity at the HWEP, Massachusetts, 2007. Tower effects estimate the probability of activity (Probability) or estimated number of calls (Count) on a night with mean temperature and wind speed at 10 m (high frequency bats) or 39 m (low frequency and hoary bats). Additional parameter effects are interpreted as odds ratios.

Phonic group/Model	Coefficient	Estimate	SE	Effect	Lower 95% CL	Upper 95% CL
High						
Probability[a]	Crum 1	1.863	0.179	0.866	0.819	0.901
	Crum 2	0.009	0.180	0.502	0.415	0.589
	Bakke 2	1.447	0.174	0.810	0.751	0.857
	31 m	-2.355	0.182	0.095	0.066	0.135
	39 m	-3.210	0.208	0.040	0.027	0.061
	T	0.162	0.023	1.175	1.123	1.230
	WS	-0.112	0.035	0.894	0.835	0.958
	T*31 m	-0.049	0.030	0.952	0.897	1.010
	T*39 m	-0.050	0.036	0.951	0.887	0.021
Count[b]	Crum 1	2.571	0.180	13.081	9.193	18.615
	Crum 2	1.764	0.229	5.837	3.729	9.136
	Bakke 2	2.702	0.173	14.912	10.627	20.924
	31 m	-3.949	0.235	0.019	0.012	0.031
	39 m	-5.292	0.459	0.005	0.002	0.012
	T	0.232	0.028	1.261	1.194	1.331
	T*31 m	-0.133	0.041	0.875	0.807	0.949
	T*39 m	-0.132	0.090	0.877	0.735	1.045
	Log (theta)[c]	0.304				
Low						
Probability[a]	Crum 1	0.197	0.150	0.549	0.476	0.620
	Crum 2	-2.120	0.209	0.107	0.074	0.153
	Bakke 2	0.203	0.151	0.550	0.477	0.622
	10 m	0.436	0.164	1.546	1.120	2.134
	31 m	0.268	0.168	1.308	0.941	1.818
	T	0.212	0.024	1.236	1.179	1.296
	Pct G5	-0.092	0.021	0.912	0.875	0.950
	T*10 m	-0.048	0.029	0.953	0.900	1.008
	T*31 m	0.008	0.030	1.008	0.950	1.070
Count[b]	Crum 1	-0.633	0.533	0.531	0.187	1.508
	Crum 2	-2.176	0.627	0.113	0.033	0.388
	Bakke 2	0.157	0.510	1.170	0.431	3.179
	10 m	0.097	0.212	1.102	0.728	1.668
	31 m	0.058	0.219	1.059	0.690	1.626
	T	0.139	0.037	1.149	1.068	1.236
	T*10 m	-0.024	0.044	0.977	0.896	1.065
	T*31 m	0.009	0.044	1.009	0.926	1.100
	Log (theta)[c]	0.145				

Table 9. Continued.

Phonic group/Model	Coefficient	Estimate	SE	Effect	Lower 95% CL	Upper 95% CL
Hoary						
Probability[a]	Crum 1	-0.944	0.187	0.280	0.213	0.359
	Crum 2	-2.851	0.308	0.055	0.031	0.096
	Bakke 2	-1.758	0.223	0.147	0.100	0.211
	31 m	-0.281	0.219	0.755	0.491	1.160
	T	0.165	0.031	1.179	1.109	1.254
	WS	-0.147	0.054	0.863	0.776	0.960
	T*31 m	0.024	0.038	1.024	0.950	1.104
Count[b]	Crum 1	-0.754	0.276	0.471	0.274	0.809
	Crum 2	-2.729	0.607	0.065	0.020	0.214
	Bakke 2	-0.680	0.306	0.506	0.278	0.923
	31 m	0.826	0.308	2.284	1.250	4.173
	T	0.213	0.053	1.238	1.117	1.372
	PctG5	0.114	0.041	1.121	1.035	1.215
	T*31 m	-0.096	0.054	0.908	0.816	1.0011
	Log (theta)[d]	N/A				

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[a] Zero Hurdle Model: Binomial with Logit Link.

[b] Count Model: Truncated Negative Binomial with Log Link.

[c] Theta estimates the extra variation of the count distribution.

[d] Theta does not apply as the count date were modeled as a Poisson distributed random variable.

The expected number of passes, on nights with mean temperature, at Crum 1 was 0.5 passes/night (Table 9). We detected higher counts at Bakke 2 (1.2 passes/night), but lower counts at Crum 2 (0.1 passes/night). For every 1° C increase in temperature, the expected number of passes increased 7–24%. We found little evidence of change in activity with altitude, or with temperature increases at higher altitudes.

Hoary bats

The best approximating model for hoary bat activity, with a 24.8% probability, was based on the full design model and incorporated average wind speed and PctG5 in the binomial and count parts of the model, respectively (Appendix 2). This model was 2 times more likely than the next best approximating model which contained the same variable, but included PctG6.5 in the binomial part of the model. The confidence set of models included the top 2 models with a sum of Akaike weights of 0.371. The location model was 5 AIC units better than the null model, accounting for approximately 2.2% of variation in activity at the site, while the full design model was 84 AIC units better than the null model, accounting for approximately 17% of variation in activity. The best fitting model was roughly 12 AIC units better than the full design model, accounting for an additional 2.5% of the variation in activity beyond the full design model.

On a night with mean wind speed and temperature, the probability of activity at Crum 1, 39 m detector was 28% (Table 9). The probability of activity was lower at both Crum 2 (0.6%) and Bakke 2 (15%). For every 1° C increase in temperature, the probability of activity increased 11–25%. The probability of bat activity was positively related to decreasing wind speed, with odds of activity increasing by 4–29% for every 1 m/s decrease in wind speed. We found little evidence of change in the probability of activity with altitude or temperature increases at higher altitudes.

The expected number of passes, on nights with the proportion of the night with wind speed >5 m/s = 50% and mean temperature, at Crum 1 was 0.47 passes/night (Table 9). We detected similar counts at Bakke 2 (0.51 passes/night), but lower counts at Crum 2 (0.07 passes/night). The expected number of passes increased with decreasing altitude and was 1.3–4.2 times greater at 31 m. For every 1° C increase in temperature, the expected number of passes increased 12–37%. Activity was positively related to PctG5, with 3–22% more passes for every 10% decrease in the proportion of night with wind speed >5 m/s. We found little evidence of change in activity with altitude, or with temperature increases at higher altitudes.

DISCUSSION

We found bat activity generally was highest from mid-July to mid-August with little activity past late September, which is consistent with other pre-construction monitoring studies. In north-central Massachusetts, Brooks (2009) recorded the highest levels of bat activity in July, with activity declining by mid-August. Arnett et al. (2006) reported the highest bat activity from mid-August through mid-September in Pennsylvania. Redell et al. (2006) observed highest levels of bat activity in southeastern Wisconsin during August with secondary peaks in late July and September. Temporal patterns of activity observed at the HWEP also are similar to those reported from post-construction acoustic studies. In Iowa, Jain et al. (2011) found that bat activity peaked in July and August, declined in September, and had mostly ceased by October. 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) also reported similar patterns in Minnesota and Wyoming, respectively. Association between timing of bat activity and overall incidence of bat fatality previously reported (Arnett et al. 2008) suggests that temporal patterns of activity may prove useful for predicting the timing of fatality events in the future. Fall migration by bats is, however, a sporadic event both spatially (Baerwald and Barclay 2009) and temporally (see Cryan 2003). Among-night variation in activity, as well as turbine-related fatality, during late summer and fall may be attributed to changes in insect abundance and availability, weather, timing of migration, migratory routes (Baerwald and Barclay 2009), life history traits of certain bat species (e.g., preparations for hibernation or migration, and reproductive condition; Horn et al. 2008), or mating behaviors (Cryan 2008). Furthermore, if bats migrate along specific routes, it likely is reasonable to expect increases in activity and fatality during certain times of the year at sites located along these routes.

The level of activity in relation to fatality and whether pre-construction activity assessments can predict post-construction fatality also are important when trying to predict post-construction fatality and, thus, risk of future wind facility locations. While the link between pre-construction bat activity and post-construction fatality has yet to be made, studies of post-construction activity and fatality offer some promise that acoustic surveys may relate to fatality (Kunz et al. 2007b). Baerwald and Barclay (2009) found a relationship between bat activity and fatality at tall turbines (towers >65 m) at 5 sites in southern Alberta, and concluded that activity assessments may allow wind facilities to be located so as to minimize bat fatalities. Ultimately, linking pre-construction acoustic data and fatality data from multiple facilities will be required to determine if pre-construction assessment can predict risk for bats (Arnett et al. 2006, Kunz et al. 2007b).

Our results are consistent with other studies showing variations in bat activity at different altitudes (Jung et al. 1999, Kalcounis et al. 1999, Hayes and Gruver 2000, Menzel et al. 2005, Lacki et al. 2007, Collins and Jones 2009). Similar studies at other proposed wind facilities also have reported greater activity by high frequency bats at lower altitudes, and greater activity by low frequency bats at higher altitudes (Arnett et al. 2006, 2007, Redell et al. 2006, Reynolds 2006, Baerwald and Barclay 2009). The airspace in which certain species of bats occur generally can be predicted by their echomorphology (body size, wing shape, call frequency; Aldridge and Rautenbach 1987). Larger, less maneuverable bats with lower call frequencies typically fly higher and in more open habitats, whereas smaller, more maneuverable bats with higher call frequencies fly lower to the ground and in more cluttered (higher vegetation, increased tree density) habitats. Although, it remains unclear as to whether vertical acoustic sampling increases predictability of fatality events, numerous studies have documented the importance of sampling at higher altitudes to adequately describe bat activity in the area. Menzel et al. (2005) concluded that ground-based acoustic surveys in forest situations may provide an inaccurate impression of open-adapted species (e.g., hoary bats) activity. In addition, Reynolds (2006) noted large, migratory events of different species of bats occur at different altitudes and may be missed without sampling into the rotor-swept area. Because bat fatalities found at wind sites are predominately comprised of low frequency species (e.g., hoary bats; Johnson 2005, Kunz et al. 2007a, Arnett et al. 2008), and because low frequency bats generally fly at higher altitudes (i.e., in and around the rotor-swept area), it is important to account for altitudinal variation during acoustic surveys (Baerwald and Barclay 2009, Collins and Jones 2009). Our findings support this position and we suggest that pre-construction acoustic surveys must include detectors placed as high as possible above ground level to at least sample the airspace within the lower portions of the rotor-swept area.

Location and temperature were consistently the most important factors in these models, with the full design model explaining 17–60% of the variation in activity. In general, we found the highest probability of activity and highest counts for each phonic group at Bakke 2, followed by Crum 1, Crum 2, and Bakke 1. This trend was consistent between years. However, location alone explained 2–8% of the variation in activity. Although it is not surprising to see spatial variations in bat activity across a project site (Arnett et al. 2006, Reynolds et al. 2006, Mabee and Schwab 2008, Hein et al. 2009), specific reasons for variability among towers remains unknown, but may be attributed to variation in weather conditions at each tower (e.g., higher temperature or lower wind speed) or possibly differences in landscape features (e.g., proximity to water or forest edge) among towers.

Erickson and West (2002) reported that regional patterns of climatic conditions as well as local weather events can be used to predict bat activity. We found bat activity was positively related to temperature. Arnett et al. (2006) and Redell et al. (2006) reported a similar relationship in Pennsylvania and Wisconsin, respectively. Reynolds (2006) found little activity of bats at a proposed wind facility in New York when temperatures were below 10.5° C. In Massachusetts, Brooks (2009) reported increases in bat activity with increasing temperature up to ~21° C. The relationship between bat activity and temperature may be explained by availability of insect prey. Insect flight occurrence decreases with temperature and little or no flight activity may occur below 10° C (Taylor 1963, Anthony et al. 1981). Insect migrations are known to be positively related to temperature (e.g., Sparks et al. 2005). Although our parameter estimates indicated little evidence of an interaction between temperature and height, we did observe trends in bat activity in relation to temperatures at different heights. High frequency bats that were more active at low altitudes were more responsive to temperature than low frequency bats, whereas low frequency bats were more responsive to temperature changes at higher altitudes. This may be related to differences in body size and thermal energetic relationships. Body temperature and body size have profound impacts on how animals function, and even small changes in body temperature can have significant effects on mammals (Speakman and Thomas 2003). Larger animals are better equipped physiologically to deal with lower ambient temperatures than are smaller ones because they have a relatively lower surface area to volume ratio through which heat is lost (Speakman and Thomas 2003), thus it is plausible that smaller-bodied, high frequency bats are more sensitive to lower ambient temperature and consequently more active during warmer nights relative to larger, low frequency bats. Another possibility is that low frequency bats are more likely to be migrating through the area (Cryan 2003, Cryan and Brown 2007) and these bats may be less responsive to temperature than local, foraging species of high frequency bats because they are occupying the site for different reasons.

While some measure of wind speed often was important, it never explained more than an additional 3.6% of the variation in activity. When parameter estimates included mean wind speed, the effect on probability of bat activity and estimated number of bat passes was always negative. The HWEP site has higher mean nightly wind speeds than other sites where comparable data have been gathered, which may explain why the relationship between activity and wind was not as strong as previously documented (Arnett et al. 2006, Redell et al. 2006, Reynolds 2006). Strong winds 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 (Anthony et al. 1981, Erkert 1982, Erickson and West 2002, Lacki et al. 2007). Wind speed and direction affected habitat use by hoary bats and silver-haired bats in Canada, with higher activity detected on the lee side of a ridge (Barclay 1985). In the Netherlands, Verboom and Spoelstra (1999) reported that foraging and commuting activity of pipistrelle bats was concentrated closer to the leeward sides of trees as wind speed increased. Patterns of bat activity and wind speed also generally corroborate recent studies of bat fatality and the relationships with wind. At Buffalo Mountain in Tennessee, Fiedler (2004) found a negative relationship between bat fatality and wind speed. Kerns et al. (2005) reported that the majority of bats killed at the Meyersdale, Pennsylvania and Mountaineer, West Virginia facilities occurred on low wind nights, and fatalities tended to increase just before and after the passage of storm fronts. Building on the relationship between bat activity and wind speed (i.e., higher bat activity at lower wind speeds), Baerwald et al. (2009) and Arnett et al. (2010) both demonstrated how raising turbine cut-in speeds to 5.5 m/s, and 5.0 m/s and 6.5 m/s, can reduce bat fatalities up to 60% and 93%, respectively.

SCOPE, LIMITATIONS, and NEXT STEPS

This study was conducted at a single proposed wind energy facility located on forested ridges in northwestern Massachusetts, and statistical inferences are limited to this site. Additional studies in the region will determine whether our findings reflect patterns of bat activity on similar forested ridges with comparable vegetation composition and topography in this region. Despite acoustic and meteorological equipment malfunctions, we were able to quantify the spatial (vertical and horizontal) and temporal (seasonal and yearly) activity patterns of bats. These data may provide useful information for predicting when, where, and which bats may be most at risk of collisions with wind turbines at the HWEP. Combining acoustic data from this site and other facilities in the region, and comparing activity to the corresponding fatality datasets will help determine if risk can be predicted with reasonable certainty. In addition, understanding the specific timings and locations of peak activity may assist with refining the use of curtailment (e.g., Arnett et al. 2010) as a mitigation option.

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

Our analyses are exploratory, in part because so little data exist upon which to develop *a priori*, confirmatory hypotheses and associated candidate models. We performed our analysis using weather data gathered only from met towers located on site; future modeling may incorporate additional weather data gathered from local weather stations to model broad-scale weather events and bat activity. The current analysis only estimates activity rates and differences in activity patterns of 3 species groups (high and low frequency bats and hoary bats), at 3 heights from 4 towers. High variation in levels of activity has consequences with respect to sampling design and level of effort required to obtain accurate estimates of activity; as fewer nights are sampled, there is an increased probability of obtaining mean estimates of activity that differ greatly from those calculated from large datasets (Hayes 1997). Low-intensity sampling could result in under- or over-estimates of activity and the most precise and accurate estimates will likely come from intensive sampling efforts (Hayes 1997, M. Huso, Oregon State University, unpublished data). Future analyses should evaluate the trade-offs among various sampling efforts regarding accuracy and precision of bat activity estimates, with the ultimate goal of optimizing sampling designs and data requirements for employing acoustic monitoring to predict bat fatality at wind facilities.

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

LITERATURE CITED

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

American Wind Energy Association (AWEA). 2010a. AWEA US wind industry annual market report year ending 2009. http://www.awea.org/la_pubs_reports.cfm. Accessed August 2010.

American Wind Energy Association (AWEA). 2010b. AWEA year end 2009 market report. http://www.awea.org/la_pubs_reports.cfm. Accessed August 2010.

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

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

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

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

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

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

Arnett E. B., M. M. P. Huso, M. R. Schirmacher, and J. P. Hayes. 2010. Altering turbine speed reduces bat mortality at wind-energy facilities. Frontiers in Ecology and the Environment. doi:10.1890/100103.

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

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

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

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

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

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

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

Brooks, R. T. 2009. Habitat-associated and temporal patterns of bat activity in a diverse forest landscape of southern New England, USA. Biodiversity Conservation 18:529–545.

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

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

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

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

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

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

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

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

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

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

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

Gerard, P. D, D. R. Smith, and G. Weerakkody. 1998. Limits of retrospective power analysis. Journal of Wildlife Management 62: 801–807.

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

Gruver, J. C. D. I. Solick, and M. K. Sonnenberg. 2009. Comparison of bat activity recorded using different acoustic sampling equipment: implications for study design at wind-energy facilities. Bat Research news 50:109.

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

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

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

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

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

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

Jain, A. A. 2005. Bird and bat behavior and mortality at a northern Iowa windfarm. Thesis. Iowa State University, Ames, Iowa, USA.

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

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

Johnson, G. D., M. K. Perlik, W. E. Erickson, and M. D. Strickland. 2004. Bat activity, composition, and collision mortality at a large wind plant in Minnesota. Wildlife Society Bulletin 32: 1278–1288.

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

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

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

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

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

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

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

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

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

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

Massachusetts Department of Fish and Game (MDFG). 2010. http://www.mass.gov/dfwele/dfw/wildlife/living/living_with_bats.htm. Accessed October 2010.

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

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

O'Shea, T. J., M. A. Bogan, and L. E. Ellison. 2003. Monitoring trends in bat populations of the United States and territories: status of the science and recommendations for the future. Wildlife Society Bulletin 31: 16–29.

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

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

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

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

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

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

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

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

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

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

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

Weller, T. J., and C. J. Zabel. 2002. Variation in bat detections due to detector orientation in a forest. Wildlife Society Bulletin 30: 922–930.

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

Zuur, A. F., E. N. Ieno, N. J. Walker, A. A. Saveliev, and G. M. Smith. 2009. Mixed effects models and extensions in ecology with R. Springer Science and Businees Media, LLC, NY, USA.

Appendix 1. List of 77 models used to predict probability of activity and expected number of passes by bats at the HWEP, Massachusetts, 2006–2007.

Model Name	Probability Model	Count Model
Null	1	1
Location	L	L
Count Design	1	L+H*T
Probability Design	L+H*T	1
Full Design	L+H*T	L+H*T
Wind 1	L+H*T+WS	L+H*T
Wind 2	L+H*T	L+H*T+WS
Wind 3	L+H*T+WS	L+H*T+WS
Wind 4	L+H*T+T*WS	L+H*T+T*WS
Wind 5	L+H*T+H*WS	L+H*T+H*WS
Wind 6	L+H*T+H*WS+T*WS	L+H*T+H*WS+T*WS
Wind 7	L+H*T+PctG3.5	L+H*T
Wind 8	L+H*T	L+H*T+PctG3.5
Wind 9	L+H*T+PctG3.5	L+H*T+WS
Wind 10	L+H*T+T*PctG3.5	L+H*T+T*WS
Wind 11	L+H*T+H*PctG3.5	L+H*T+H*WS
Wind 12	L+H*T+H*PctG3.5+T*PctG3.5	L+H*T+H*WS+T*WS
Wind 13	L+H*T+PctG3.5	L+H*T+PctG3.5
Wind 14	L+H*T+T*PctG3.5	L+H*T+T*PctG3.5
Wind 15	L+H*T+H*PctG3.5	L+H*T+H*PctG3.5
Wind 16	L+H*T+H*PctG3.5+T*PctG3.5	L+H*T+H*PctG3.5+T*PctG3.5
Wind 17	L+H*T+WS	L+H*T+PctG3.5
Wind 18	L+H*T+T*WS	L+H*T+T*PctG3.5
Wind 19	L+H*T+H*WS	L+H*T+H*PctG3.5
Wind 20	L+H*T+H*WS+T*WS	L+H*T+H*PctG3.5+T*PctG3.5
Wind 21	L+H*T+PctG5	L+H*T
Wind 22	L+H*T	L+H*T+PctG5
Wind 23	L+H*T+PctG5	L+H*T+WS
Wind 24	L+H*T+T*PctG5	L+H*T+T*WS
Wind 25	L+H*T+H*PctG5	L+H*T+H*WS
Wind 26	L+H*T+H*PctG5+T*PctG5	L+H*T+H*WS+T*WS
Wind 27	L+H*T+PctG5	L+H*T+PctG3.5
Wind 28	L+H*T+T*PctG5	L+H*T+T*PctG3.5
Wind 29	L+H*T+H*PctG5	L+H*T+H*PctG3.5
Wind 30	L+H*T+H*PctG5+T*PctG5	L+H*T+H*PctG3.5+T*PctG3.5
Wind 31	L+H*T+PctG5	L+H*T+PctG5
Wind 32	L+H*T+T*PctG5	L+H*T+T*PctG5
Wind 33	L+H*T+H*PctG5	L+H*T+H*PctG5
Wind 34	L+H*T+H*PctG5+T*PctG5	L+H*T+H*PctG5 + T*PctG5
Wind 35	L+H*T+WS	L+H*T+PctG5
Wind 36	L+H*T+T*WS	L+H*T+T*PctG5
Wind 37	L+H*T+H*WS	L+H*T+H*PctG5
Wind 38	L+H*T+H*WS+T*WS	L+H*T+H*PctG5+T*PctG5
Wind 39	L+H*T+PctG3.5	L+H*T+PctG5
Wind 40	L+H*T+T*PctG3.5	L+H*T+T*PctG5
Wind 41	L+H*T+H*PctG3.5	L+H*T+H*PctG5
Wind 42	L+H*T+H*PctG3.5+T*PctG3.5	L+H*T+H*PctG5+T*PctG5
Wind 43	L+H*T+PctG6.5	L+H*T
Wind 44	L+H*T	L+H*T+PctG6.5
Wind 45	L+H*T+PctG6.5	L+H*T+WS

Appendix 1. Continued.

Model Name	Probability Model	Count Model
Wind 46	L+H*T+T*PctG6.5	L+H*T+T*WS
Wind 47	L+H*T+H*PctG6.5	L+H*T+H*WS
Wind 48	L+H*T+H*PctG6.5+T*PctG6.5	L+H*T+H*WS + T*WS
Wind 49	L+H*T+PctG6.5	L+H*T+PctG3.5
Wind 50	L+H*T+T*PctG6.5	L+H*T+T*PctG3.5
Wind 51	L+H*T+H*PctG6.5	L+H*T+H*PctG3.5
Wind 52	L+H*T+H*PctG6.5+T*PctG6.5	L+H*T+H*PctG3.5+T*PctG3.5
Wind 53	L+H*T+PctG6.5	L+H*T+PctG5
Wind 54	L+H*T+T*PctG6.5	L+H*T+T*PctG5
Wind 55	L+H*T+H*PctG6.5	L+H*T+H*PctG5
Wind 56	L+H*T+H*PctG6.5+T*PctG6.5	L+H*T+H*PctG5 + T*PctG5
Wind 57	L+H*T+PctG6.5	L+H*T+PctG6.5
Wind 58	L+H*T+T*PctG6.5	L+H*T+T*PctG6.5
Wind 59	L+H*T+H*PctG6.5	L+H*T+H*PctG6.5
Wind 60	L+H*T+H*PctG6.5+T*PctG6.5	L+H*T+H*PctG6.5+T*PctG6.5
Wind 61	L+H*T+WS	L+H*T+PctG6.5
Wind 62	L+H*T+T*WS	L+H*T+T*PctG6.5
Wind 63	L+H*T+H*WS	L+H*T+H*PctG6.5
Wind 64	L+H*T+H*WS+T*WS	L+H*T+H*PctG6.5+T*PctG6.5
Wind 65	L+H*T+PctG3.5	L+H*T+PctG6.5
Wind 66	L+H*T+T*PctG3.5	L+H*T+T*PctG6.5
Wind 67	L+H*T+H*PctG3.5	L+H*T+H*PctG6.5
Wind 68	L+H*T+H*PctG3.5+T*PctG3.5	L+H*T+H*PctG6.5+T*PctG6.5
Wind 69	L+H*T+PctG5	L+H*T+PctG6.5
Wind 70	L+H*T+T*PctG5	L+H*T+T*PctG6.5
Wind 71	L+H*T+H*PctG5	L+H*T+H*PctG6.5
Wind 72	L+H*T+H*PctG5+T*PctG5	L+H*T+H*PctG6.5+T*PctG6.5

Appendix 2. Model selection for the confidence set of models by year and phonic group at the HWEP, Massachusetts, 2006–2007.

Year/Group	Probability Model	Count Model	AIC	ΔAIC	Wt	Rel. Wt	Cumm wt	pR^2	aR^2
2006/ High	L+H*T+PctG5	L+H*T	1692.277	0.000	0.100	1.000	0.100	0607	0.003
	L+H*T+PctG5	L+H*T+PctG6.5	1692.717	0.440	0.080	1.246	0.180	0.608	0.004
	L+H*T+PctG3.5	L+H*T	1692.753	0.476	0.079	1.269	0.259	0.607	0.003
	L+H*T+PctG5	L+H*T+PctG3.5	1693.086	0.809	0.067	1.499	0.326	0.608	0.004
	L+H*T+PctG3.5	L+H*T+PctG6.5	1693.192	0.916	0.063	1.581	0.389	0.608	0.004
	L+H*T+PctG3.5	L+H*T+PctG3.5	1693.562	1.285	0.053	1.901	0.441	0.607	0.004
	L+H*T+PctG6.5	L+H*T	1693.884	1.607	0.045	2.233	0.486	0.606	0.002
	L+H*T+PctG5	L+H*T+PctG5	1694.155	1.879	0.039	2.558	0.525	0.607	0.003
	L+H*T+PctG5	L+H*T	1694.277	2.000	0.037	2.718	0.562	0.607	0.003
	L+H*T+PctG6.5	L+H*T+PctG6.5	1694.324	2.047	0.036	2.782	0.598	0.607	0.003
	L+H*T+PctG3.5	L+H*T+PctG5	1694.631	2.354	0.031	3.245	0.629	0.607	0.003
	L+H*T+PctG6.5	L+H*T+PctG3.5	1694.693	2.416	0.030	3.347	0.658	0.607	0.003
	L+H*T+PctG3.5	L+H*T+WS	1694.752	2.476	0.029	3.448	0.687	0.607	0.003
	L+H*T+T*Pct6.5	L+H*T+T*PctG3.5	1695.003	2.726	0.026	3.908	0.713	0.609	0.005
	L+H*T	L+H*T+T*PctG3.5	1695.589	3.312	0.019	5.238	0.732	0.609	0.005
	L+H*T+T*Pct6.5	L+H*T+T*PctG6.5	1695.648	3.371	0.019	5.396	0.751	0.608	0.005
	L+H*T+PctG6.5	L+H*T+PctG5	1695.762	3.486	0.017	5.713	0.768	0.606	0.003
	L+H*T+T*Pct6.5	L+H*T+T*WS	1695.777	3.500	0.017	5.755	0.785	0.608	0.005
	L+H*T+PctG6.5	L+H*T+WS	1695.884	3.607	0.016	6.070	0.802	0.606	0.002
	L+H*T	L+H*T	1696.102	3.825	0.015	6.771	0.817	0.604	0.000
	L+H*T+T*Pct6.5	L+H*T+T*PctG6.5	1696.234	3.957	0.014	7.231	0.830	0.608	0.005
	L+H*T	1	1973.021	280.744	0.000	>1000	1.000	0.395	-0.208
	1	L+H*T	2042.294	350.017	0.000	>1000	1.000	0.334	-0.270
	L	L	2275.709	583.432	0.000	>1000	1.000	0.073	-0.530
	1	1	2319.213	626.936	0.000	>1000	1.000	0.000	-0.604
2006/Low	L+H*T+T*WS	L+H*T+T*WS	2095.670	0.000	0.478	1.000	0.478	0.377	0.038
	L+H*T+H*WS+T*WS	L+H*T+H*WS+T*WS	2097.142	1.472	0.229	2.088	0.707	0.383	0.044
	L+H*T+T*PctG5	L+H*T+T*WS	2098.853	3.183	0.097	4.911	0.804	0.374	0.036
	L+H*T	L+H*T	2130.535	34.865	0.000	>1000	1.000	0.338	0.000
	L+H*T	1	2157.958	62.288	0.000	>1000	1.000	0.297	-0.041
	L	L	2359.722	264.053	0.000	>1000	1.000	0.067	-0.271
	1	L+H*T	2371.165	275.495	0.000	>1000	1.000	0.058	-0.281
	1	1	2398.588	302.918	0.000	>1000	1.000	0.000	-0.388

Appendix 2. Continued.

Year/Group	Probability Model	Count Model	AIC	ΔAIC	Weight	Rel. Wt	Cumm. Wt	pR^2	aR^2
2006/Hoary	L+H*T+WS	L+H*T	912.012	0.000	0.201	1.000	0.201	0.315	0.017
	L+H*T+WS	L+H*T+WS	912.827	0.814	0.134	1.503	0.335	0.317	0.019
	L+H*T+WS	L+H*T+PctG6.5	913.166	1.154	0.113	1.780	0.447	0.317	0.019
	L+H*T+WS	L+H*T+PctG3.5	913.934	1.922	0.077	2.614	0.524	0.315	0.017
	L+H*T+WS	L+H*T+PctG5	914.012	2.000	0.074	2.718	0.598	0.315	0.017
	L+H*T+T*WS	L+H*T+T*WS	915.465	3.453	0.036	5.621	0.634	0.319	0.021
	L+H*T+T*WS	L+H*T+T*PctG6.5	915.560	3.548	0.034	5.894	0.668	0.319	0.021
	L+H*T+PctG5	L+H*T	915.678	3.666	0.032	6.252	0.700	0.309	0.011
	L+H*T+H*WS	L+H*T+H*WS	915.975	3.962	0.028	7.252	0.728	0.319	0.021
	L+H*T	L+H*T	920.372	8.359	0.003	65.346	0.731	0.298	0.000
	L+H*T	1	939.741	27.729	0.000	>1000	1.000	0.244	-0.054
	1	L+H*T	1029.264	117.252	0.000	>1000	1.000	0.069	-0.229
	L	L	1032.731	120.718	0.000	>1000	1.000	0.062	-0.237
	1	1	1048.634	136.621	0.000	>1000	1.000	0.000	-0.298
2007/High	L+H*T+WS	L+H*T	3674.254	0.000	0.144	1.000	0.144	0.518	0.004
	L+H*T+H*WS	L+H*T+H*WS	3674.459	0.205	0.130	1.108	0.274	0.523	0.009
	L+H*T+WS	L+H*T+PctG3.5	3675.316	1.062	0.085	1.701	0.359	0.519	0.005
	L+H*T+WS	L+H*T+PctG5	3675.750	1.496	0.068	2.113	0.427	0.519	0.005
	L+H*T+T*WS	L+H*T+WS	3676.015	1.761	0.060	2.412	0.487	0.520	0.006
	L+H*T+H*WS+T*WS	L+H*T+H*WS+T*WS	3676.077	1.823	0.058	2.488	0.545	0.524	0.010
	L+H*T+WS	L+H*T+PctG6.5	3676.207	1.953	0.054	2.655	0.600	0.519	0.004
	L+H*T+WS	L+H*T+WS	3676.242	1.988	0.053	2.702	0.653	0.519	0.004
	L+H*T+T*WS	L+H*T+T*PctG6.5	3676.344	2.090	0.051	2.844	0.704	0.520	0.006
	L+H*T+H*WS	L+H*T+H*PctG6.5	3676.487	2.233	0.047	3.054	0.751	0.522	0.008
	L+H*T+T*WS	L+H*T+T*PctG3.5	3676.674	2.420	0.043	3.353	0.794	0.520	0.006
	L+H*T+T*WS	L+H*T+T*PctG5	3676.712	2.458	0.042	3.417	0.836	0.520	0.006
	L+H*T+H*WS+T*WS	L+H*T+H*PctG6.5+T*PctG6.5	3677.856	3.602	0.024	6.055	0.860	0.523	0.009
	L+H*T	L+H*T	3672.753	8.499	0.002	70.078	0.862	0.514	0.000
	L+H*T	1	4045.257	371.002	0.000	>1000	1.000	0.326	-0.188
	1	L+H*T	4129.009	454.755	0.000	>1000	1.000	0.276	-0.238
	L	L	4467.172	792.917	0.000	>1000	1.000	0.027	-0.487
	1	1	4491.512	817.258	0.000	>1000	1.000	0.000	-0.514

Appendix 2. Continued.

Year/Group	Probability Model	Count Model	AIC	ΔAIC	Weight	Rel. Wt	Cumm. Wt	pR^2	aR^2
2007/Low	L+H*T+PctG5	L+H*T	3336.189	0.000	0.161	1.000	0.161	0.276	0.013
	L+H*T+PctG5	L+H*T+PctG5	3336.723	0.534	0.124	1.306	0.285	0.277	0.014
	L+H*T+PctG5	L+H*T+PctG3.5	3337.667	1.477	0.077	2.093	0.362	0.276	0.013
	L+H*T+H*PctG5	L+H*T+H*PctG6.5	3337.854	1.665	0.070	2.299	0.432	0.281	0.018
	L+H*T+PctG5	L+H*T+PctG5	3337.945	1.756	0.067	2.406	0.499	0.276	0.013
	L+H*T+PctG5	L+H*T+WS	3338.172	1.982	0.060	2.694	0.559	0.276	0.013
	L+H*T+WS	L+H*T	3338.504	2.315	0.051	3.182	0.610	0.274	0.011
	L+H*T+WS	L+H*T+PctG5	3339.038	2.849	0.039	4.155	0.649	0.275	0.012
	L+H*T+T*PctG5	L+H*T+T*PctG5	3339.304	3.114	0.034	4.745	0.683	0.278	0.014
	L+H*T+H*PctG5	L+H*T+H*WS	3339.877	3.688	0.026	6.321	0.708	0.280	0.017
	L+H*T+WS	L+H*T+PctG3.5	3339.981	3.792	0.024	6.659	0.733	0.275	0.011
	L+H*T+H*PctG5	L+H*T+H*PctG5	3339.992	3.803	0.024	6.696	0.757	0.280	0.017
	L+H*T	L+H*T	3353.536	17.346	0.000	>1000	1.000	0.263	0.000
	L+H*T	1	3398.484	62.294	0.000	>1000	1.000	0.224	-0.040
	1	L+H*T	3589.477	253.288	0.000	>1000	1.000	0.076	-0.187
	L	L	3627.039	290.850	0.000	>1000	1.000	0.050	-0.213
	1	1	3671.987	335.798	0.000	>1000	1.000	0.000	-0.263
2007/Hoary	L+H*T+WS	L+H*T+PctG5	913.956	0.000	0.248	1.000	0.248	0.196	0025
	L+H*T+PctG6.5	L+H*T+PctG5	915.359	1.404	0.123	2.018	0.370	0.194	0.023
	L+H*T+H*WS	L+H*T+H*PctG5	916.176	2.220	0.082	3.034	0.452	0.199	0.028
	L+H*T+PctG5	L+H*T+PctG5	916.878	2.922	0.057	4.310	0.510	0.191	0.020
	L+H*T+H*PctG5	L+H*T+H*PctG5	917.038	3.082	0.053	4.669	0.563	0.197	0.026
	L+H*T+T*WS	L+H*T+T*PctG5	917.458	3.502	0.043	5.761	0.606	0.197	0.026
	L+H*T+H*PctG6.5	L+H*T+H*PctG5	917.932	3.976	0.034	7.301	0.640	0.196	0.025
	L+H*T	L+H*T	923.225	12.269	0.001	461.533	1.000	0.171	0.000
	L+H*T	1	941.377	27.421	0.000	>1000	1.000	0.132	-0.039
	1	L+H*T	944.792	80.836	0.000	>1000	1.000	0.044	-0.127
	L	L	1005.158	91.202	0.000	>1000	1.000	0.022	-0.149
	1	1	1009.944	95.988	0.000	>1000	1.000	0.000	-0.171