Behavioral Responses of Bats to Operating Wind Turbines

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ABSTRACT Wind power is one of the fastest growing sectors of the energy industry. Recent studies have reported large numbers of migratory tree-roosting bats being killed at utility-scale wind power facilities, especially in the eastern United States. We used thermal infrared (TIR) cameras to assess the flight behavior of bats at wind turbines because this technology makes it possible to observe the nocturnal behavior of bats and birds independently of supplemental light sources. We conducted this study at the Mountaineer Wind Energy Center in Tucker County, West Virginia, USA, where hundreds of migratory tree bats have been found injured or dead beneath wind turbines. We recorded nightly 9-hour sessions of TIR video of operating turbines from which we assessed altitude, direction, and types of flight maneuvers of bats, birds, and insects. We observed bats actively foraging near operating turbines, rather than simply passing through turbine sites. Our results indicate that bats 1) approached both rotating and nonrotating blades, 2) followed or were trapped in blade-tip vortices, 3) investigated the various parts of the turbine with repeated fly-bys, and 4) were struck directly by rotating blades. Blade rotational speed was a significant negative predictor of collisions with turbine blades, suggesting that bats may be at higher risk of fatality on nights with low wind speeds. (JOURNAL OF WILDLIFE MANAGEMENT 72(1):123–132; 2008)

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Recent studies indicate that migratory tree-roosting bats are being killed in unprecedented numbers at wind power facilities in forested regions of eastern North America (Fielder 2004, Kerns and Kerlinger 2004, Arnett et al. 2005, Johnson 2005). Current understanding of how and why bats come into contact with turbines is lacking because of our limited ability to observe how they behave at night around these structures as they pass through on migratory flights or forage for insects. Answering basic questions about where, when, how, and why wind turbines kill bats requires careful observations of the timing and types of flight maneuvers near both operating and nonoperating wind turbines (Kunz et al. 2007*b*). Bats may be killed directly by moving blades or by simply colliding with stationary turbine structures such as the monopole (the structure on which the turbine generator and blades are mounted). It seems unlikely that aerial-feeding insectivorous bats, which are capable of making remarkable aerobatic maneuvers to capture small insects, should be so frequently killed by moving turbines blades. One possible explanation is that bats increase their risk of fatality by approaching and investigating operating turbines. To study this problem, it is important to observe and identify bats that fly near wind turbines under a variety of weather conditions.

To date, only a handful of studies have attempted to evaluate the impact of wind turbines on resident and migrating bats (Kerns and Kerlinger 2004, Brinkmann et al. 2006, Arnett et al. 2007). These studies have focused on quantifying the impact of wind turbines on bats by enumerating injured and dead animals beneath and adjacent to operating turbines. Although these studies have established that bat fatalities do indeed occur at these facilities, they do not directly address causal factors, integrate the behavior and ecology of the species affected, or experimentally test hypotheses that might explain the observed fatalities. Prior to this study, there had been no direct observations of bats being struck by moving turbine blades. This underscores a conspicuous gap in our understanding of how and why bats are killed at wind energy facilities, the circumstances that might predict fatal interactions, and what approaches might be used to reduce fatalities.

We suggest there are 3 hypotheses that may account for the discovery of injured, dead, or moribund bats on the ground beneath and near turbines. First, flying bats may randomly come into contact with rotating blades. Bats at risk of being killed by wind turbines represent a mix of local forest-dwelling species and migrants traveling through the area. All of the small insectivorous species discovered dead beneath turbines in a companion study (Kerns et al. 2005) use frequency modulated (FM) echolocation calls. Because these high frequencies attenuate quickly in air (Griffin 1971), bats may not have time to move out of the path of a fast-approaching blade by the time they are able to detect its presence. Secondly, bats may be attracted to wind turbine structures, leading to an increased potential for contact. Audible sound and ultrasound produced by rotating blades, generator operation, or other moving components of turbines may elicit interest, or otherwise alter the behavior of flying bats, although there is yet no support for this hypothesis (J. Szewczak, Humboldt State University, unpublished data). Similarly, bats may view turbine monopoles (the structure on which the turbine generator and blades are mounted) standing in open space as roost trees, and investigate them for potential roosting spaces. Thirdly, several factors may be causing an increased density of bats in the general area of wind energy facilities.

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Although the relative abundances of the bat species observed in the study area are unknown, the species are probably less abundant than the numbers of observed fatalities would suggest (Arnett et al. 2007). Forest edges created by the construction of access roads may create favorable foraging grounds where bats can more easily capture aerial insect prey, creating hotspots of bat activity (Barclay 1985, Kunz et al. 2007*b*). Use of these habitats is likely driven by prey density and availability. Thus, bat activity, and the likelihood of bats being struck by rotating turbine blades, may be predicted by seasonal weather patterns and the temporal phenology of insects. Migratory behavior of bats may also explain increases in bat fatalities at certain times of year. Migratory flights of some species may be punctuated with short stopovers when individuals or groups pause to feed, drink, and roost in trees (Griffin 1970, Fleming and Eby 2003, Cryan and Diehl 2008). As with local populations, migrant bats making stopovers may be similarly attracted to areas with high insect populations. It is important to note that these hypotheses are not mutually exclusive and supporting or validating each of them requires unambiguous observations and quantification of foraging and flight behavior near turbines.

There are several established methods for monitoring flight activity of bats during dark hours, including mist-netting, night-vision observations (Boogher and Slusher 1978; Kunz et al. 1996*a*, *b*), videography, visual chemiluminescent tracking, radiotelemetry, and reflective infrared imaging (Kunz 2004, Kunz et al. 2007*a*, National Research Council 2007, Kunz and Parsons 2008). Each of these techniques, although effective for certain applications, has limitations for monitoring nocturnal activity of bats, especially near large utility-scale wind turbines. Imaging techniques that require illumination sources such as night-vision, ceilometry, and reflective infrared cameras are largely inadequate because it is difficult, if not impossible, to evenly illuminate the entire turbine tower and blade-swept area. Moreover, the ability to detect bats with these methods decreases markedly with distance. In addition, images from photo-multiplier (night-vision) devices contain inherent noise, making discrimination of small objects at a distance difficult.

We employed thermal infrared (TIR) cameras for monitoring the activity of bats (Sabol and Hudson 1995, Frank et al. 2003, Simmons 2005, Betke et al. 2008). Thermal infrared cameras detect heat emitted from and reflected off of objects in the field of view. No illumination is required and, thus, images can be captured in complete darkness. The distance at which objects can be imaged is limited only by the optics chosen and the size of the imaging sensor, significantly extending the range at which one can observe wildlife (Hill and Clayton 1985). Wherever there is sufficient contrast in temperatures, objects such as birds, bats, and insects can be resolved against a cooler sky (Fortin et al. 1999, Ahlen 2003, Desholm 2003, Desholm et al. 2004, Gauthreaux and Livingston 2006). Temperature differences can also be detected at relatively long distances. Moreover, because infrared light is less scattered than visual wavelengths by water vapor and fine particles in air, it is sometimes possible to see through fog, a common occurrence in some montane regions such as our study site.

Because there was no evidence from the literature that bats in flight were being struck by rotating turbine blades, our primary objective was to document how bats behaved while flying within the rotor-swept zone where there was potential for direct contact. We conducted multiple full-night (dusk to dawn) observations from which we enumerated and classified bats, birds, and insects aloft, scored behavior types, and collected environmental variables that could be predictors of collisions. A secondary objective was to examine temporal patterns of activity and to determine if environmental variables such as wind speed and temperature are associated with variation in activity levels. We originally designed the study to test the effect of slowing or stopping blade rotation on bat behavior around turbines and on the number of fatalities. Unfortunately, we were unable to execute this experiment because the operators of the facility would not permit us to experimentally stop rotation by feathering the blades at predetermined times. Finally, we compared activity levels between lighted and unlighted turbines at the facility to test if aviation obstruction lighting mounted on turbines attracts bats (either directly, or indirectly through increased insect abundance).

STUDY AREA

We conducted the study from 2 August to 27 August 2004 at the Mountaineer Wind Energy Center, located in the Mid-Atlantic Highlands near Thomas, West Virginia, USA. The facility was located on a mountain ridge in Appalachian mixed mesophytic forest and consisted of 42 NEG-Micon 72c (now Vestas, Randers, Denmark) wind turbines arranged along the ridge on a cleared access road. Each turbine was 106 m tall and had a 72-m-diameter, 4,071-m^2 area that was swept by the rotating turbine blades. Turbines operated in the range of wind speeds from 3 m per second to 18 m per second, and the rotor blades spun at up to 17 revolutions per minute (RPM). Twelve of the 42 turbines were lit with both steady and strobing aviation obstruction lights.

METHODS

To observe interactions of bats with wind turbines, and to document nightly flight activity of bats near operating wind turbines, we employed 3 FLIR Systems S60® (Billerica, MA) uncooled microbolometer TIR cameras. Each camera has a 320 × 240-pixel sensor that measures infrared wavelengths in the range of 7.5–13 μm. We matched each camera with a 24° field-of-view lens that we calibrated to the camera sensor array. We mounted all 3 cameras on tripods and we placed them 0.5 m apart to form a single observation point (Fig. 1). We used FLIR ThermaCAM Researcher® (Billerica, MA) software on laptop computers to capture real-time streams of radiometric data from each of the 3 cameras directly to external 250-GB hard drives.

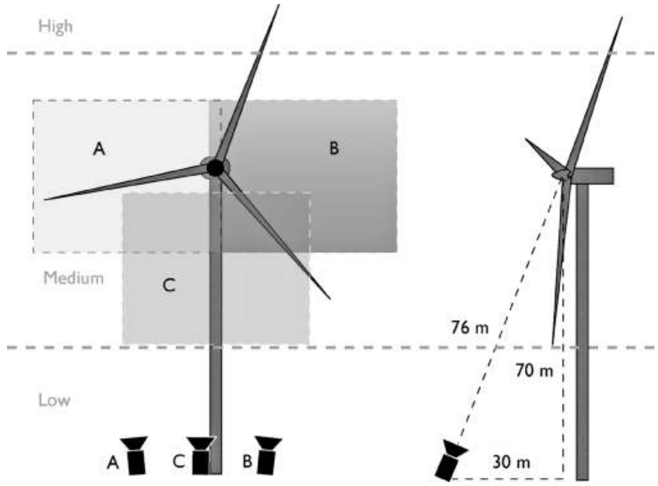

Figure 1. Field configuration for conducting nightly observations of birds, bats and insects with thermal infrared cameras at the Mountaineer Wind Energy Center in West Virginia, USA, August 2004. The facility contains 42 turbines that are positioned along a cleared access road on a forested mountain ridge. Cameras were positioned together 30 m from the turbine base and pointed directly upwind and perpendicular to the plane of blade rotation. Observed bats, birds and insects were classified into high, low, and medium height categories corresponding to flight elevation relative to the height of the area swept by the turbine blades.

Our system captured data at a rate of 30 frames per second and stamped each frame of data with the time accurate to 0.001 seconds.

To facilitate observations of nightly flight behavior of bats, we placed the observation station near the base of wind turbines at dusk. Terrain permitting, we positioned them as close to 30 m as possible from the base of each turbine tower (Fig. 1). In general, we positioned camera stations directly upwind and perpendicular to the plane of rotation, based on typical turbine orientation. In most cases, the station was at an equal elevation as the base of the tower, so that the straight-line distance from the camera to the hub was 76 m. We positioned and focused each camera on a different part of the rotor-swept area: camera A on the left, upswing portion of the rotor-swept area, camera B on the right, downswing side, and camera C on the lower portion of the rotor-swept area.

We recorded 3 9-hour video sequences (one for each camera angle) nightly for 10 nights. We recorded images continuously beginning at 2030 hours and continuing until 0530 hours the following morning. We started the 3 cameras simultaneously $\leq$1 second from each other and, thus, synchronized our recordings. To test the potential of aviation lighting on the turbines to attract bats, we placed the cameras alternatively at randomly selected lighted and unlighted turbines for 5 nights each.

We analyzed our data by manually observing playback of all video sequences in real time or 2× real time, recording the appearance and timing of flying objects. We recorded each object observed with a time stamp and categorized it according to a set of qualitative criteria as a bat, insect, bird, aircraft, or unknown (unidentifiable) object. Criteria included object size, object morphology, estimations of inertia and velocity, evaluation of flight maneuvers and behaviors, wing-beat frequency, and interaction with the rotating turbine blades. In an effort to reduce false positives and observer biases, we were highly conservative when classifying objects, categorizing many as unknown. We made every effort to make accurate identifications, and to reduce false positives, including counting multiple passes that belonged to a single individual as a single appearance. We also assigned a behavior type to each object observation. Objects flying through the field of view without incident we labeled as fly. Those making sharp or sudden course corrections synchronous with a nearby moving turbine blade we labeled avoid. To distinguish these behaviors from normal foraging and pursuit maneuvers, we were careful to label behaviors as avoid only when they occurred at the same time that a turbine blade was moving through nearby airspace. Any obvious collisions or contact with any part of the turbine structure we labeled contact. Each observation record also included an estimation of flight elevation, based on the rotor-swept zone of the turbine structure. We classified elevation as low, medium, or high. Low corresponded to flying objects below the rotor-swept zone, medium to those in the range of heights of the swept zone, and high to those above the swept zone. We also noted the entry and exit points from the field of view as an estimate of flight heading of an object.

We compiled observation records into a database along with 10-minute observations of wind speed, wind heading, temperature, and blade rotation speed that were generated from the instrumentation on each turbine nacelle (the structure at the top of the monopole to which the rotor hub and blades are attached that contains the electrical generator, gearbox, and electronic controls). We also compiled data on wind speed, wind heading, and barometric pressure from 2 installed meteorological towers (met towers) that were located at 2 midpoints along the string of turbines. We analyzed and processed data from this database, and we performed all statistical tests using the statistical software R (The R Foundation for Statistical Computing, http://www.r-project.org/). The Boston University Animal Care and Use Committee approved protocols used in this study.

RESULTS

We recorded 30 continuous nightly video sequences, of which we analyzed 19, representing 171 hours of video and observation time. We divided the observations into 2 categories: a subset of nights for which we analyzed data from all 3 cameras (A, B and C; $n = 4$), and nights for which we analyzed data from camera A only ($n = 10$; left upswing portion of the rotor-sweep area; Fig. 1). For all cameras combined, we observed 4,568 moving objects: 1,810 bats (39%), 872 insects (19%), 46 birds (1.0%), 5 aircraft (0.1%), and 1,835 unknown (40%). For the A-camera dataset, we recorded a total of 2,404 observations: 998 bats (41%), 503 insects (20%), 39 birds (1%), 2 aircraft (0.1%), and 862 unknown (35%; Table 1). We observed bats at a mean rate of 99 per turbine per night, and 11 per turbine per

Table 1. Observations from camera A (left half of the rotor-swept area) that were recorded at the Mountaineer Wind Energy Center in West Virginia, USA, in 2004. "Avoid" indicates cases when a bat either changed flight path to avoid colliding with a moving blade, and "contact" indicates a blade striking a bat.

		Observations of bats, birds, and insects at wind turbines						
Date	Turbine no.	Total	Bats	Birds	Insects	Unknown	Bat avoid	Bat contact
8 Aug	18	72	17	2	37	16	2	0
10 Aug	27	27	9	0	12	6	0	0
11 Aug	25	251	124	5	47	75	6	0
13 Aug	26	52	42	0	5	5	5	0
14 Aug	37	362	129	2	63	168	3	0
16 Aug	41	788	292	1	133	362	13	1
17 Aug	31	236	74	1	117	42	0	0
21 Aug	10	82	51	11	7	13	0	0
22 Aug	20	355	221	17	60	57	12	2
24 Aug	16	179	39	0	22	118	0	2
Total		2404	998	39	503	862	41	5
Total/turbine/night		240.4	99.8	3.9	50.3	86.2	4.1	0.5
Total/turbine/hr		26.7	11.1	0.4	5.6	9.6	0.5	0.1
Extrapolated total/facility/night		10,097	4,192	164	2,113	3,620	172	21

hour. We compared the number of bats observed with each of the cameras, left (A), right (B), and lower (C), during 3 nights of observations (Table 2). In general, we observed more bats from camera C ($n = 545$) than from A or B ($n = 389$, $n = 244$ respectively). This may be due to the slightly lower elevation angle of camera C, allowing it to capture objects that were closer to the lens and, therefore, more easily identified as bats. However, total numbers of bats observed were variable from camera A to camera B and we found no significant difference between mean numbers of bats observed from any single camera ($n = 3$; A vs. B, $t = 0.86$, $P = 0.46$; A vs. C, $t = -0.61$, $P = 0.57$; B vs. C, $t = -1.46$, $P = 0.26$). We, therefore, treated observations from camera A as proportionately representative of bat activity during any given recording session, and decided to focus the analysis on a single camera and a larger sampling of nights and turbine locations.

Bats were usually distinguishable from other near-field objects (birds and insects) based on the orientation of the body and wings, which aided in their identification. We observed pursuit and terminal-phase capture maneuvers (Griffin 1960), with individuals turning and persisting in the field of view for durations of 5–120 seconds. We classified 40% of all observations as unknown, reflecting both our effort to avoid inaccurate identifications, and the difficulty of discriminating bats from birds and insects in foggy or cloudy conditions.

Table 2. Objects observed with each of 3 thermal infrared cameras aimed at different parts of a wind turbine rotor-swept zone at the Mountaineer Wind Energy Center in West Virginia, USA, in 2004.

	No. of observations from each camera			
Object	Camera A	Camera B	Camera C	Total
Bats	389	244	545	1,178
Insects	145	112	251	508
Birds	19	1	6	26
Aircraft	0	2	1	3
Unknown	343	345	608	1296
Total	896	704	1,411	3,011

Among flying bats, altitude above ground level (AGL) was highly variable, with some individuals flying within 10 m AGL, and others forging at or above the height of the turbine nacelle (70 m AGL). We observed few birds, mostly individuals, but also occasional flock formations. Insects were abundant within the low-altitude band (below the rotor-swept zone), and they often appeared as cooler and less well-defined objects because they were outside of the camera's depth of field (Fig. 2). Insects were not generally visible in the medium to high elevation ranges owing to their small size and lower body temperature. The vast majority of bats we observed were flying at the medium-altitude band (within the rotor-swept zone; 65.9 bats/night)—>3 times the number observed flying at low or high altitudes (22.7 and 11.2 bats/night, respectively). Although camera resolution and cloud cover may bias our estimates of high-flying bats downward, the number of medium-flying bats still greatly outnumbered low-flying bats by a factor of 6:1. Bats appeared to spend much of their time foraging and flying at the range of altitudes at which the turbine blades were operating (29–111 m AGL).

To determine if objects identified as bats were within the altitude range of the rotor-swept zone, we analyzed 5 single instances of avoidance behavior, wherein bats appeared to be buffeted by passing blades, or changed course abruptly to avoid contact with blades. Given the field of view of the lens (24°), the detector array size (320 × 240 pixels), and the average length (11 cm) of the species found in the companion study (Kerns et al. 2005), we calculated that a single illuminated pixel in the video image corresponds to a single bat at 82.5 m from the camera. Therefore, given the mean number of pixels per bat in these images, the mean distance of the bats from the camera in the 5 avoidance sequences was 29.98 ± 7.56 m (SD). This distance corresponds to the distance to the boundary of the low- and medium-altitude bands. Although this measure adds confidence to the identification of bats in the video

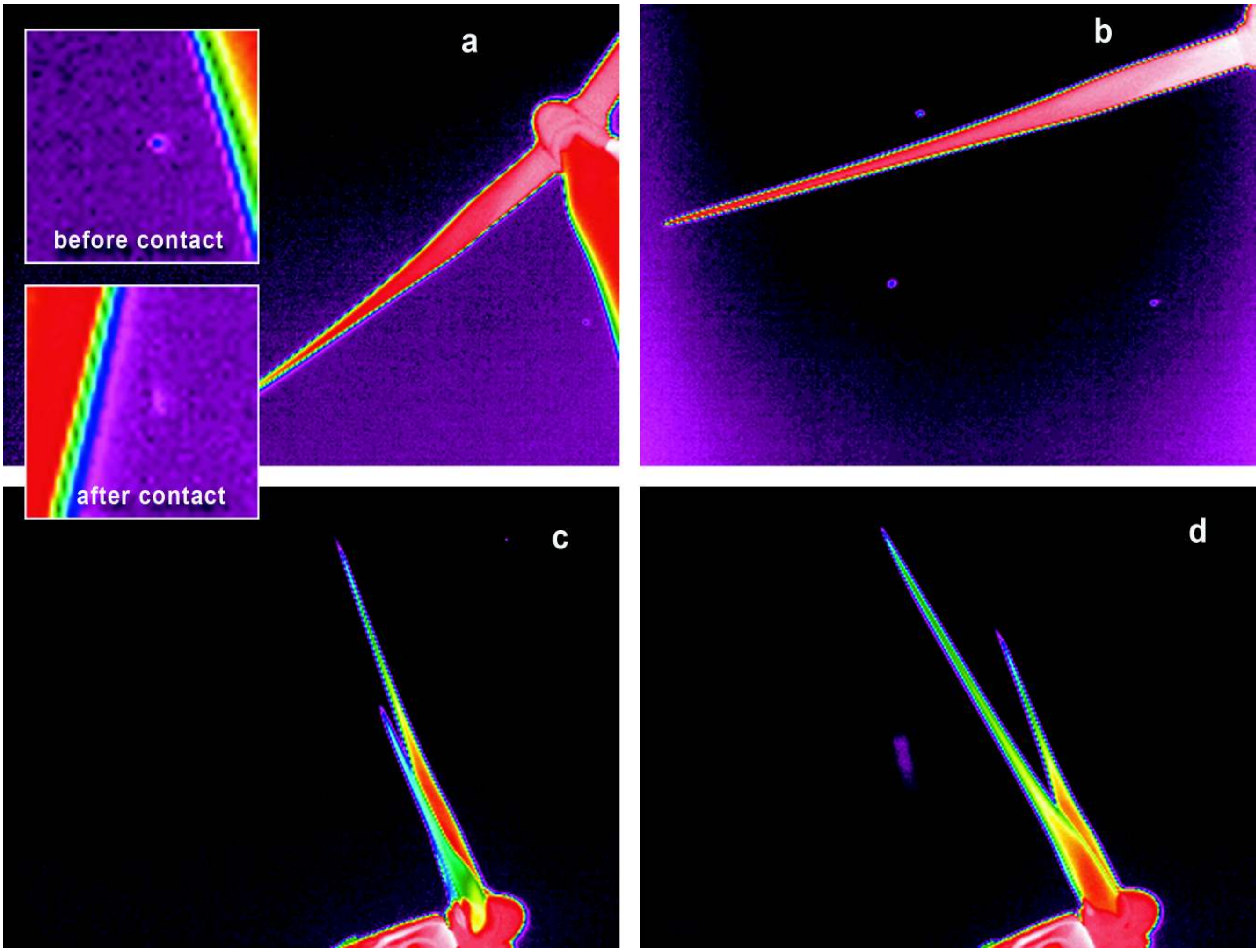

Figure 2. Single frames of thermal infrared camera images illustrate common observations at the Mountaineer Wind Energy Center in West Virginia, USA, in August 2004. (a) The moments immediately before and after contact with a turbine blade; (b) 3 low–medium flying bats at one time in the camera field of view; (c) a typical high bat flying above the height of the turbine blades; and (d) a typical low-flying insect, characterized by the low contrast (cool) blurry streak, an artifact caused by the camera's integration time, indicating fast motion close to the camera. Thermal infrared video segments of this and other bat flight behaviors near turbines recorded during this study can be viewed at http://www.bu.edu/cecb/wind/video.

sequences, it should be noted that many factors can influence the number of pixels representing a bat in an image, including fog, camera focus, the integration time of the sensor array (image blurring), and the orientation of wings to the camera lens.

The number of bats we observed on a nightly basis was highly variable, with as few as 9 per night, and as many as 292 ± 92 (SD; Fig. 3). In fact, there was a significant difference in the mean number of bat passes observed on a nightly basis ($n = 10$, $t = 3.37$, $P = 0.008$). Insect activity also was highly variable, but proportional to bat activity ($R^2 = 0.51$, $P = 0.02$). There was a significant correlation between insect passes and bat passes observed across all nights ($r = 0.71$, $F = 4.03$, $P = 0.039$). A regression analysis indicates that insect activity was a significant positive predictor of bat passes ($R^2 = 0.51$, $F = 8.14$, $P = 0.02$; Fig. 4).

Analysis of temporal distribution of bat activity throughout the night revealed that activity was conspicuously higher in the first 2 hours after sunset, and then tapered off with a lull in activity near midnight (Fig. 5). We observed higher numbers of bat passes after the midnight lull in some datasets, but the overall trend can be characterized by a gradual decrease throughout the night. Flying insects appeared to be most active in the hours immediately after sunset, with their numbers declining steadily throughout the night (Fig. 5).

Aviation lighting did not appear to affect the incidence of foraging bats around turbines. Although we observed more nightly bat passes at lighted turbines ($n = 562$, $\bar{x} = 112$, ± SD = 108) than at unlighted ($n = 435$, $\bar{x} = 87$ ± SD = 86.2), there was no difference between these groups ($t = 0.42$, $P = 0.68$). Interestingly, the mean number of insect passes was slightly higher at lighted turbines than at unlighted turbines, but the difference was not significant at the 0.05 level ($t = 1.62$, $P = 0.14$). This suggests that aviation lights may attract insects, but that the increased insect abundance may not result in increased bat activity. However, this test has low statistical power because of the small sample size ($n = 10$, power = 0.53).

We evaluated the effects of nightly wind speed at the

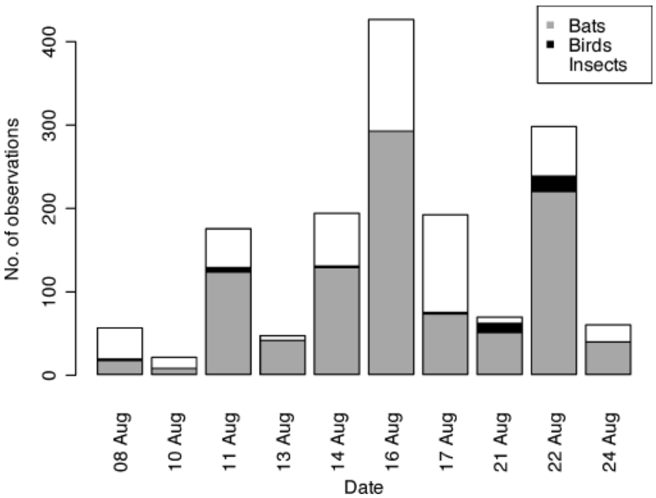

Figure 3. Total number of bat, bird, and insect passes per night for 10 nights between 8 August and 24 August 2004 based on thermal infrared images recorded at the Mountaineer Wind Energy Center, West Virginia, USA.

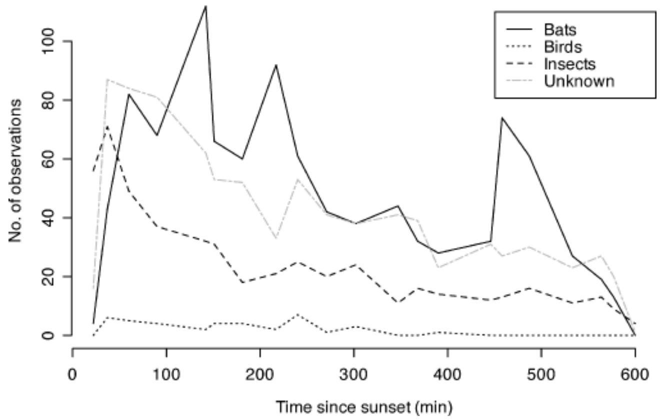

Figure 5. The mean number of bats, birds, insects, and un-categorized objects observed with thermal infrared cameras over time during dark hours in August 2004 at the Mountaineer Wind Energy Center in West Virginia, USA. Bat activity peaks during the first 3 hours after sunset.

turbine, mean wind speed for all turbines, mean wind speed at the meteorological towers, temperature at the turbine, mean temperature for all turbines, turbine rotation speed (measured in RPM), mean turbine RPM, turbine heading, mean turbine heading, and insect abundance on bat activity in separate regression analyses. Of these variables, we found that mean turbine RPM and insect abundance were the most significant predictors of number of bat passes observed (Fig. 4). Ambient temperature and pressure did not significantly predict bat passes. A multivariate regression analysis of wind speed, temperature, and turbine RPM shows that together these variables predict the number of bat passed observed (R^2 = 0.95, F = 14.4, P = 0.012).

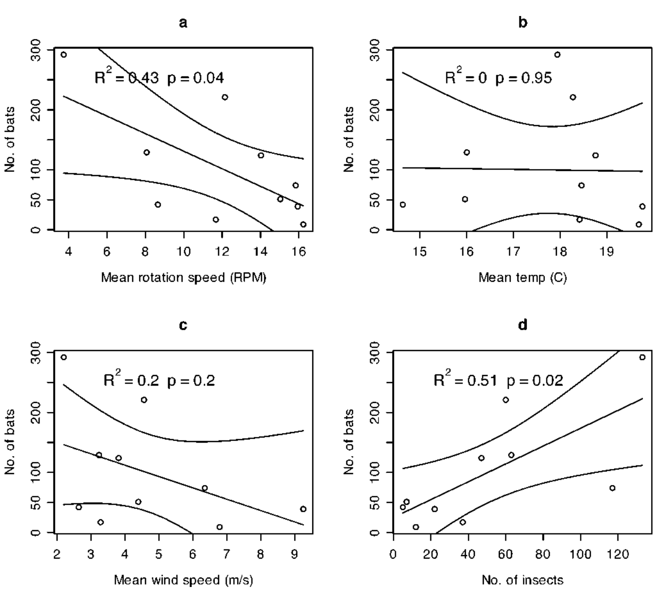

Figure 4. Relationship between number of bat passes observed nightly at wind turbines at the Mountaineer Wind Energy Center in West Virginia, USA, in August 2004 and several nightly variables including (a) mean turbine rotational speed (rotations/min [RPM]), (b) mean temperature, (c) mean wind speed, and (d) number of insect passes observed.

Turbine RPM ($t = 6.44$, $P = 0.02$) and insect abundance ($t = 7.21$, $P = 0.001$) were both positive predictors of bat passes.

Although most bats were observed foraging or flying around turbines, we also recorded clear instances of avoidance of blades and bats being struck by turbine blades. From 998 total bat observations, we observed avoidance behavior 41 times (4.1%, 4.1 instances of avoidance/turbine/night). In this analysis, we excluded, to the extent possible, observations involving multiple appearances of the same bat. Avoidance involved sharp, evasive flight maneuvers that were coincident with a moving blade. Notably, many of the instances of avoidance behavior involved multiple passes. Bats often appeared to investigate the turbine blades after a near miss, rather than fly off quickly. This often resulted in several additional near misses in a row, with the bat appearing to be repeatedly buffeted by turbulence close to the blade surface. We estimate that such interactions occurred within 5 m of the blade surface. Thermal infrared video segments of this and other bat flight behaviors near turbines recorded during this study can be viewed at http://www.bu.edu/cecb/wind/video.

We observed direct contact with moving blades 5 times out of a total 998 passes (0.5%, 0.5 instances of contact/turbine/night). Extrapolating to the size of the entire facility (42 turbines), bats may be struck at a rate of 21 bats per night at the Mountaineer Facility. Contact was only observed with moving blades. In no cases did we observe a bat striking the turbine monopole, nacelle, or stationary blades. Collisions were marked by an abrupt, angular change in heading and velocity (Fig. 6) and were generally of 2 types: glancing blows and direct hits. One collision was a glancing blow and the bat experienced a sudden deceleration and change of heading but appeared to recover and continue normal flight. We also witnessed 4 direct hits in which bats appeared to be struck closer to the centerline of a moving blade, and were greatly accelerated. We were unable to confirm that bats struck by the blades landed beneath the turbine, as the field of view of the cameras did not include the ground. The 4 collisions we observed occurred when the

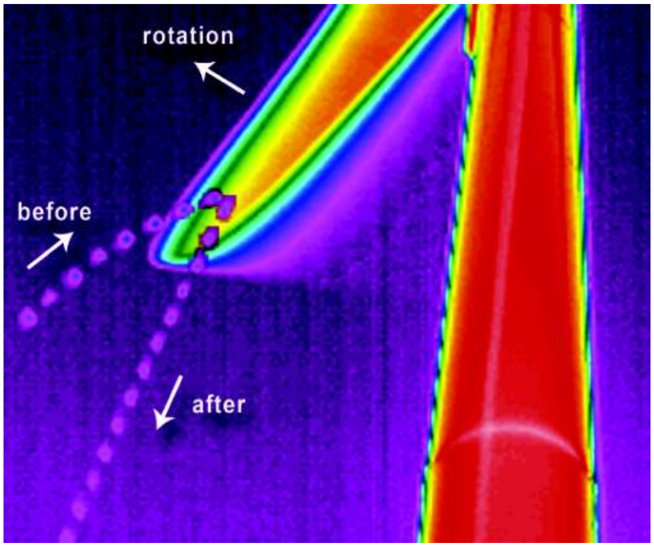

Figure 6. A time-lapse series thermal infrared images taken of a bat being struck by a blade of a wind turbine at the Mountaineer Wind Energy Center in West Virginia, USA, in August 2004. Twenty-one sequential frames of video are shown of the bat just before and after collision with a rotating blade. The bat approaches the area swept by the turbine blades on a curving trajectory before contact, but its heading and speed are rapidly changed as the bat is accelerated toward the ground. For clarity, the position of the wind turbine itself is shown only for the single frame of video in which contact occurred.

turbine blades were rotating at or near peak angular velocity (17 m/sec; Table 3).

We also observed a variety of what we judged to be exploratory behaviors by bats. Bats often make several check passes before alighting on and entering roost structures such as trees and buildings. We frequently observed bats making check passes or making repeated flight loops near moving blades. On 4 separate occasions, we also observed bats executing check passes and briefly alighting on the monopole itself. This usually occurred at approximately one-half to two-thirds of the height of the hub. This behavior was particularly well-illustrated in one instance when an individual bat, while investigating the length of a motionless turbine blade, made several check passes before briefly alighting on the blade surface, approximately two-thirds down the length of the blade toward its distal end. We also observed 3 instances of bats either chasing the tips of slow-moving blades, or perhaps being drawn into a blade-tip vortex during low wind conditions when turbine blades were moving slowly.

DISCUSSION

Several hypotheses have been advanced about how and why bats are killed at wind energy facilities (Kunz et al. 2007*b*). Many of these hypotheses focus on the idea that bats are in some way attracted to wind turbine areas or to turbine structures, and the result is a greater than normal probability of being struck by a moving blade. Indeed, in a companion study conducted at the Mountaineer facility at the same time as the current study (Kerns et al. 2005), searchers walking daily transects beneath every other turbine found 466 dead bats in 42 days (11.1 bats/night or 0.26 bats/turbine/night). Given that searcher efficiency during the study was measured at 25%, the actual rate of mortality at the facility is likely much higher. Although the density of bats in the region around the facility is not known, this rate of mortality seems to suggest that bats are more abundant near turbines. The present study generally supports this hypothesis by providing some of the first evidence that collisions may be nonrandom interactions between bats and moving turbine blades.

The large variation in numbers of both bats and insects that we observed on a nightly basis and the significant correlation between insect and bat activity suggest that bats may be attracted to patches of insects, although weather patterns may amplify this relationship. Modifications to the forested landscape that results from construction of wind energy facilities, including the creation of open space in which turbines are installed and the linear landscape along access roads, may create favorable foraging grounds for insectivorous bats (Kunz et al. 2007*b*). Forest edges may be favorable to insect activity and to the ability of bats to capture them in flight. Migratory flights also may account for increased bat density around wind farms as individuals or groups of some species make stopovers to feed, drink, and roost in trees (Fleming and Eby 2003, Cryan and Brown 2007). As with resident populations, migrants or groups of bats making stopovers may be similarly attracted to these areas to feed.

In addition to attraction to wind power facilities, it is possible that locally foraging bats also are attracted to some attribute of the turbines themselves. Ultrasound emissions may attract the curiosity of bats (Kunz et al. 2007*b*), although recent investigations suggest that sounds produced by at least some wind turbines likely do not attract bats (J. Szewczak, unpublished data). Although the results show that there is no significant difference between the levels of bat activity at lighted versus nonlighted turbines at the Mountaineer Wind Energy Facility, light sources may attract insects to some wind turbine sites.

Perhaps the most important observations of this study were those of bats actively investigating both moving and motionless turbine blades. That bats alighted upon and investigated turbine blades and monopoles suggests that they may indeed be attracted to wind turbines themselves. One possible hypothesis to explain this behavior is that bats view these tall structures, standing in open space, as roost trees (Kunz et al. 2007*b*). Forest bats often seek out large trees and snags as desirable roosting habitat (Kunz 1982, Vonhof and Barclay 1996, Kunz and Lumsden 2003). The openings and forest edges that wind sites provide may represent favorable conditions for roosting and foraging, even for migrating tree bats during stopovers. Migratory bats also may investigate wind turbine structures in an attempt to evaluate their potential as mating sites (P. Cryan, United States Geological Survey, personal communication). It is unknown why bats might choose to investigate or pursue moving blades, but once they engage in such

Table 3. Wind speed at times when bats made contact with turbine blades, Mountaineer Wind Energy Center, West Virginia, USA, August 2004. RPM indicates revolutions per minute.

	Wind and turbine speed at times of contact with bats			
Date	Time (hr:min:sec)	Turbine no.	Turbine speed (RPM)	Wind speed (m/sec)
24 Aug	21:11:12	16	17.1	8.4
24 Aug	3:20:20	16	17.1	8.6
22 Aug	1:15:56	20	17.1	7.1
22 Aug	3:03:29	20	17.1	7.3
16 Aug	21:46:17	41	3.1	0.0

behavior, they may be caught by vortices that form in the wake of the blades (Kunz et al. 2007*b*, National Research Council 2007). This curious and exploratory behavior increases the probability of a collision with a moving blade over random encounters.

We observed bats primarily feeding and foraging around and in the rotor-swept zone of the turbine. Our results do not show that bats are struck by turbine blades while passing through the wind energy facility in straight-line flight en route to other destinations. To understand this relationship more fully, future investigations will need to monitor fluctuations in bat abundance aloft throughout the entire season (Apr–Oct in temperate regions).

That bat activity was so highly variable on a nightly basis suggests that stochastic variables such as weather conditions may affect their abundance. Because insect abundance is ephemeral and dependent on weather patterns, bat activity and the likelihood of being struck by rotating turbine blades could be predicted by a combination of insect seasonality and local weather patterns. The lack of statistically significant effects of temperature, barometric pressure, and wind may be due to the small sample size ($n = 10$). However, data from carcass searches obtained in a parallel study suggest that fatalities increased on low wind nights (Kerns et al. 2005), times when insects generally are most active.

There are some important limitations to the interpretation of these data. Based on our conservative classification scheme, we consider our estimates of bat activity to be reliable and the number of false positives to be low. However, identifications were a challenge given the varying weather conditions and the geometric problem of maximizing the field of view of the cameras without reducing our ability to resolve flying bats, particularly those at middle to high elevations. Low fog and cloud cover are common at the Mountaineer facility, and although infrared light is less scattered by water vapor than visual wavelengths, fog and cloud cover nevertheless reduce visibility and clarity in the images. Thus, to a certain extent, the number of objects observed may tend to be auto-correlated with low fog and cloud cover. This is partly due to the limitation of the camera's capacity to clearly resolve bat-sized objects at distances above the reach of the turbine's blades. Deployment of TIR cameras with higher resolution sensor arrays would greatly reduce this problem in future studies.

This study revealed some important considerations for future research. We originally designed the study to test the effect of slowing or stopping blade rotation on bat behavior around turbines and on the number of fatalities. However, we were unable to execute this experiment because the operators of the facility reversed their decision to allow us to experimentally stop rotation by feathering the blades at predetermined times. Future studies should include experimental control of blade rotation (including stopping rotation) to separate the effect of rotation from the effect of the existence of the tall turbine structures themselves. This should be done with the time budget of nightly bat foraging in mind, as bat abundance may decrease after an initial bout of foraging (Kunz 1982, 2004; Kunz and Lumsden 2003) and then later increase with foraging periods in the early morning (Kunz 1973, Eckert 1982). Future studies should also compare levels of bat activity between turbine areas, deforested areas at wind energy facilities without turbines, and adjacent forested areas. This comparison is necessary to separate the effects of landscape modification created during turbine facility construction from the effects of the turbines themselves on bat activity.

Future research must also gather observations for the full length of the season (early spring through late autumn) in which bats are active in order to address the effects of transient populations and migration, as well as the presence of resident bats. Finally, to better understand factors that may contribute to fatalities, it will be important to determine what actually happens to a bat in the moments before it is struck by a rotating turbine blade (Kunz et al. 2007*b*). Our results indicate that in many cases bats successfully avoid moving turbine blades. However, the infrared images that we collected were limited in resolution and detail. Bats close to rotating blades are between 41 m and 114 m from the camera, and appear as objects of 2–10 pixels in size. To resolve the interaction in finer spatio-temporal detail, $\geq$2 high-resolution cameras should be used to capture synchronized stereo images, from which 3-dimensional spatial models can be constructed. Such visualization could provide, in each instance, the distance that bats are from blades, how bats avoid blades, and what factors contribute to collisions that could suggest important mitigation strategies.

MANAGEMENT IMPLICATIONS

These findings have implications for mitigating bat fatalities at wind facilities, and investigations of nightly activity can help to evaluate the responses of bats to operating wind turbines. A primary finding of this research is that the nightly distribution of bats aloft is nonuniform. We found that most of the bat activity near wind turbines occurs in the first 2 hours after sunset. This observation, combined with the finding that weather patterns and nightly availability of insects may be reliable predictors of bat abundance suggests that collisions of bats with wind turbines could be greatly reduced by focusing mitigation efforts (such as turbine blade feathering) on periods of high bat activity. Curtailment of operations during predictable nights or periods of high bat kills could reduce fatalities considerably, with potentially modest reduction in power production and associated economic impact on project operations. Future studies employing TIR cameras have the potential to answer some pressing questions about the cause of bat fatalities at wind turbines. Moreover, employing TIR imaging during planning and development of new wind power facilities has the potential to inform developers and decision makers about the abundance, frequency, duration, and types of bat activity.

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LITERATURE CITED

Ahlen, I. 2003. Wind turbines and bats—a pilot study. SLU Department of Conservation Biology Final Report. Swedish National Energy Administration, Eskilstuna, Sweden.

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

Arnett, E. B., W. P. Erickson, J. Kerns, and J. W. Horn. 2005. Relationships between bats and wind turbines in Pennsylvania and West Virginia. An assessment of fatality search protocols, patterns of fatality and behavioral interactions with wind turbines. Bats and Wind Energy Cooperative. <http://www.batcon.org/wind/BWEC2004finalreport.pdf>. Accessed 15 Feb 2007.

Barclay, R. M. R. 1985. Long-range 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.

Betke, M., D. E. Hirsch, N. C. Makris, G. F. McCracken, M. Procopio, N. I. Hristov, S. Teng, A. Bacchi, J. Reichard, J. W. Horn, S. Crampton, C. J. Cleveland, and T. H. Kunz. 2008. Thermal imaging reveals significantly smaller Brazilian free-tailed bat colonies than previously estimated. Journal of Mammalogy 89:in press.

Boogher, B., and J. A. Slusher. 1978. Successful photographic techniques through night vision devices. Bulletin of the Entomological Society of America 24:203–206.

Brinkmann, R., H. Schauer-Weisshahn, and F. Bontadin. 2006. Survey of possible operational impacts on bats by wind facilities in Southern Germany. Administrative District of Freiburg—Department 56; Conservation and Landscape Management. <http://www.buero-brinkmann.de/downloads/Brinkmann_Schauer-Weisshahn_2006.pdf>. Accessed 14 Feb 2007.

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

Cryan, P. M., and R. H. Diehl. 2008. Analyzing bat migration. *In* T. H. Kunz and S. Parsons, editors. Ecological and behavioral methods for the study of bats. Johns Hopkins University Press, Baltimore, Maryland, USA. In press.

Desholm, M. 2003. Thermal animal detection system (TADS). Development of a method for estimating collision frequency of migrating birds at offshore wind turbines. National Environmental Research Institute, Roskilde, Denmark. <http://www2.dmu.dk/1_viden/2_Publikationer/3_fagrapporter/rapporter/FR440.pdf>. Accessed 15 Feb 2007.

Desholm, M., A. D. Fox, and P. D. Beasley. 2004. Best practice guidance for the use of remote techniques for observing bird behaviour in relation to offshore wind farms. Report produced for Collaborative Offshore Wind Research into the Environment (COWRIE) consortium. <http://www.offshorewindfarms.co.uk/Downloads/REMOTETECHNIQUES-FINALREPORT.pdf>. Accessed 15 Feb 2007.

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.

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

Fleming, T. H., and P. Eby. 2003. Ecology of bat migration. Pages 156–208 *in* T. H. Kunz and M. B. Fenton, editors. Bat ecology. University of Chicago Press, Chicago, Illinois, USA.

Fortin, D., F. Liechti, and B. Bruderer. 1999. Variation in the nocturnal flight behaviour of migratory birds along the northwest coast of the Mediterranean Sea. Ibis 141:480–488.

Frank, J. D., T. H. Kunz, J. W. Horn, C. J. Cleveland, and C. Petronio. 2003. Advanced infrared detection and image processing for automated bat censusing. Infrared Technology and Applications XXIX Proceedings of SPIE 5074:261–271.

Gauthreaux, S. A., and J. W. Livingston. 2006. Monitoring bird migration with a fixed-beam radar and a thermal-imaging camera. Journal of Field Ornithology 77:319–328.

Griffin, D. R. 1960. The echolocation of flying insects by bats. Animal Behaviour 8:141–154.

Griffin, D. R. 1970. Migration and homing of bats. Pages 233–264 *in* W. A. Wimsatt, editor. Biology of bats. Academic Press, New York, New York, USA.

Griffin, D. R. 1971. The importance of atmospheric attenuation for the echolocation of bats. Animal Behaviour 19:55–61.

Hill, S. B., and D. H. Clayton. 1985. Wildlife after dark: a review of nocturnal observation techniques. Occasional Papers, James Ford Bell Museum of Natural History 17:1–21.

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

Kerns, J., W. P. Erickson, and E. B. Arnett. 2005. Bat and bird fatality at wind energy facilities in Pennsylvania and West Virginia. Pages 24–95 *in* E. B. Arnett, editor. Relationships between bats and wind turbines in Pennsylvania and West Virginia. Final Report. Bats and Wind Energy Cooperative. 15 February 2007. <http://www.batcon.org/wind/BWEC2004finalreport.pdf>. Accessed 15 Feb 2007.

Kerns, J., and P. Kerlinger. 2004. A study of bird and bat collision fatalities at the Mountaineer Wind Energy Center, Tucker County, West Virginia. FPL Energy and Mountaineer Wind Energy Center Technical Review Committee. Curry and Kerlinger, LLC, Cape May, New Jersey, USA. <http://www.responsiblewind.org/docs/MountaineerFinalAvianRpt3-15-04PKJK.pdf>. Accessed 15 Mar 2007.

Kunz, T. H. 1973. Resource utilization—temporal and spatial components of bat activity in central Iowa. Journal of Mammalogy 54:14–32.

Kunz, T. H. 1982. Roosting ecology of bats. Pages 1–55 *in* T. H. Kunz, editor. Ecology of bats. Plenum Press, New York, New York, USA.

Kunz, T. H. 2004. Foraging habits of North American insectivorous bats. Pages 13–25 *in* R. M. Brigham, E. K. V. Kalko, G. Jones, S. Parsons, and H. J. G. A. Limpens, editors. Bat echolocation research: tools, techniques, and analysis. Bat Conservation International, Austin, Texas, USA.

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

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. 2007*b*. Ecological impacts of wind energy development on bats: questions, research needs, and hypotheses. Frontiers in Ecology and the Environment 5:315–324.

Kunz, T. H., and L. F. Lumsden. 2003. Ecology of cavity and foliage roosting bats. Pages 3–89 *in* T. H. Kunz and M. B. Fenton, editors. Bat ecology. University of Chicago Press, Chicago, Illinois, USA.

Kunz, T. H., and S. Parsons, editors. 2008. Ecological and methods for the study of bats. Johns Hopkins University Press, Baltimore, Maryland, USA. In press.

Kunz, T. H., G. R. Richards, and C. R. Tidemann. 1996*a*. Capturing small volant mammals. Pages 157–164 *in* D. E. Wilson, F. R. Cole, J. D. Nichols, R. Rudran, and M. S. Foster, editors. Measuring and monitoring biological diversity: standard methods for mammals. Smithsonian Institution Press, Washington, D.C., USA.

Kunz, T. H., D. W. Thomas, G. R. Richards, C. D. Tidemann, E. D. Pierson, and P. A. Racey. 1996*b*. Observational techniques for bats. Pages 105–114 *in* D. E. Wilson, F. R. Cole, J. D. Nichols, R. Rudran, and M. S. Foster, editors. Measuring and monitoring biological diversity: standard methods for mammals. Smithsonian Institution Press, Washington, D.C., USA.

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

Sabol, B. M., and M. K. Hudson. 1995. Technique using thermal infrared-imaging for estimating populations of gray bats. Journal of Mammalogy 76:1242–1248.

Simmons, J. A. 2005. Big brown bats and June beetles: multiple pursuit strategies in a seasonal acoustic predator–prey system. Acoustics Research Letters Online 6:238–242.

Vonhof, M. J., and R. M. R. Barclay. 1996. Roost site selection and roosting ecology of forest dwelling bats in southern British Columbia. Canadian Journal of Zoology 74:1797–1805.

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