Assessing Impacts of Wind-Energy Development on Nocturnally Active Birds and Bats: A Guidance Document

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Front Cover--Three species of migratory tree bats most often killed by utility-scale wind turbines in North America--silver-haired bat, *Lasionycteris noctivagans* (upper left), eastern red bat, *Lasiurus borealis* (lower left), and hoary bat, *Lasiurus cinereus* (upper right)--flying in the vicinity of the Mountaineer Wind Energy Center, Tucker County, West Virginia. Images of bats by Merlin D. Tuttle, wind turbines by Edward B. Arnett, and cover design by Jason Huerta, Bat Conservation International.

Invited Paper

Assessing Impacts of Wind-Energy Development on Nocturnally Active Birds and Bats: A Guidance Document

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ABSTRACT Our purpose is to provide researchers, consultants, decision-makers, and other stakeholders with guidance to methods and metrics for investigating nocturnally active birds and bats in relation to utility-scale wind-energy development. The primary objectives of such studies are to 1) assess potential impacts on resident and migratory species, 2) quantify fatality rates on resident and migratory populations, 3) determine the causes of bird and bat fatalities, and 4) develop, assess, and implement methods for reducing risks to bird and bat populations and their habitats. We describe methods and tools and their uses, discuss limitations, assumptions, and data interpretation, present case studies and examples, and offer suggestions for improving studies on nocturnally active birds and bats in relation to wind-energy development. We suggest best practices for research and monitoring studies using selected methods and metrics, but this is not intended as cookbook. We caution that each proposed and executed study will be different, and that decisions about which methods and metrics to use will depend upon several considerations, including study objectives, expected and realized risks to bird and bat populations, as well as budgetary and logistical considerations. Developed to complement and extend the existing National Wind Coordinating Committee document "Methods and Metrics for Assessing Impacts of Wind Energy Facilities on Wildlife" (Anderson et al. 1999), we provide information that stakeholders can use to aid in evaluating potential and actual impacts of wind power development on nocturnally active birds and bats. We hope that decision-makers will find these guidelines helpful as they assemble information needed to support the permitting process, and that the public will use this guidance document as they participate in the permitting processes. We further hope that the wind industry will find valuable guidance from this document when 1) complying with data requirements as a part of the permitting process, 2) evaluating sites for potential development, 3) assessing impacts of operational wind-energy facilities, and 4) mitigating local and cumulative impacts on nocturnally active birds and bats. (JOURNAL OF WILDLIFE MANAGEMENT 71(8):2449–2486; 2007)

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Wind energy is one of the fastest growing sectors of the energy industry (Pasqualetti et al. 2004, National Research Council [NRC] 2007), a relatively recent development that has led to unexpected environmental consequences (Morrison and Sinclair 2004, Manville 2005, Kunz et al. 2007). The large number of raptor fatalities discovered at Altamont Pass in California in the early 1980s triggered widespread concern from environmental groups and wildlife agencies about possible impacts to bird populations (Anderson and Estep 1988; Estep 1989; Orloff and Flannery 1992, 1996). Anderson et al.'s (1999) comprehensive review and analysis of methods and metrics for the study of impacts of wind-energy facilities on birds provided valuable guidelines for assessing diurnally active wildlife but offered limited guidance on methods for assessing impacts on nocturnally active birds and bats. Given the projected growth of the wind-energy industry in the United States and emerging concerns over possible cumulative impacts of wind-energy facilities on nocturnally active birds and bats (Government Accountability Office [GAO] 2005, Manville 2005, NRC 2007, Arnett et al. 2008), we developed this document to supplement the earlier methods and metrics document.

The methods and metrics we consider herein include those suitable for assessing both direct and indirect impacts of wind energy. Direct impacts of wind-energy facilities refer to fatalities resulting from night-flying birds and bats being killed directly by collisions with wind turbine rotors and monopoles. Indirect impacts of wind-energy development refer to disruptions of foraging behavior, breeding activities, and migratory patterns resulting from alterations in landscapes used by nocturnally active birds and bats. Direct and indirect impacts on birds and bats can contribute to increased mortality, alterations in the availability of food, roost and nest resources, increased risk of predation, and potentially altered demographics, genetic structure, and population viability (NRC 2007).

LIMITS OF CURRENT KNOWLEDGE ABOUT IMPACTS ON NOCTURNALLY ACTIVE BIRDS AND BATS

Songbirds

Songbirds are by far the most abundant flying vertebrates in most terrestrial ecosystems, and until recently have been

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among the most frequently reported fatalities at utility-scale wind facilities in the United States. In a review of bird collisions reported from 31 studies at utility-scale wind-energy facilities in the United States, Erickson et al. (2001) showed that 78% of carcasses found at wind-energy facilities outside of California were songbirds protected by the Migratory Bird Treaty Act (16 United States Code 703–712); among these, approximately half were nocturnal, migrating passerines. The number of passerine fatalities reported in other studies has ranged from no birds during a 5-month survey at the Searsburg Vermont Wind Energy Facility, Searsburg, Vermont, USA (Kerlinger 1997) to 11.7 birds per megawatt (MW) per year during a 1-year study at Buffalo Mountain Wind Energy Center, Anderson County, Tennessee, USA (Nicholson 2003). Given the increasing number of installed and proposed wind-energy facilities, the relatively large number of passerine fatalities at wind-energy facilities on forested ridge tops in the eastern United States, such as Buffalo Mountain Wind Energy Center, Anderson County, Tennessee, and the Mountaineer Wind Energy Center, Tucker County, West Virginia has raised concern regarding the potential risk to nocturnally active songbirds (Kerns and Kerlinger 2004, GAO 2005, Fiedler et al. 2007, NRC 2007, Arnett et al. 2008).

Bats

Recent monitoring studies indicate that utility-scale wind-energy facilities in the continental United States have killed considerably more bats than were expected based on early monitoring studies where birds have been the primary focus of attention (NRC 2007). Large numbers of bats have been killed at wind-energy facilities constructed along forested ridge tops in the eastern United States (GAO 2005, Kunz et al. 2007, NRC 2007, Arnett et al. 2008). The highest fatality rates at these facilities have ranged from 15.3 bats/MW/year at the Meyersdale Wind Energy Center, Somerset County, Pennsylvania to 41.1 bats/MW/year at the Buffalo Mountain Wind Energy Center (Fiedler 2004, Kunz et al. 2007, NRC 2007, Arnett et al. 2008). A recent follow-up study conducted at the Buffalo Mountain site reported fatality rates of 53.3 bats/MW/year at 3 small (0.66-MW) Vestas V47 wind turbines (Vestas Wind Systems A/S, Ringkøbing, Denmark) and 38.7 bats/MW/year at 15 larger (1.8-MW) Vestas V80 turbines (Fiedler et al. 2007). Another recent study, conducted at the Maple Ridge Wind Power Project, Lewis County, New York, USA estimated bat fatalities ranging from 12.3 bats to 17.8 bats/MW/year (depending on carcass search frequency) at 1.65-MW Vestas wind turbines (Jain et al. 2007). Bat fatalities reported from most other regions of the United States have ranged from 0.8 bats to 8.6 bats/MW/year, although these estimates were largely based on studies designed to estimate bird fatalities (but see Johnson et al. 2003, 2004, 2005). In addition to these fatalities, bats have been killed at wind-energy facilities located in agricultural areas of southwestern Alberta, Canada (Barclay et al. 2007), and in a mixed woodland–shrub–grassland landscape in north-central Oklahoma, USA (Piorkowski 2006). Little is known, however, about potential risks and fatalities in other regions in North America where wind-energy facilities are being developed at an unprecedented rate.

Challenges to Impact Assessment and Prediction

Predicting impacts on bird and bat populations based on fatalities reported from existing wind facilities presents several challenges. Lack of reliable correction factors for biases associated with searcher efficiency and scavenging make it difficult to derive reliable estimates of fatalities for a given site or season, let alone to compare results from different regions and years to confidently predict cumulative impacts (Kunz et al. 2007, NRC 2007, Arnett et al. 2008). Several studies using radar have been conducted during preconstruction periods in efforts to estimate potential risks to nocturnal migrants. However, to date, none have provided sufficient evidence to reliably predict actual risk. In part, this may reflect the fact that existing sites typically have different ecological characteristics both before and after development (e.g., undisturbed forested ridge top vs. cleared ridge top with installed wind turbines).

Bias correction factors.—Scavengers are known to remove bird and bat carcasses before researchers are able to discover them and, thus, fatality rates will most likely be underestimated unless reliable estimates of scavenging rates are developed and applied to observed fatalities (Morrison 2002). Bias correction factors also are needed to adjust fatality estimates for searcher efficiency. For example, a study in West Virginia used test subjects (fresh and frozen bats or birds) to evaluate searcher efficiency and found that, on average, only about half of the animals were found by human observers (Arnett 2005, Arnett et al. 2008). Moreover, bats killed by wind turbines were twice as likely to be found by human observers in grassland areas compared to those in agricultural landscapes and along cleared forested ridge tops. In a recent study, trained dogs were able to find 71% of the bat carcasses during searcher-efficiency trials at the Mountaineer site in West Virginia and 81% at the Meyersdale site in Pennsylvania, compared to 42% versus 14%, respectively, for human searchers (Arnett 2006).

Causal mechanisms of impact.—Cooperation of the wind-energy industry is needed to help researchers develop a better understanding of how birds and bats interact with wind-energy facilities and to help identify the causal mechanisms of impact (Kunz et al. 2007, NRC 2007). Research and monitoring studies are needed to assess activities and abundance of birds and bats 1) before construction (e.g., before forests have been cleared and linear landscapes have been created); 2) after turbines have been installed (but before they become operational); and 3) after they have become operational, to test hypotheses needed to assess impacts of wind-energy facilities on birds and bats (Kunz et al. 2007, NRC 2007).

Results of such research could help researchers identify and the wind industry implement mitigation measures to avoid or minimize impacts on nocturnally active wildlife at existing facilities. For example, studies using thermal infrared imaging (Horn et al. 2008) and evidence from bat carcasses recovered at the Mountaineer and Meyersdale Wind Energy Centers in 2004 (Arnett 2005, Arnett et al. 2008) indicate that most fatalities occurred at times of low wind speeds (typically <6 m/sec), conditions under which rotor blades are moving but the amount of electricity generated is minimal (NRC 2007). These data suggest that a first-order priority should be to test the hypothesis that bat fatalities could be markedly reduced by mechanically feathering turbine blades (i.e., electronically pitching the blades parallel to the wind, effectively making them stationary) at low wind speeds (Kunz et al. 2007, Arnett et al. 2008).

Well-designed before-after-control impact (BACI) and comparative studies, and those that test responses of birds and bats to different operational conditions, are needed to fully evaluate options for mitigating fatalities to birds and bats at wind-energy projects (Kunz et al. 2007, NRC 2007). In this context, some success has been achieved with the installation of new turbine designs (e.g., lattice towers replaced with monopoles and fewer and taller turbines), and by testing visual deterrent by using different colors on turbine blades (Hodos 2003). A current study is underway to test the efficacy of acoustic deterrents (E. B. Arnett, Bat Conservation International, unpublished data).

We summarize methods for assessing risks to birds and bats associated with proposed and operational wind-energy facilities. A number of methods are available to observe nocturnal activities of birds and bats, including: night-vision observations, thermal infrared imaging, radar monitoring, acoustic recordings, and radiotracking (telemetry). Other research methods, including direct capture, collection of tissue for stable isotopes and DNA analysis, estimates of population size and genetic structure, and fatality assessments, provide critical information needed to assess direct, indirect, and cumulative impacts.

METHODS AND METRICS FOR OBSERVING NOCTURNAL BEHAVIOR OF BIRDS AND BATS

Current understanding of where, when, how, and why bats and nocturnally active birds come into contact with wind turbines is limited by our ability to observe how they behave near these structures. Answering some of the most basic questions requires careful observations with appropriate methods to assess the nocturnal and seasonal timing of flight behavior of birds and bats in the vicinity of proposed and operating wind turbines. No single method or protocol can be used to unambiguously assess temporal and spatial variation in natural populations or the impacts of wind turbines on nocturnally active birds and bats. Each device or method has its own strengths, limitations, and biases, and the selection and application of one or multiple methods will depend on the specific objectives to be addressed. Sufficient information should be acquired to enable researchers to meet the stated goals of a proposed study. To avoid misinterpreting results, assumptions and limitations of each method must be explicitly acknowledged and evaluated (e.g., Hayes 2000, Gannon et al. 2003). Moreover, individuals charged with monitoring the activities of birds and bats must be thoroughly familiar with the operation and limitations of each method or device before initiating field studies.

Visual Methods for Monitoring Nocturnal Activity

Making meaningful visual observations requires not only selecting the appropriate methods and equipment (Allison and De Stefano 2006), but it is essential that temporal and spatial scales of observations also be included to answer relevant questions.

Moon watching.—Early investigators used a moon-watching technique during full-moon periods with clear skies to observe migratory birds (Lowery 1951, Lowery and Newman 1955). By directing a telescope of sufficient power (20–30×) toward the full moon during periods of migration, it is possible to observe silhouettes of birds and bats as they pass before the illuminated disc of the moon. The primary limitation of this method is that sampling conditions are limited to cloudless nights with a full moon.

Ceilometry.—Given the limitations of moon watching, Gauthreaux (1969) developed a portable ceilometer to observe low-altitude nocturnal migrations on nights when the moon was not visible. This method employed an auxiliary light source (e.g., 100-W lamp) to illuminate a portion of the night sky that could then be sampled using binoculars or a spotting scope. This method has been used to detect large numbers of bird species flying ≤305 m above ground level (agl) with 7× binoculars, several bird species ≤457 m agl with a 20× telescope, and at detecting larger passerines (e.g., thrushes) ≤640 m agl with a 20× telescope (Gauthreaux 1969).

Able and Gauthreaux (1975) used a ceilometer to quantify the nocturnal migration of passerines, and expressed the magnitude of migration as the number of birds per 1.6 km of migratory front per hour, a metric derived from moon watching that also is currently used in some radar studies. Williams et al. (2001) used 300,000 candle power (Cp) spotlights instead of portable ceilometers for observing activity of thrush-sized passerines ≤500 m agl. The ability to detect airborne targets at night using artificial illumination diminishes with the square of distance from the observer and, thus, will depend on the intensity and effective range of the source of illumination.

Although ceilometers can provide information about relative traffic rates of nocturnal migrants, the beam of light samples a very small area relative to the available area potentially occupied by nocturnal migrants. Additionally, visible light from the ceilometer tends to attract birds and insects and, thus, can lead to biased results. This problem was recognized by Williams et al. (2001), where birds were observed around dim light scattered from the ceilometer. Estimates of flight altitude derived from this method also might be biased due to the greater probability of visually detecting lower flying birds and the general difficulty of visually estimating flight altitude. Detection biases associated with this method have not been objectively quantified.

Figure 1. Method for observing and recording activity of bats and birds at wind-energy projects using night-vision goggles and 2 supplementary light sources equipped with infrared filters (B. A. Cooper, Alaska Biological Research, Inc., unpublished data).

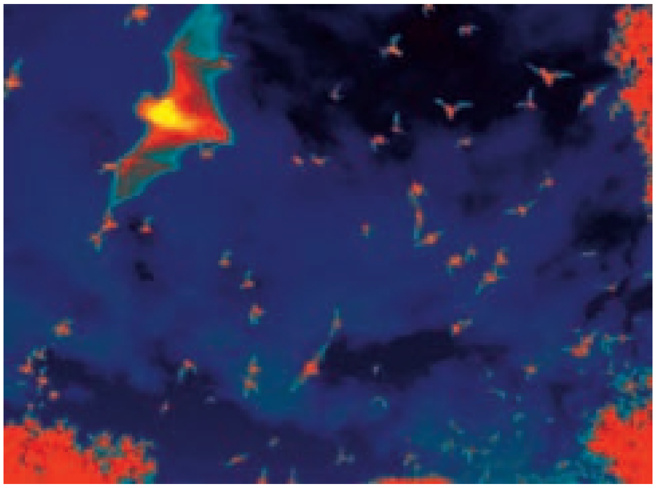


Figure 2. Thermal infrared image of foraging Brazilian free-tailed bats (*Tadarida brasiliensis*) in south-central Texas, USA. Warm bats are distinguished from the cooler background of clear sky and clouds (T. H. Kunz and M. Betke, Boston University, unpublished data).

Night-vision imaging.—Visual observations that employ night-vision goggles (NVG) and scopes, powerful (3-million Cp) spotlights, and reflective infrared cameras have greatly improved in recent years. Improvements of the NVG method over earlier visual methods include 1) greater freedom to follow and identify birds, bats, and insects; 2) use of both fixed and mobile spotlights that increase the ability to detect and identify animals correctly; and 3) infrared filters that eliminate the attraction of insects, birds, and bats to supplemental sources of visible light.

These improvements have made it possible to identify small birds and bats aloft at distances $\leq$150 m. Mabee et al. (2006*a*) used third-generation NVG with a 1× eyepiece (Model ATN-PVS7; American Technologies Network Corporation, San Francisco, CA), along with 2 3-million–Cp spotlights fitted with infrared filters to illuminate flying targets aloft at a planned wind-energy facility in New York state. Using this method, Mabee et al. (2006*a*) viewed the night sky through NVG and were able to track and identify moving targets using one stationary spotlight (mounted on a tripod with the beam oriented vertically) and a mobile spotlight (handheld with the beam parallel to the fixed spotlight's beam; Fig. 1).

For each bird or bat detected, flight direction, flight altitude, and flight behavior (e.g., straight-line, zig-zag, circling, hovering) often can be detected. Species identification, however, is rarely possible using this method. Video recordings of flight behavior can be recorded and analyzed repeatedly to determine how birds or bats respond to moving wind turbines. Metrics produced from NVG images include proportions of birds and bats observed flying at low altitudes ($\leq$150 m agl, the max. distance that passerines and bats can be discerned using this method), flight direction, and relative number of birds and bats observed per hour (standardized by estimating distance to targets if and when comparisons among studies are made).

Limitations of the NVG method include variable detectability of animals because of cloud cover, atmospheric moisture, and the effect of distance on detection. Night-vision devices, each of which contain photo-multiplier cells, also produce inherent visual noise, often making it difficult for observers to distinguish small birds from bats at night, even within the height of the rotor-swept zone of utility-scale wind turbines.

Thermal infrared imaging.—In contrast to night-vision technology, thermal infrared imaging cameras are designed to detect heat emitted from objects in a field of view without the need for artificial illumination. The metabolic heat produced by birds and bats (and some insects) produces a distinct image against a cooler background (Fig. 2). Typically, images can be captured at rates ranging from 30 frames to 100 frames per second (fps), depending on the camera, and digitally recorded to computer hard drives. Automated detection and tracking algorithms have been developed that may prove useful for assessing the behavior of birds and bats flying in the vicinity of wind turbines (Descholm et al. 2006, Betke et al. 2008).

Several studies have employed thermal infrared imaging cameras to observe movements of birds and bats flying near wind-energy facilities. Desholm (2003) and Desholm et al. (2004, 2006) used a long-wave (7–15 μm) thermal infrared camera (Thermovision IRMV 320V; Forward Looking Infrared [FLIR], Boston, MA), deployed as part of the Thermal Animal Detection System for automatic detection of avian collisions at an offshore wind-energy facility in Denmark. This system is triggered automatically when a target is detected and can be controlled remotely. In southwest Germany, Brinkmann et al. (2006) used a Mitsubishi Thermal Imager (IR-5120AII; Mitsubichi Electric Corporation, Kamakura, Japan) to observe bats in the vicinity of 2 wind turbines. This thermal camera operated at short wave lengths (3–5 μm) at 60 fps, and had a detector array consisting of 512 × 512 pixels, and with a 50-mm, F 1.2 infrared lens, provided a 14° × 11° field of

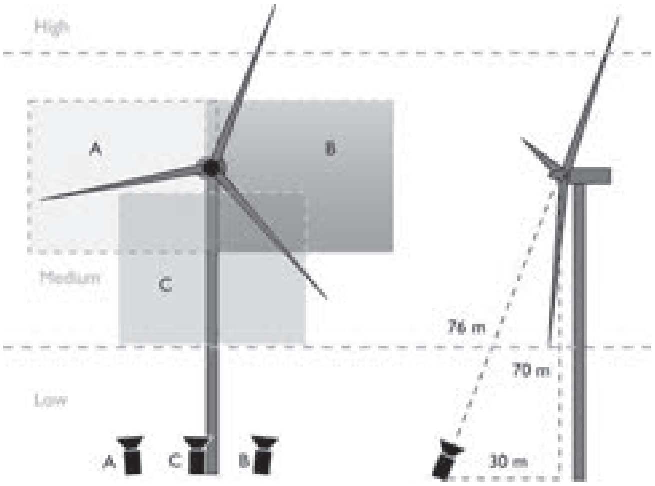


Figure 3. Configuration of 3 thermal infrared cameras for recording nightly observations of airborne targets (i.e., bats, birds, and insects) at the Mountaineer Wind Energy Center in Tucker County, West Virginia, USA. Cameras are positioned 30 m from the turbine base and pointed directly upwind and perpendicular to the plane of blade rotation. Observed bats, birds, and insects were classified into high, low, and medium categories corresponding to flight elevation above ground level (from Horn et al. 2008).

view. With this system, flight patterns of bats could be distinguished at a distance of 100 m.

Liechti et al. (1995) used a long-range thermal imaging unit (Long Range Infrared System, IRTV-445L; Inframetrics, Nashua, NH) with a 1.45° telephoto lens and were able to detect nearly 100% of all small passerines within the field of view at a distance of 3,000 m. The same unit was used in Sweden to monitor autumn bird migration (Zehnder and Karlsson 2001, Zehnder et al. 2001) and in Africa, on the edge of the Sahara desert, to study nocturnal bird migration (Liechti et al. 2003). Gauthreaux and Livingston (2006) used a thermal imager (Radiance 1; Amber Raytheon, Goleta, CA) to study nocturnal migration at Pendleton, South Carolina, and Wallops Island, Virginia, USA, when weather conditions (no rain and relatively clear skies) allowed data collection. Daylight observations were made at McFaddin National Wildlife Refuge, Texas, USA. This thermal imaging camera, with a 100-mm lens, and a field of view of 5.57° (horizontal screen dimension) and 4.19° (vertical screen dimension), recorded data at 60 fps, and yielded an image of 482 × 640 pixels at full-screen resolution. A vertically directed thermal imaging camera and a fixed-beam vertical pointing Pathfinder radar, Model 3400 (Raytheon Inc., Manchester, NH) was used with a parabolic antenna (61-cm diam) that produced a beam width of 4° to monitor bird, bat, and insect movements based on the characteristics of tracks in the video images and the altitude of the target derived from the radar unit. Data from the thermal imaging camera and radar were combined into a single video image and stored on digital videotape. This approach produced quantitative data on migration traffic at several altitudinal bands and made it possible for the investigators to distinguish birds from insects and foraging bats.

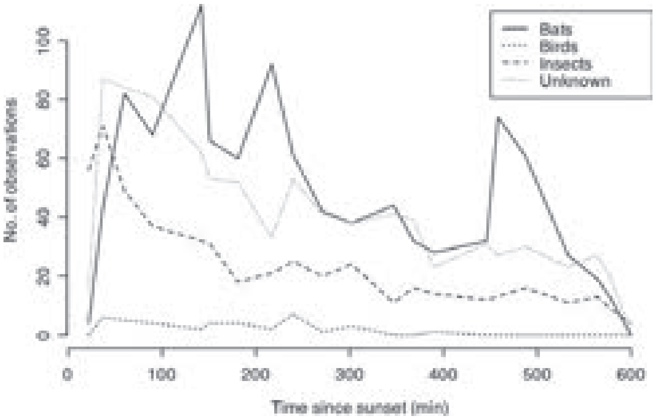


Figure 4. The distribution of activity during the night for bats, birds, insects, and unknown objects recorded with thermal infrared cameras from 2030 hours to 0530 hours at the Mountaineer Wind Energy Center, Tucker County, West Virginia, USA, August 2005 (from Horn et al. 2008).

Horn et al. (2008) deployed 3 FLIR Systems S-60, uncooled, microbolometer thermal infrared cameras (FLIR, North Billerica, MA), with matched and calibrated 25° lenses to observe the behavior of bats in the vicinity of operating wind turbines at the Mountaineer Wind Energy Center in the Mid-Atlantic Highlands, West Virginia (Fig. 3). Data were captured at a rate of 30 fps and recorded directly to external 250-gigabyte hard drives that were connected to laptop computers. Horn et al. (2008) showed that bat activity near wind turbines during August was highly variable on a nightly basis, with most of the activity of bats occurring during the first 2–3 hours after sunset (Fig. 4). Although airborne insects were most active in the first several hours after sunset, their activity was highly variable.

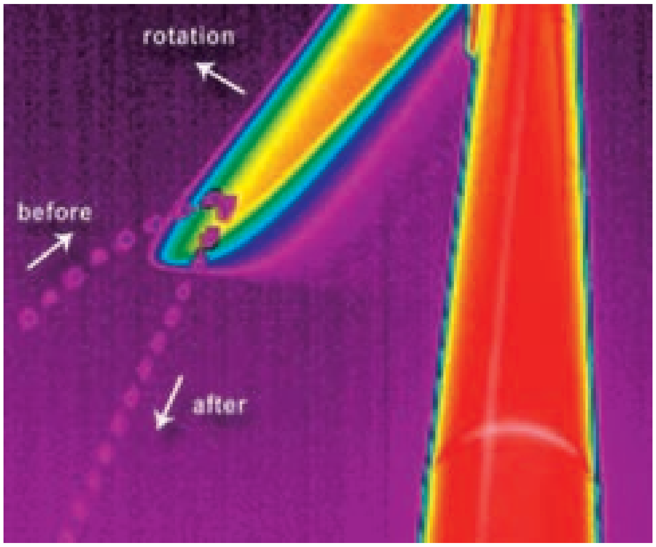


Figure 5. A time-lapse series of 21 sequential frames of thermal infrared video of a medium-height bat immediately before and after collision with an operational wind turbine recorded on 14 August 2004 at the Mountaineer Wind Energy Center, Tucker County, West Virginia, USA. The bat approached the moving blade on a curving trajectory before contact, but its heading and speed changed rapidly as the bat accelerated toward the ground. Only the single frame of video in which contact occurred is shown for clarity (from Horn et al. 2008).

Horn et al. (2008) suggested that the probability of being struck by moving turbine blades (Fig. 5) could be predicted by a combination of insect activity aloft and nightly weather conditions. In addition to bats struck directly by moving turbine blades, Horn et al. (2008) also observed flying bats investigating moving rotors and the monopole. Bats sometimes alighted upon and appeared to explore the monopole and rotor blades, suggesting that they may be attracted to these structures.

Results from thermal infrared imaging cameras ideally should be compared with other methods including radar and acoustic detection for monitoring bird and bat movements in the lower atmosphere at the height of wind turbines (Liechti et al. 1995, Gauthreaux and Livingston 2006). Many of the limitations of other visual methods are common to thermal infrared imaging, but the latter method also incurs a relatively high cost with large data-processing requirements. Current costs for the purchase of suitable thermal infrared cameras ($60,000–200,000) are expected to decrease in the near future.

Light tagging.—Small chemiluminescent light tags or mini glow sticks offer the potential for observing the flight behavior of individual bats in the vicinity of proposed and operational wind-energy facilities. Light tags have been used to mark bats for investigations of roosting and foraging behavior (Barclay and Bell 1988, Kunz and Weisse 2008). Small, chemiluminescent capsules (2 × 11 mm), manufactured as fishing lures, make excellent temporary light tags for marking and observing bats at night. Battery-powered light-emitting diodes (LEDs) also can be used for marking and observing bats flying at night (Barclay and Bell 1988, Kunz and Weisse 2008). Depending upon the size of the battery and the oscillation frequency of LEDs, such tags can last up to 14 days. Commercially produced LED tags are available in green and red light and are relatively small (3 × 12 mm and 1.0 g), with the battery and circuitry encapsulated in inert waterproof epoxy (Holohil Systems Ltd., Carp, ON, Canada).

Chemiluminescent tags and LEDs should be attached to the mid-dorsal region of bats with SkinBond™ surgical adhesive (Smith & Nephew, Largo, FL). Attaching light tags to the ventral surface of bats should be avoided, because a tag in this position may interfere with females if they have dependent young. Buchler (1976) and Buchler and Childs (1981) used chemiluminescent light tags to assess the dispersal, commuting, and foraging behavior of insectivorous bat species. Other investigators (e.g., LaVal and LaVal 1980, Aldridge and Rautenbach 1987) have used chemiluminescent and LED tags with the greatest success when observations were made in open areas, in flyways, and along forest edges and, thus, such tags may be particularly valuable for observing bats in the vicinity of wind turbines.

Use of chemiluminescent light tags may offer opportunities to observe the behavior of bats in response to sounds produced by moving wind-turbine blades or to insects that may attract bats to these structures (NRC 2007). Buchler and Childs (1981) attached light tags to big brown bats (*Eptesicus fuscus*) and found that individuals navigated to feeding grounds by following acoustic cues produced by calling frogs and stridulating insects. Light tags also can be used to follow individuals while their echolocation calls are monitored with ultrasonic detectors and, thus, can be used to validate species-specific calls (J. Swewczak, Humboldt State University, personal communication).

The primary limitation of chemiluminescent tags is that they remain illuminated only for a few hours. By contrast, LED tags can last upwards of 2 weeks. Another limitation is that bats often fly rapidly beyond the field of view, and generally cannot be followed in heavily forested areas. Moreover, in some instances light-tagged bats may be difficult to distinguish from flashing fireflies. More recent evidence suggests that bats carrying light tags may interfere with the social interactions of roosting bats (Kunz and Weisse 2008).

Analysis of visual data.—With the exception of data derived from light tags, visual-based surveys of bat activity using ceilometers, night vision, and thermal imaging cameras should report number of passes per recording hour or mean number of passes per recording hour. For consistency and comparison, recording time should be normalized to minutes past sunset. This protocol facilitates pooling and comparing data throughout a season or across multiple seasons (Horn et al. 2008). In addition to assessing overall activity, data should be documented by date, camera type, and lenses used to characterize temporal or spatial peaks in activity. Data on bat, bird, and insect activity derived from thermal infrared imaging or other visual methods should be compared with meteorological data to establish potential effects of these variables on relative abundance and nightly and seasonal activity.

Radio Detection and Ranging (Radar)

Radio detection and ranging (radar) has been used for over half a century to investigate nocturnal flight activity of birds, insects, and bats (Eastwood 1967, Vaughn 1985, Gauthreaux and Belser 2003, Larkin 2005, NRC 2007). However, only recently has this technology been used to evaluate the activity of airborne targets in the vicinity of wind-energy facilities (Mabee and Cooper 2004, Desholm et al. 2006, Gauthreaux and Livingston 2006, Mabee et al. 2006*a*, *b*). Radar operates by transmitting pulses of electromagnetic radiation (radio waves) and then receives the waves that reflect back from an object (e.g., insect, bird, bat, plane, or ship). Radio waves travel close to the speed of light and the distance to the object is, thus, related to the time lapse between transmission and reception of the echo. Detection of objects at a distance depends upon many factors, including area of the radar cross-section of the object, and the wavelength and power output of the radar. For birds, this distance may vary from a few hundred meters when using the smallest marine radars to >200 km in the case of long-range weather surveillance radars. For more details on theory and operation of radar, see Skolnik (1990) and Larkin (2005).

Weather surveillance radar.—Weather Surveillance Radar-1988 Doppler, also known as Next Generation Radar (NEXRAD) provides a network of weather stations in the United States operated by the National Weather Service (NWS), making it possible to monitor movements of insects, birds, and bats that move over large areas (i.e., within approx. 200 km). The United States military, local television stations, and municipal airports use similar weather radar systems, but data generated by these installations generally are not available to researchers. Data generated by the NWS-operated NEXRAD facilities can be downloaded free of charge via the Internet. Data generated from these weather surveillance radars can be used to determine general migratory patterns, migratory stopover habitats, roost sites, and nightly dispersal patterns (Fig. 6), and to assess the effects of weather conditions on these behaviors (Diehl et al. 2003, Gauthreaux and Belser 2003, Diehl and Larkin 2004, Horn 2007, NRC 2007).

However, NEXRAD cannot be used to characterize high-resolution passage rates or altitudinal data over small spatial scales (the min. resolution is 1° × 250 m, which is about 0.2 km^2 at 40-km range). The high resolution of NEXRAD often makes it difficult to filter out insect noise from data on birds and bats because it does not provide information on individual targets. Owing to the curvature of the earth and resultant shadows (e.g., areas behind hills or other objects that shield targets from radar), NEXRAD radar cannot provide spatial coverage at or below wind turbine height. Notwithstanding, NEXRAD can be a valuable tool for assessing spatial and temporal patterns of daily and nightly dispersal of birds and bats (Russell and Gauthreaux 1998, Diehl et al. 2003, Kunz 2004, Horn 2007; Fig. 7).

Tracking radar.—Tracking radar systems, originally designed to lock onto and follow targets such as aircraft or missiles, can provide information on flight paths of individual insects, birds, and bats (including altitude, speed, and direction) including wing-beat signatures to discriminate these taxa while in flight (Fig. 8). Several applications using tracking radar have been described for birds (Able 1977, Kerlinger 1980, Larkin 1991, Bruderer 1994, Liechti et al. 1995), bats (Bruderer and Popa-Lisseanu 2005), and insects (Drake 1985, Drake and Farrow 1989, Wolf et al. 1995, Chapman et al. 2004, Geerts and Miao 2005). To date, tracking radar has not been commonly used to assess movements of birds and bats at wind-energy facilities because 1) this instrument does not provide a broad view of migration over a given site, 2) it is not widely available, and 3) it is difficult and expensive to maintain and repair.

Marine radar.—Marine (X-band) radar systems were originally designed for use on moving boats, but they also have been used as mobile units on land for research and monitoring of airborne targets, including passage rates, flight paths, flight directions, and flight altitudes of nocturnal migrating targets. Mobile marine radar laboratories often consist of units that are mounted on top of a vehicle, trailer, or on a ground-based platform (Fig. 9). When the antenna is in the horizontal position (i.e., in surveillance mode), the radar scans the surrounding area and can be used to collect information on flight direction, flight behavior, passage rates, and ground speeds of targets (Table 1). When the antenna (or a second antenna, if unit is equipped with 2 radars) is placed in the vertical position (i.e., in vertical mode), it can be used to measure flight altitudes (Table 1). Configurations of marine radar antenna also can be modified to measure flight altitudes with a parabolic dish (Cooper et al. 1991, Gauthreaux 1996) or by a horizontal antenna configured in a vertical position (Harmata et al. 1999).

Marine radars have been used at several proposed and operational wind-energy facilities in the United States. The principal advantage of these systems over Doppler and tracking radars is that they are relatively inexpensive, are available off-the-shelf, require little modification or maintenance, have repair personnel readily available worldwide, are dependable and easy to operate, are highly portable (can mount on vehicles, boats, or small platforms on land), have high resolution, and can be modified to collect altitudinal information by changing their broadcast to a vertical mode.

Largely because of these factors, most research and monitoring studies conducted on birds and bats have been accomplished using marine radar systems (Harmata et al. 1999, Cooper and Day 2004, Mabee and Cooper 2004, Desholm et al. 2006, Mabee et al. 2006*a*). However, like NEXRAD, marine radar generally is not capable of differentiating bird and bat targets. Although it has long been assumed that marine radar can be used to document the presence and flight activity of bird targets (Cooper and Day 2003, Mabee and Cooper 2004, Raphael et al. 2002, Day et al. 2005), researchers have recently acknowledged that images derived from marine radar targets also include bats (Gauthreaux and Livingston 2006, Larkin 2006).

Numerous preconstruction studies have used marine radar to estimate passage rates and altitudinal distributions of migrating targets (Mabee and Cooper 2004, Mabee et al. 2006*b*). Typically, a single radar unit is deployed at a central location on a wind-energy project area to maximize observable airspace for 30–45 days during spring (approx. 1 Apr through late May) and autumn (approx. early Aug through early Oct) migration periods. Rarely have portable radar units been deployed for a full annual cycle associated with wind-energy projects, and rarely have radar-sampling protocols been designed to address specific research hypotheses. Most monitoring studies of airborne targets near proposed or operational wind-energy facilities have deployed marine radar between civil sunset and 0230 hours, assuming this to be the peak period of nocturnal migration for birds on a given night (Gauthreaux 1972, Kerlinger 1995, Mabee et al. 2006*b*).

Objectivity and accuracy in identifying flying animals at night is a major challenge when using radar (Larkin 1991). Differentiating among various targets (e.g., birds, bats, and insects) is central to any biological radar study. However, because flight speeds of bats overlap with flight speeds of passerines (i.e., >6 m/sec; Larkin 1991; Bruderer and Boldt

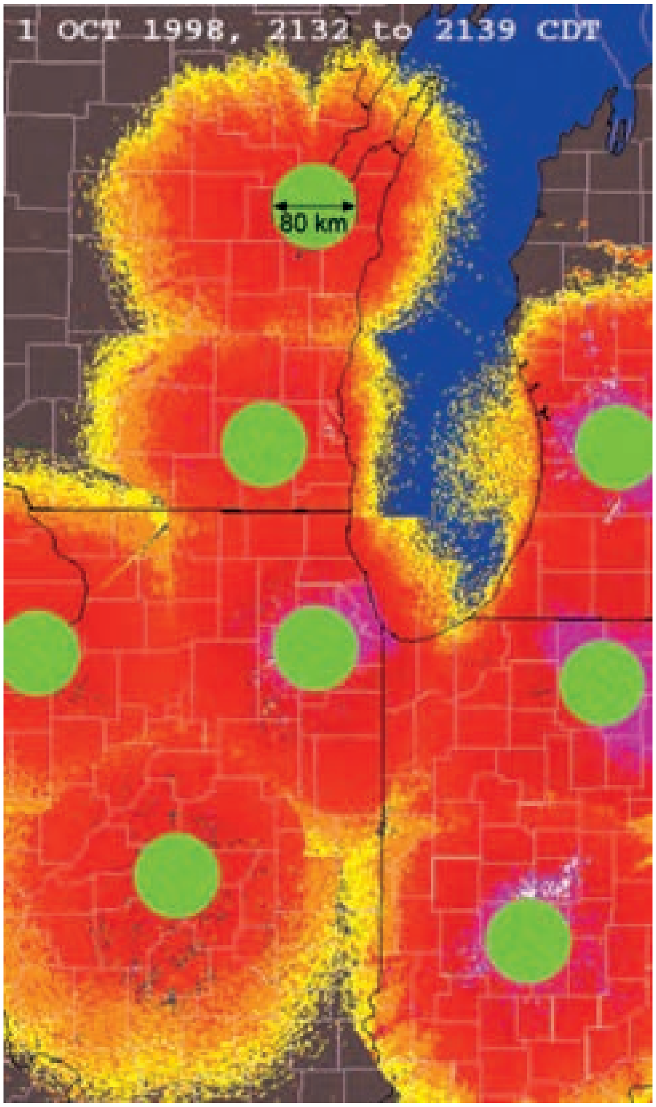


Figure 6. Composite of 8 Next Generation Radar (Weather Surveillance Radar-1988 Doppler) images taken at the lowest elevation angle (0.5°) on a typical night of widespread migratory activity in the mid-western USA, 1 October 1998. All pixels that are not background color (gray) are radar echoes from a mixture of flying birds, bats, and insects. Because of Earth's curvature, the radar beam is so high at a certain distance (range) that it no longer detects flying animals, thus producing a roughly circular echo around each radar installation. Green circles show the approximate maximum radar range at which flying animals can be detected at or below the height of the top of the rotor sweep of a modern wind turbine. Radar echoes outside those circles are higher than a wind turbine. Typical of such images from large radars, no flyways or migratory corridors are visible (R. H. Diehl, University of Southern Mississippi, unpublished data).

2001; B. A. Cooper and R. H. Day, Alaska Biological Research [ABR, Inc.]), unpublished data), generally it is not possible to separate bird targets from bat targets based solely on flight speeds. Foraging bats sometimes can be separated based on their erratic flight patterns. However, migratory bat species and those that do not engage in erratic flight behavior while foraging may be indistinguishable from migratory songbirds on radar. Visual verification of a sample of radar targets can be accomplished using night-vision devices or thermal imaging cameras and information on the proportion of birds versus bats from a site within the zone of radar coverage can be related to the radar targets (Gauthreaux 1996; Gauthreaux and Livingston 2006; B. A. Cooper and T. Mabee, ABR, Inc., unpublished data). Use of double-sampling or other quantitative methods for estimating detection probabilities (e.g., Program DISTANCE [Anderson et al. 1999]) should be used in such studies to characterize detection biases.

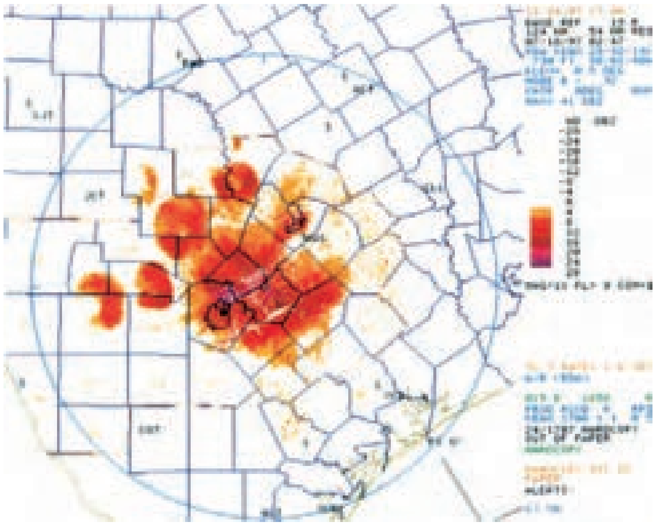


Figure 7. Next Generation Radar (Weather Surveillance Radar-1988 Doppler) images of Brazilian free-tailed bats (*Tadarida brasiliensis*) dispersing nightly from selected cave and bridge roosts in south-central Texas, USA, 18 July 1997. Similar images can be observed when colonial birds disperse from roosting sites early in the morning. Such images make it possible to identify major roosts but also show directions and relative densities of dispersing bats or birds. Data were recorded at an elevation angle of 0.5° (from Kunz 2004).

Because insects also are detected with marine radar, it may be necessary to reduce or eliminate the radar signals from insects if both birds and bats are the targets of interest. Reflectivity from insects in radar surveillance can be reduced by filtering out all small targets (grain size) that only appear within approximately 500 m of the radar and targets with poor reflectivity (i.e., targets that move erratically or inconsistently at locations with good radar coverage) and by editing data prior to analysis by omitting flying animals with corrected airspeeds <6 m per second (Diehl et al. 2003). Application of a 6-m/second–airspeed threshold is based on radar studies that have determined most insects have airspeeds of <6 m per second, whereas flight speeds of birds and bats usually are ≥6 m per second (Larkin 1991; Bruderer and Boldt 2001; B. A. Cooper and R. H. Day, unpublished data).

Energy reflected from the ground, surrounding vegetation, and other solid objects that surround the radar unit typically creates ground-clutter echoes that appear on display screens. Ground clutter can obscure targets, although it can be minimized by elevating the forward edge of the antenna and by siting the radar unit in locations that are surrounded closely by low vegetation, hills, and anthropogenic structures. These objects act as radar barriers by shielding the radar from low-lying objects further away from the radar, while producing only a small amount of ground clutter in

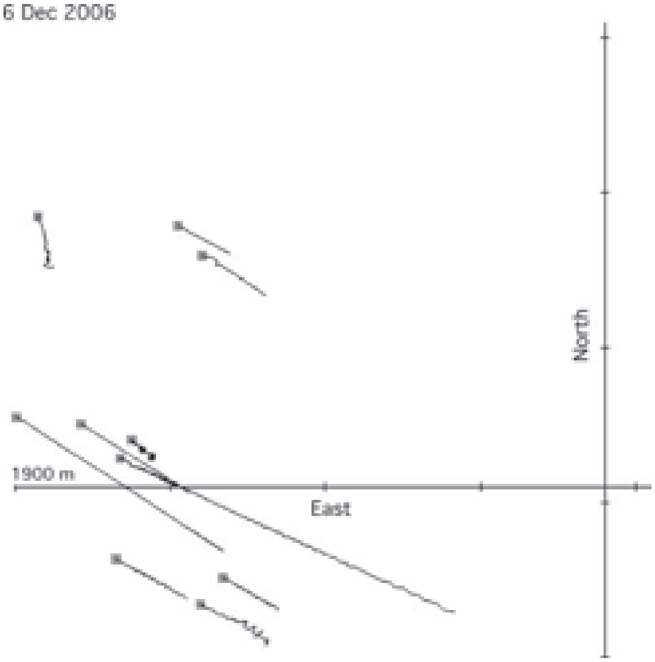


Figure 8. A composite of 10 paths of flocks of waterfowl in late autumn recorded with an instrumentation tracking radar (WF-100) at the Illinois Natural History Survey, USA, recorded 6 December 2006. North is at the top and tic marks are at 1-km intervals. The start of each path is marked with a square. The average error (SE of a linear fit) is <0.4 m for the straight paths; irregularities are largely due to flocks that were partly obstructed by intervening buildings. The northwestern-most track, which is nonlinear, is a flock descending through a dry, micro-weather front. Echo size and modulations (not shown), verification from Doppler radar KILX (Lincoln, Illinois), and time of day and year helped establish the identity of these targets (R. P. Larkin, Illinois Natural History Survey, unpublished data).

Figure 9. Mobile marine (X-band) laboratory equipped with capacity for vertical and horizontal antenna positions (B. A. Cooper, Alaska Biological Research, Inc., unpublished data). Depending upon specific applications, the antenna can be aligned in a horizontal (for assessing direction and passage rate) and vertical mode (for assessing altitude).

the center of the display screen (Eastwood 1967, Williams et al. 1972, Skolnik 1990, Cooper et al. 1991, Larkin 2005).

Simultaneous deployment of marine radar with other methods (e.g., night-vision devices, thermal infrared imaging, and acoustic detectors) should improve our knowledge of nocturnal species activity and our ability to estimate exposure (i.e., use and risk) at proposed sites, and is likely to improve our ability to distinguish birds from bats during monitoring efforts. Species composition and size of biological targets observed with marine radar is usually unknown. Thus, the term target, rather than flock or individual, is currently used to describe animals detected with marine radar. Occasionally, there are situations where a particular species has unique flight patterns that make it possible to identify species-specific targets. For example, marbled murrelets (*Brachyramphus marmoratus*) can be identified on radar with a high degree of accuracy at inland nesting locations (Hamer et al. 1995; Burger 1997, 2001; Cooper et al. 2001, 2006), and Hawaiian petrels (*Pterodroma sandwichensis*) and Newell's shearwaters (*Puffinus auricularis newelli*) were identified as they dispersed to and from colonies in Hawaii (Day and Cooper 1995, Cooper and Day 2003, Day et al. 2003). However, such results should be verified with simultaneous acoustic and visual observations. For studies using marine radar, independent confirmation of

Table 1. Comparison of flight directions, overall passage rates, and flight altitudes of radar targets at central and other sites near Mt. Storm, West Virginia, USA, during autumn 2003 (*n* = no. of nights surveyed).

			Comparison site		Central site		Test statistics[b]		
Variable	**Site**	***n***	$\bar{x}$	**Dispersion[a]**	$\bar{x}$	**Dispersion[a]**	***Z***	***W***	***P***
Flight direction (degrees)	Northern	18	197°	0.58	177°	0.56		1.40	0.496
	Southern	22	191°	0.53	207°	0.42		1.06	0.588
	Eastern	19	193°	0.91	178°	0.31		19.25	<−0.001
	Western	17	219°	0.70	191°	0.36		3.23	0.199
Passage rate (targets/km/hr)	Northern	17	225	57	292	66	−1.49		0.136
	Southern	21	168	31	239	37	−1.96		0.050
	Eastern	21	54	10	220	52	−3.77		<−0.001
	Western	20	127	22	230	47	−2.70		0.007
Flight altitude (m above ground level)	Northern	16	448	29	439	37	−0.52		0.605
	Southern	21	447	31	467	33	−0.57		0.566
	Eastern	16	509	23	427	41	−2.02		0.044
	Western	17	436	20	472	30	−0.97		0.332

[a] $\bar{x}$ vector length (r) for directional data; SE of the $\bar{x}$ for passage rates and flight altitudes.

[b] Test statistics are for Wilcoxon paired-sample test (Z) and Mardia–Watson–Wheeler (Uniform Scores) test (W).

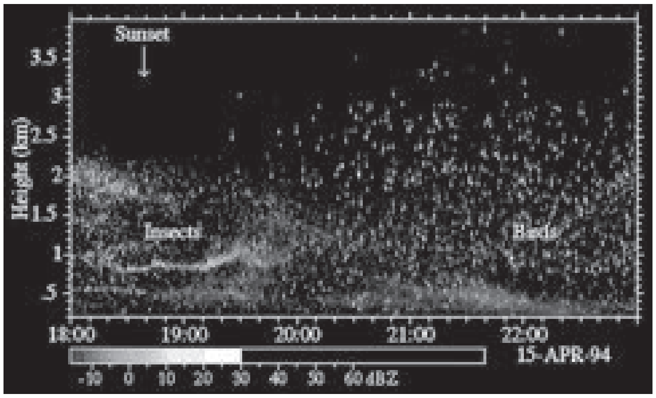


Figure 10. Vertical distribution of airborne fauna, recorded using vertically pointing profiler radar on 15 April 1994. Note that targets identified as insects drop markedly in altitude in the period before sunset until 2400 hours. Most of the larger targets (assumed to be migrating birds and bats) are active at a wide range of altitudes (McGill University, Montreal, Canada 2000).

species identity is needed if species-specific information is being reported.

A concern common to all marine radar studies is that there are locations where even a skilled and experienced radar operator cannot find a suitable sampling site because the zone of primary interest (i.e., at or below turbine ht) is obscured by shadow zones of radar or areas of ground clutter. One of the most important and difficult-to-learn aspects of using marine radar is the selection of sampling locations. The site chosen has important implications for data quality and comparability among sites. Sites must be chosen where ground clutter and shadow zones do not obscure or omit important portions of the study area. One additional technique that allows greater flexibility in siting is to mount the radar on a lift that can be elevated to a desired height above surrounding vegetation (Cooper and Blaha 2002). This technique is particularly useful in relatively flat, heavily wooded areas. To ensure reliable data acquisition, all radar devices must be calibrated before being deployed in the field and users must be fully trained in field-sampling techniques to ensure reliable data collection.

Case study I: nocturnal migration at the Mount Storm wind project.—Mabee et al. (2006*b*) used a portable marine radar system in 2003 to collect information on the migration characteristics of nocturnal birds (particularly passerines) during the autumn migration period in the vicinity of the Mt. Storm Wind Power Project in West Virginia. The objectives were to 1) collect and compare information on flight directions, migration passage rates, and flight altitudes of nocturnal migrants at multiple sites near or within this proposed development; 2) determine if nocturnal bird migration occurred in a broad front; and 3) determine if nocturnal migrants follow the Allegheny Front ridgeline within the proposed project area.

The study design involved using one marine radar at a central site (sampling approx. 6 hr/night) and a second radar unit that could be moved between 4 secondary sites (i.e., northern, southern, eastern, or western locations) and sampled approximately 2.5–3 hours per site per night. All paired comparisons were made with concurrent data from the central site. Observer assignments and starting locations of the second mobile radar laboratory were varied systematically to minimize bias among sites and observers. Flight directions and altitudes at sites along or near the ridgeline were not different from each other, but significant differences in passage rates were observed among some of these sampling sites (Table 1). These data demonstrated that nocturnal migrants crossed rather than followed the Allegheny Front ridgeline (Mabee et al. 2006*b*).

Case study II: nocturnal bird migration at the Stateline wind project.—Situated on privately owned dryland agricultural and grazing land, the Stateline wind-energy facility consisted of 454 Vestas V-47 wind turbine (Danish Wind Technology, Ringkøbing, Denmark) rated at 660 kW each, with 273 turbines located in Walla Walla County, Washington, USA, and 181 turbines located in Umatilla County, Oregon, USA. Several studies were conducted by Mabee and Cooper (2004) to meet the permit requirements in Oregon (state permitting process) and in Washington (county permitting process). After the original permits were granted, the developer (Florida Power and Light Energy [FPLE]) sought an amendment of its county permit in Washington to build strings farther to the north and closer to the Columbia River. Based on negotiations with the Blue Mountain Audubon Society, a condition of permit approval was granted that required FPLE to support these nocturnal studies. The results of this research were evaluated by a technical advisory committee to determine whether the risk associated with siting turbines in this area was tolerable.

The specific hypotheses tested were that the mean flight altitudes and mean target rates were the same near the area where the new turbines were proposed compared to the altitudes and passage rates observed at a control area to the south, away from the Columbia River. To test this hypothesis, 2 marine radar units were used concurrently during 2 autumn and one spring period for 6 hours per night per radar (Mabee and Cooper 2004). Mean passage rates and flight altitudes were compared between the 2 locations using the nonparametric Wilcoxon signed-rank test (Tables 2, 3). No significant differences between mean passage rates and flight altitudes were determined between the 2 locations (Tables 2, 3).

Emerging radar technologies and applications.—The National Aeronautics and Space Administration recently developed high-resolution polarimetric weather radar (NPOL) that promises to be more useful for studying movements of birds and bats than NEXRAD. Because of its high resolution, NPOL can be used to collect data on individual targets and potentially discriminate between insects, birds, and bats. More recent developments of Collaborative Adaptive Sensing of the Atmosphere (University of Massachusetts, Amherst, MA) have designed a series of Distributed Collaborative Adaptive Sensing networks that will sample the atmosphere at altitudes below those typically detected with NEXRAD. Use of data

Table 2. Mean nocturnal rates of movement (targets/hr ± 1 SE) of all targets observed during short-range radar sampling (1.5 km) at Hatch Grade, Washington, USA, and Vansycle Ridge sites, Oregon, USA, during autumn 2000, spring 2001, and autumn 2001. (n = no. of concurrent sampling nights).

		Movement rate			Wilcoxon signed-ranks test		
Season	Location	$\bar{x}$	SE	N	Z	N	P
Autumn 2000	Hatch Grade	58.1	6.3	23			
	Vansycle Ridge	53.1	5.7	23	−0.08	23	0.94
Spring 2001	Hatch Grade	135.3	19.9	43			
	Vansycle Ridge	144.8	18.6	43	−1.2	43	0.23
Autumn 2001	Hatch Grade	64.8	7.6	23			
	Vansycle Ridge	78.8	7.5	23	−2.18	23	0.03

generated using Multiple Antenna Profiler Radar (MAPR) also holds considerable promise for characterizing temporal and elevational profiles of insects, birds, and bats during clear air periods. A MAPR is an advanced radar system being developed at the National Center for Atmospheric Research and Earth Observing Laboratory to make rapid wind measurements of targets within the Earth's boundary layer (Fig. 10). These and other recent radar developments (NRC 2002, Larkin 2005) promise to advance future research on the behavior and activity of airborne organisms, including those in the vicinity of wind-energy facilities (A. Kelly, DeTect, Inc., personal communication).

Acoustic Monitoring of Birds

Ornithologists have long used acoustic monitoring of nocturnal migrants to better understand bird migration (Libby 1899, Ball 1952, Graber and Cochran 1959, Balcomb 1977, Thake 1981). With the publication of type-specimen (archived) flight calls annotated by experts (Evans and O'Brien 2002), the practice of listening to flight calls of birds at night has broadened from being an academic to a practical method of monitoring bird migration (reviewed in Farnsworth 2005).

Because nocturnal calls of passerines (songbirds) are heard most frequently, research has centered on this group (Palmgren 1949, Svazas 1990, Farnsworth 2005). However, birds such as upland sandpiper (*Bartramia longicauda*) and woodcock (*Scolopax minor*) also produce calls at night.

Equipment requirements.—Any outdoor acoustic study poses challenges for sensors and cables, including moisture, vandalism, lightning, and physical abuse. Exclusive of supports such as masts, towers, and kites required to elevate, stabilize, and shelter a multi-microphone array, equipment for an acoustic study of birds involves the following:

More than one microphone is necessary to obtain information on location and flight altitude. An ideal microphone offers good sensitivity (current generated by slight changes in pressure), low internal noise level (e.g., low hum, shot noise, and crackle inside the electronic equipment), resistance to extremes of moisture and temperature, and affordable cost. Sensitivity usually is desired more in one direction than others. A good directional microphone (which varies by cost and portability) will greatly amplify sounds arriving on its axis and be less sensitive to sounds from other directions. Any microphone used for bird flight calls should be sensitive to sounds ranging from about 10 kilohertz (kHz) to 1.5 kHz, preferably lower. Preamplifiers are placed close to microphones to amplify weak electrical signals from the microphone to a level that can be transmitted to a recording device without distortion. Preamplifiers require power to operate, and most will function for an entire night or longer on a set of small batteries.

Unless all equipment is bundled, good weatherproof cables are necessary, not optional, for outdoor work. A complete set of replacement cables will eventually save a night's worth

Table 3. A comparison of mean nocturnal flight altitudes (m above ground level ± 1 SE) of targets observed during vertical radar sampling (1.5-km range) at Hatch Grade, Washington, USA, and Vansycle Ridge, Oregon, USA, during spring and autumn, 2001. Mean altitudes are calculated from total number of targets (n_{total}), whereas tests are based on the number of sampling nights (n_{nights}). Test statistics are Mann–Whitney (U) and Wilcoxon signed-rank (Z) values.

		Flight altitudes			Test results			
Season	Location	$\bar{x}$	SE	n_{total}	U	Z	n_{nights}	P
Intraseasonal[a]								
Spring 2001	Hatch Grade	505.6	4.7	6,296				
	Vansycle Ridge	578.5	4.8	6,521	181.0		40	0.64
Autumn 2001	Hatch Grade	647.4	7.0	2,172				
	Vansycle Ridge	605.6	7.5	2,553		−1.60	14	0.11
Interseasonal								
Spring 2001	Hatch Grade	454.8	33.9					
Autumn 2001	Hatch Grade	649.4	21.9		45.0		36	<0.01
Spring 2001	Vansycle Ridge	481.1	36.3					
Autumn 2001	Vansycle Ridge	610.8	27.9		69.0		32	0.03

[a] One FR-1510 vertical radar alternated between sites (spring 2001), whereas 2 radars sampled concurrently during autumn 2001.

of data. Alternatively, an elevated acoustic sensor (microphone + preamplifier) might be used to transmit a radio signal to a nearby receiving station on the ground. Digital devices such as high-density computer disks are an attractive substitute for the formerly used audiotape or video home system (VHS) videotape. Changing batteries and starting and stopping recording devices can involve substantial personnel costs if many units are deployed. Postconstruction studies may have line power available from wind turbines.

In field applications, the most serious problem will often be the masking of flight calls by ambient noise, including wind noise, insects, wave noise, and turbine nacelle and rotor noise (for postconstruction studies). Because researchers prefer to block spurious reflections into the microphone, the interior of any sound barrier should be made of a nonreflective surface. (Hay bales and closed-cell foam are excellent for absorbing extraneous sounds.) Because most flight calls of interest are produced at moderately high frequencies (>1.5 kHz), sound barriers should be nearly airtight to prevent sound from passing through small openings. Widescreen, open-cell foam is often used to reduce wind noise when sound transducers are exposed to wind.

Acoustic identification of calling songbirds.—Early studies regarded species identification of flight calls at night to be more art than science. More recently, intensive fieldwork has enabled researchers to identify many individual species and a few broader groups of similar-sounding species, but confidence in identification largely depends on the skill of the individuals conducting the studies. Whereas some nocturnal flight calls of birds are easy to identify because they are identical to well-known and distinctive ones heard during the day, discriminating groups of species with flight calls that are similar-sounding to the ear and similar-looking on sonograms is a major challenge that calls for more sophisticated analyses of flight calls beyond detailed changes in acoustic frequency and bandwidth over time. For example, song recognition in some *Catharus* thrushes appears to be accomplished largely by sensing the sound frequency (pitch) ratio of different notes to each other (Weary et al. 1991).

For most field studies relying on acoustic monitoring of bird calls, an important cost question is whether an expert listener will spend hundreds of hours listening to and classifying recordings or if sophisticated voice-recognition software will be used to speed or perhaps assume that task (Larkin et al. 2002). If project design requires a comprehensive analysis of nocturnal flight calls, only partial automation is technologically realistic at the present time. Recent developments in recognition of animal vocalizations, particularly bird song and cetacean sounds, may in the future be adapted for classification of bird calls made in flight (NRC 2007). However, computer methods used to sort flight calls also rely on expert-system algorithms and the experts who develop and refine them. Flight calls that are readily identifiable with confidence include some species of conservation concern (Russell et al. 1991), especially species whose populations are declining.

Enumerating nocturnal songbirds.—Quantification of flight calls of migrating songbirds from acoustic recordings has suffered partly because, even when one can enumerate the calls from various identified species, the volume of air being sampled is difficult to estimate for calls of poorly known intensity (i.e., loudness). However, if researchers concerned with wind power and wildlife issues and using a good acoustic recording system know that flight calls are within the rotor-swept zone, they can state that those calls are at most about 125 m above the ground for a modern, onshore, utility-scale wind turbine. At such distances, neither spreading loss nor atmospheric absorption should be important. Assuming that ambient noise is acceptable, such distances should provide good signal-to-noise ratios, and careful measurement of the directionality of the microphones should permit calculation of the sampling volume. If the passage rate of birds over or among the microphones and within the useful range of heights can also be measured (e.g., using marine radar), and calls per rotor area per time can be estimated.

The numbers of calls vary over the course of a night. Variables include temporal variation from the ground (as birds gain or lose ht), numbers of migrants of different species above a microphone at different times, time-varying shadows of large bodies of water from which no land birds took flight at sunset (W. R. Evans, OldBird, Inc., personal communication), and temporal variation in the rate of calling of individual birds. Like other methods of monitoring nocturnal migrant birds, there is also high variability in the number of calls heard among nights, so that sampling must be conducted over an extended period to achieve confidence in the results (Evans 2000, Howe et al. 2002). Not all migrating passerines produce calls at night, and those that do may not call when they pass over a microphone.

To reliably estimate bird abundance or, more ambitiously, species numbers flying past wind turbines or potential wind turbines, one must count birds, not just flight calls (Lowery and Newman 1955). How often do birds of each species call? What is the relationship between the number of animals and the number of calls (when some animals are silent) and calls per animal (when animals vocalize more than once in the microphone range)? Little is known about the calling rate of migrating birds at night, and no biological theory exists even to formulate an hypothesis. Some observers report binaural tracking of a series of same-sounding notes in the dark, as if a single migrant were calling at intervals passing overhead, indicating that multiple calls from one bird do occur. By contrast, radar data show many more targets aloft than one hears from the ground; thus, most birds (including whole groups of species; reviewed in Farnsworth 2005) apparently do not regularly produce flight calls.

This conundrum is ameliorated by recent radar work showing that, in some instances, numbers of radar targets are

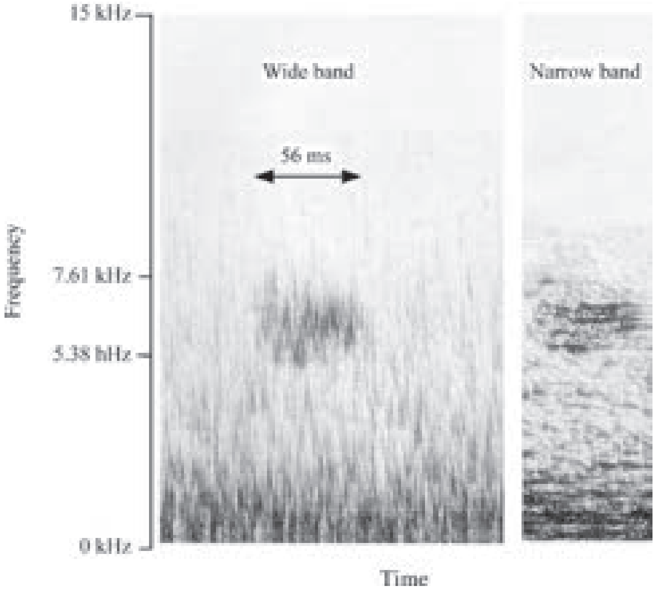


Figure 11. Sound spectrogram (sonogram) of flight call (unknown species) recorded on 22 September 1974 at Millbrook, New York, USA (R. P. Larkin, Illinois Natural History Survey, unpublished data).

correlated empirically with numbers of recorded flight calls (Evans 2000, Larkin et al. 2002, Farnsworth et al. 2004), indicating that flight calls may provide an index of migratory activity, at least in some circumstances. However, the basis for such correlations are yet to be discovered (Larkin et al. 2002), and currently there is no way to know if the finding can be applied generally or only in some situations.

Flight altitude.—Birds at night typically are not vulnerable to wind turbines unless they are in the height range of the rotor-swept zone, or when they are descending to ground level or taking off from the ground. Migrating birds in cruising flight often fly higher than the height of existing wind turbine rotors, and nocturnal aerial displays of birds often do not reach rotor height, with possible exceptions during inclement weather, take-offs, and landings. Bats may fly upward or downward toward wind turbines, but migrating birds do not seem to be attracted to them. However, assignment of flight altitude (agl) is challenging at best. It is not possible to localize a sound using a single microphone. A single-directional microphone is even poorer because the source of a sound that registers faintly may be on the axis of high sensitivity at a great distance or off the axis but still nearby.

More than one microphone and an accurate multi-channel recording or registering device can help detect the calls of flying birds (Evans 2000). If the signal to noise ratio is adequate, the difference in arrival latency of a flight call at different microphones separated in space can help locate the bird making the call. For locating a sound in *N* dimensions, one needs high-quality sounds on *N*–1 microphones. Although marking a distinctive feature of a single call on multiple sonograms and measuring between the marks is often accurate enough, cross-correlation among several identical microphones generally produces better latency measures and better estimates of height, especially when a call contains no distinctive features.

A variant of this technique was used to estimate, or in rare cases measure, altitudes of birds flying over a prospective wind-energy facility in Nebraska, USA (Howe et al. 2002). Investigators used differences in sound arrival-times at 2 microphones vertically aligned at different altitudes on an open-framework tower, permitting conclusions about the altitudes of the calling birds.

Creative and complex variations on the multi-microphone approach include measuring the Doppler effect at each microphone, suspending additional microphones on aerial platforms (e.g., kite balloons), and using several calibrated directional microphones. For example, consider 2 directional microphones both positioned within the rotor-swept zone, spaced one above the other and aimed horizontally in the same direction. Any loud flight call arriving approximately simultaneously at the 2 microphones (depending on their spatial separation) should be from a bird at rotor height, either relatively close to the microphone or in the direction in which they are aimed.

Researchers using single microphones often report an estimated maximum effective range of the microphone for sounds such as bird calls, but fail to distinguish among birds flying above, within, or below rotor height. In this case, the acoustic recordings are of little value except to provide a partial species list of which kinds of birds are overhead, which kinds vocalize on a given night, and to what degree they vocalize. Moreover, flight calls of different species contain sound frequencies that attenuate at very different rates in the atmosphere and, thus, are audible at different maximum distances (see below) and rates of calling are sometimes related to cloud cover and perhaps cloud ceiling.

It is nearly impossible to interpret data gathered using acoustic recordings alone, in part because the biological context of the calls is open to question. Vocalizations are usually presumed to have a social function (Marler 2004), but nocturnal passerines in North America are not thought to fly in flocks the way birds fly in the daytime (Gauthreaux 1972, Larkin 1982, but see Moore 1990), and communication with birds on the ground is not out of the question. A plausible hypothesis has even been made for a height-finding function of flight calls by echolocation of the ground (Lowery and Newman 1955, Griffin and Buchler 1978). (This hypothesis should predict frequent calling when birds pass flow over a ridgeline.) Finally, it is not known whether sounds made by operating wind turbines interfere with recording the calls made by nocturnally migrating birds.

Case example: recorded call quality.—A sound spectrogram (sonogram) from a flight call was recorded on 22 September 1974 using a 2.5-cm sound-calibrated condenser microphone and Nagra analog tape deck (Fig. 11). Ambient noise lies mostly below 2 kHz and the call is in the mid-range of frequencies of calls of migrant birds. The fuzzy appearance indicates a marginal signal-to-noise ratio. Rather than a clear textbook example of a known species, this sonogram is representative of many ambiguous flight calls even when recorded on modern, high-quality equipment. This call lacks distinctive features useful for measuring time of arrival at the microphone or for determining the species of bird with any degree of certainty. A thorough discussion of call quality is treated by Evans (1994).

Case study: pre- and postconstruction monitoring.—Preconstruction studies at wind turbine facilities (Evans 2000, Howe et al. 2002) and postconstruction studies in Nebraska and New York (Evans 2000) have employed multiple microphones to estimate the altitude of passing migrants. Birds flying around tall communication towers on overcast nights are often reported to show a high rate of calling (Avery et al. 1976). Thus, postconstruction studies of calling birds must allow for the possibility that wind turbines attract calling birds, in which case calls may indicate increased vulnerability to collision with the tower structure or blades rather than a record of passing birds. Direct observation of bird flight paths, for example, from detailed tracking radar data, can verify or rule out this possibility.

Acoustic Monitoring of Echolocating Bats

All North American bats emit regular pulses of vocalizations during flight that create echoes used for navigation and for detecting and pursuing prey. Biological sonar, or echolocation, provides important acoustic information that can be detected and used to indicate the presence of bats, and in many cases to identify species. Except for a few species of bats that emit audible (to humans) echolocation calls, most bats vocalize at ultrasonic frequencies (well above the range of human hearing, >20 kHz). Various devices are available for detecting and converting ultrasonic calls of bats into audible sounds or data that can be captured on a tape recorder or a computer hard drive. However, the rapid aerial attenuation of high-frequency calls (Griffin 1971) can bias detection rates toward species that produce low-frequency sound. Bats can also generate sound intensities as high as 133 dB, among the loudest source levels recorded for any animal (Holderied et al. 2005). This renders many species detectable at ranges ≤30 m.

High-intensity call bias.—Because different bat species vary in their loudness (i.e., intensity), those that vocalize at low intensities will be less detectable and, thus, introduce a bias toward those species that produce high-intensity echolocation calls (Griffin 1958, Faure et al. 1993, Fullard and Dawson 1997). Low-intensity echolocators (e.g., *Corynorhinus* spp.), or so-called whispering bats, have a smaller effective volume of detection and, thus, may be missed during acoustic surveys unless they fly close to an ultrasonic detector (within 3–5 m for some species). However, this limited detection range also provides an advantage of increased spatial resolution (e.g., distinguishing between bats at ground level vs. those at rotor ht for acoustic monitoring programs with detectors placed at these different ht above the ground; Arnett et al. 2006, Reynolds 2006).

Bat passes.—Acoustic detection of bats provides a practical and effective means to monitor for bat presence, activity, and relative abundance (Fig. 12). We emphasize relative abundance, because, as with monitoring bird calls, current acoustic monitoring technology cannot determine the number of individual bats detected; it can only record events of detection, termed bat passes, of bats that enter the volume of airspace within detection range. A bat pass is defined as a sequence of >2 echolocation calls, with each sequence, or pass, separated by >1 second (Fenton 1970, Thomas and West 1989, Hayes 1997). Bat passes are commonly used as an index of activity or abundance, but it is important to understand that they do not indicate the number of individuals. One hundred different bats of the same species passing near an ultrasonic detector are generally indistinguishable from a single bat that returns to pass a detector 100 times. Thus, the data from monitoring echolocation calls of bats can only provide population indices or statistical proxies of relative activity or abundance (Hayes 2000).

Quantifying bat passes as an index of abundance can provide guidance as an index of bat occurrence, and with an appropriate study design these data can be resolved spatially and temporally (Parsons and Swezaczk 2008). Recorded levels of activity at any one site are not necessarily proportional to abundance because 1) of differential detectability of bat species, 2) all bat species may not call at the same rate (e.g., *Myotis* vs. *Lasiurus*), 3) all individuals within a given species may not call at the same rates (e.g., migrating vs. feeding), 4) some species may remain out of detection range of a detector despite their presence, 5) variable foraging behavior of some species (e.g., a detector deployed in the open is likely to miss bats that forage along the edge of vegetation), 6) weather and environmental factors, and 7) temporal variations in activity. The latter factor can vary on a scale of days as bats follow local insect activity or while in residence or during migration.

Bats exhibit dynamic movements across the landscape where they typically forage in several different locations each night (Lacki et al. 2007). Nightly activity as measured by bat passes can vary significantly at any one location so that a single night of data will not statistically represent the overall trend of bat activity at that location (Hayes 1997, Gannon et al. 2003). Beyond assessing the presence of a bat, confident identification to species requires even longer survey efforts, typically on the order of weeks (Moreno and Halffter 2001). Longer term temporal variations due to seasonal movements of bats, such as migration, are of vital concern because of the documented relationship between bat fatalities at wind-energy facilities during presumed migration (Johnson et al. 2004, Arnett et al. 2008). For each of these considerations, the best strategy for assessing potential interactions between bats and wind turbines is to implement a long-term acoustic monitoring program, best conducted throughout an entire annual cycle (Apr through Nov in temperate North America) to account for all potential variables and ideally covering ≥3 years to assess both within-year and inter-annual variability.

Acoustic monitoring generally cannot provide information on age, sex, or reproductive condition of bats, although recent evidence suggests that this may be possible for some

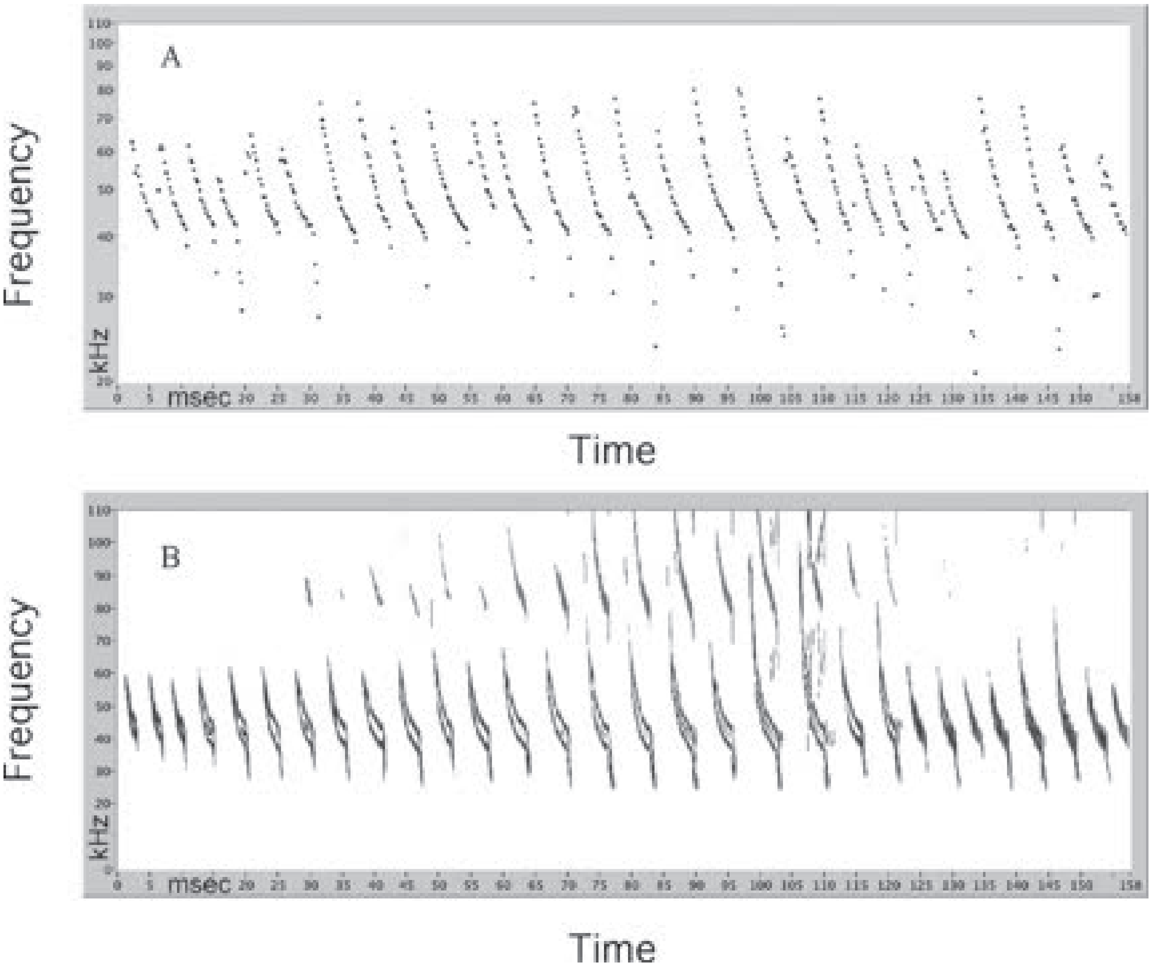


Figure 12. Sonograms of a small-footed myotis (*Myotis ciliolabrum*) flying past a recording bat detector recorded at (Birchim Canyon, near Bishop, CA, USA, 11 Jun 2001). Both panels display the same bat pass rendered with zero-crossing data reduction in the manner of an Anabat bat detector and Analook software (Titley Electronics, Ballina, New South Wales, Australia; A), and in full-spectrum data revealing amplitude distribution using a Pettersson detector (Pettersson Electronik AB, Uppsula, Sweden) and SonoBat software (SonoBat, Arcada, CA; B). In each sonogram the actual time between calls has been compressed to better display the calls. The zero-crossing processed sonogram is plotted with the frequency scale mapped logarithmically as is the convention with Analook, the Anabat processing software (J. Szewczak, Humboldt State University, unpublished data).

species (Siemers et al. 2005). For most species, however, obtaining such data requires that bats be captured, although captures are difficult or impractical to achieve in open environments at the heights of rotor-swept areas. Acoustic, visual, and radar observation methods provide an alternative to capture methods because the former do not interfere with the normal behavior and flight trajectories of bats. In addition, compared with visual methods and radar, acoustic monitoring methods better support long-term monitoring because of their lower data burden and ability to proceed remotely without the need for operating personnel (Reynolds 2006). However, questions remain as to whether migrating bats echolocate continuously while they are flying (Van Gelder 1956, Griffin 1970, Johnson et al. 2005). Thus, methods such as thermal infrared imaging or other night-vision methods should be used simultaneously with acoustic monitoring during expected times of migration until this issue can be resolved.

Acoustic detection and monitoring of bats begins with acquisition of a signal using a microphone sensitive to ultrasonic frequencies. A microphone and detector–recorder system having a frequency response up to 150 kHz suitably covers all North American bat species. The acquired ultrasonic signals must then be translated into a useable form. This can be accomplished by transforming ultrasonic signals into humanly audible tones for manual monitoring, or by directly converting the digital data for storage and processing. Digital data can then be transduced and interpreted by one of 3 primary approaches of increasing signal resolution: 1) heterodyne, 2) frequency division, including zero-crossing, and 3) full-spectrum, including time expansion (Table 4).

Heterodyning reduces the frequency of the signal from the microphone by mixing it with a synthesized tone (Andersen and Miller 1977). This mixing produces an output signal with a frequency based on the frequency difference between the 2 mixed signals (i.e., the beat frequency). The frequency of an artificially generated signal is set by the user by tuning the detector to listen for calls at a particular frequency. Heterodyne units are the simplest ultrasound detector to

Table 4. Methodologies used for ultrasonic bat detection.

Technique	Information obtained	Strengths	Weaknesses
Heterodyne	Bat activity as indicated by bat passes	Relatively inexpensive Sensitive	Labor-intensive monitoring Should be performed manually Requires multiple units for broadband coverage No effective species discrimination
Zero-crossing frequency division	Bat activity as indicated by bat passes Some species discrimination	Low data burden Bat passes automatically registered as separate files Software tools available for processing	Incomplete information content of signals Limited species discrimination
Full-spectrum time expansion	Bat activity indicated by bat passes Near complete species discrimination	Bat passes automatically registered as separate files Software tools for processing Automated species discrimination on the horizon	High data burden Bat passes can be missed if data is acquired by time expansion rather than high-speed data acquisition

implement and typically have excellent sensitivity. Although they produce a signal that allows detection of bat presence, they only render a distorted version of the original signal and the operating principle limits the detection to a narrow bandwidth of about 10–15 kHz above and below the tuned frequency. Combining ≥2 heterodyne units can cover a broader bandwidth, but this increases complexity and there are no existing practical digital recording solutions or computerized analysis systems available to support this approach.

Frequency division reduces the original data generated by sampling at high frequencies needed to interpret ultrasound (a sampling rate of 300,000 signals/sec is required to render a 150-kHz signal). Frequency division can be a numeric division of cycles (e.g., a divide-by-10 approach) that retains amplitude and multiple-frequency information as with a Pettersson D230 detector (Pettersson Electronik AB, Uppsala, Sweden), or this information can be deleted, thus distilling the original to the basic time-frequency domain of the signal's most dominant frequency, as is done with the rapid processing zero-crossing algorithm. Zero crossing is the operating principle used by Anabat detectors (Titley Electronics, Ballina, New South Wales, Australia).

The data reduction of zero crossing accomplished by the Anabat system makes it a practical choice for long-term monitoring projects. A single Anabat unit may generate only one megabyte (MB) of data per night. However, lacking fine-scale resolution essential for discriminating many species, acoustic data generated from Anabat detectors are suitable for monitoring presence and activity patterns, and species identification for some (varies by species and region). More rigorous species discrimination may be accomplished with supplemental full-spectrum acoustic data or by capture methods.

Full-spectrum acoustic data retains the full information content of the signal (i.e., time, multiple frequency content, and signal amplitude) and is thus suitable for detailed bioacoustic analysis including recording of calls for playback experiments, digital signal analysis, and acoustic species identification (Parsons and Szewczak 2008). Playback of full-spectrum recordings at a reduced speed or time expansion (e.g., by a factor of 10) renders a 40-kHz ultrasonic signal as an audible 4 kHz and facilitates recording and data storage using standard audio equipment. Time expansion does not alter the information content of the signal. Pettersson model D240x and D1000x ultrasonic detectors are examples of this type. The rich information content of full-spectrum data generates a large amount of digital data, upward to 100–500 MB of data per night depending on bat activity and data compression (Preatoni et al. 2005).

Acoustic monitoring of bats at wind-energy projects.— Acoustic monitoring of bats at wind-energy projects is best considered in the context of pre- and postconstruction surveys. Activity of bats can be assessed at proposed wind-energy facilities by determining the presence and activity levels and potential temporal events of high activity (e.g., migratory pulses and swarming activity). Ideally, acoustic monitoring should be conducted at the site of each proposed wind-energy facility, although practical limitations prevent coverage at all potential turbine sites. The Alberta Bat Action Team recommended a minimum number of preconstruction monitoring stations placed at each north, east, south, and west periphery of a proposed project area, with one station in the center (Lausen et al. 2006); however, we suggest additional stations be placed in the vicinity of any variations in terrain, especially those that may potentially serve as a flyway (e.g., a forest gap). Alternatively, a systematic sample of the area of interest is recommended with a random starting point along the axis of the wind resource area.

If a 3-dimensional sample survey using a vertical array of bat detectors is deployed (Fig. 13), a grid could be placed over the wind resource area with some systematic selection rule. For example, the minimum number of detectors for a site with 5 turbines would require deployment of 15 bat detectors. For larger projects, more detectors would be needed. An initial site assessment using bat detectors may yield little or no evidence of bat activity at a proposed wind development area. However, thorough temporal sampling

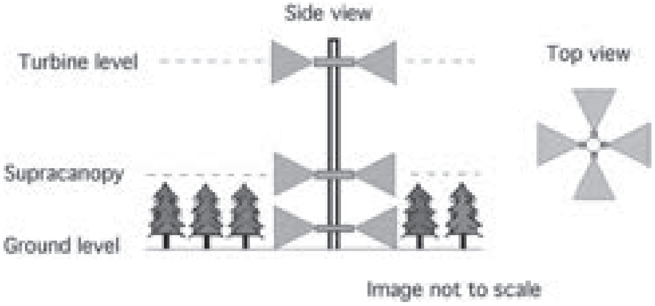


Figure 13. Schematic model showing a vertical array of ultrasonic bat detectors attached to meteorological towers used for assessing nightly migratory and foraging activity of echolocating bats from ground level to the height of the turbine nacelle. (D. S. Reynolds, North East Ecological Services, unpublished data).

Figure 14. Temporary (portable) tower used for a preconstruction acoustic survey at the Casselman River Wind Project, Somerset County, Pennsylvania, USA. Although the tower extends to the local tree-canopy height, bat foraging behavior and activity will likely change markedly when the forest is cleared for construction, creating edge habitat and open space that is not present during the preconstruction period (E. B. Arnett, Bat Conservation International, unpublished data).

would be needed to assess the existence of possible seasonal pulses of activity from migration. With current understanding of bat biology, it is difficult and largely indefensible to conclude that the absence of bat activity on one or a few nights of recordings (as might be typical of a preconstruction survey) supports the appropriateness of a given site for wind facility development.

Given their limitations, ultrasonic detectors placed at ground level cannot detect bats at the rotor height of modern utility-scale wind turbines. Because bat fatalities recorded to date are thought to result mostly from direct strikes by turbine rotors (Horn et al. 2008), it is essential to deploy detectors at the height of the rotor-swept area to effectively assess potential flight activity through the relevant airspace. This height will vary according to the size of the turbine, but where possible, detectors should be deployed ≥30 m above the ground to adequately assess flight activity of temperate insectivorous bats. Where possible, detectors should be placed at existing meteorological towers, which are typically available at both preconstruction and postconstruction wind-energy facilities (Reynolds 2006). In the absence of such structures, temporary towers can be deployed (Fig. 14). In addition to detectors placed at rotor-height, each monitoring location should also have a detector placed near ground level (2–3 m agl) to optimize the volume of airspace for detecting bats, because at this height the detector reception will reach ground level and also detect flying bats flying above it, at least in the range limits of detection. A third detector deployed at an intermediate height would more effectively cover the vertical distribution of expected bat activity. Ground-level detectors will assist in assessing bat presence, and rotor-height detectors will assess potential interactions of bats with rotors (Reynolds 2006).

A lack of documented bat activity at rotor-height during preconstruction surveys does not preclude risk of collision, because bats may be attracted to a site once turbines are constructed (Ahlén 2003, Kunz et al. 2007, Arnett et al. 2008). Thus, surveys at ground level may only serve to indicate presence of bats that could potentially become attracted to the height of operating wind turbines. Alternatively, changes in vegetation cover and conditions from preconstruction to postconstruction may also affect the height at which bats fly, thus leading to more bats feeding, commuting, or migrating through an area, and potentially increasing exposure risk with turbine rotors.

Reynolds (2006) deployed a vertical array of acoustic detectors on meteorological towers that recorded continuously for several nights during the spring migration period at a proposed wind facility in New York. More recently, 2 other studies have deployed detectors at multiple levels on the available meteorological towers and remotely monitored bat activity for several months (Arnett et al. 2006, Redell et al. 2006). Establishing vertical arrays of detectors to allow sampling near or within the rotor-swept area is desirable and recommended by all entities requesting such information for preconstruction studies.

Unfortunately, only a few (e.g., 1–3) meteorological towers are available at most wind-energy projects, which severely limit the ability to distribute sampling points in vertical arrays in any given project. The number of sampling points required to achieve a desired level of precision for describing activity and species composition at a proposed site is currently unknown, owing in part to the relatively small datasets gathered to date. A preliminary analysis of data gathered at meteorological towers and supplemental portable towers in Pennsylvania (Arnett et al. 2006) suggests that 2 or 3 towers typically monitored with detectors during preconstruction studies may fail to adequately represent bat activity on a given site (M. Huso, Oregon State University, unpublished data). Moreover, the number of towers required to reliably predict postconstruction fatality remains to be determined and likely will vary depending on the size of the proposed development.

Despite its limitations, acoustic detection of bats provides a practical and effective means to assess relative activity of

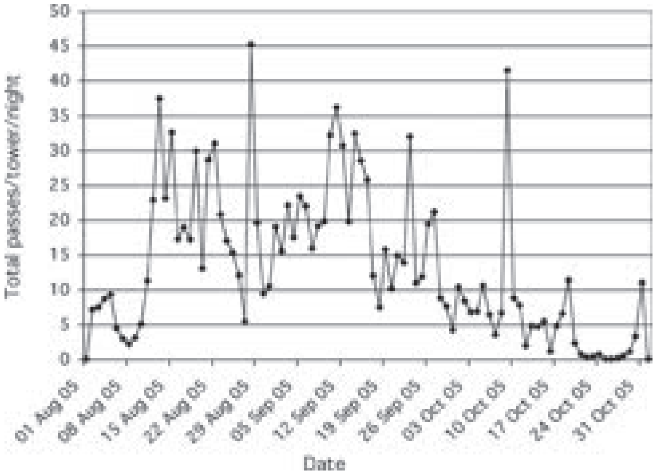


Figure 15. Sample data from a preconstruction acoustic survey conducted at the Casselman River Wind Project, Somerset County, Pennsylvania, USA (1 Aug–1 Nov 2005) showing total number of bat passes per tower per night. These pooled data suggest a potential migratory pulse during October that invites further evaluation on a tower-by-tower basis to assess potential migratory flyways (modified from Arnett et al. 2006).

species that can be identified. Acoustic detectors should be deployed in vertical arrays, with ≥2 levels (at 1.5–2 m above ground and as high as permitted by existing meteorological towers), preferably 3 levels, on all available towers. Sampling additional points with portable towers may be necessary to achieve sufficient spatial replication at a development site. Detailed guidelines for detector deployment and operation are reported elsewhere (Arnett et al. 2006, Reynolds 2006).

Postconstruction acoustic surveys can be used to support carcass surveys and provide information on changes in baseline activity acquired during preconstruction surveys. These data would help verify estimates of risk made during preconstruction monitoring and could aid in assessing success of mitigation measures. Postconstruction monitoring could also reveal unanticipated impacts from project-related changes (e.g., clearing of a forested area). Increased detection of fatalities from carcass surveys may also provide justification to heighten the level of postconstruction acoustic monitoring as a means of evaluating causes and consequences.

By convention, most acoustic surveys of bat activity report mean passes per detector-hour or mean passes per detector-night per tower (Fig. 15). For consistency and comparison, detector-hours should be normalized to hours past sunset for each date considered. This facilitates pooling and comparing data throughout a season or multiple seasons and years. In addition to assessing overall activity, data should be assessed by date and by detector to recognize temporal or spatial peaks in activity that may indicate particular threats to bats. Specific recommendations for how much activity poses a threat and responsive mitigation and avoidance guidelines remain an area of active research (Arnett et al. 2006).

Acoustic identification.—Acoustic identification of bat species poses a greater challenge than would be expected from experience with birds. Unambiguous species recognition using acoustics has remained an elusive goal for many bat researchers. In contrast to birds, whose calls have undergone selection to be different from those of other species, echolocating bats use their calls for acquiring information from the environment (including size, shape, and wing flutter), and in general natural selection has operated to optimize prey detection. For some syntopic species (e.g., *Myotis* and *Eptesicus–Lasionycteris*) there appears to be little selective pressure to emit calls differently among species. Based on current technology, many species appear to lack obvious discriminating differences in their vocal characteristics (Betts 1998, Barclay 1999, Szewczak 2004, Parsons and Szewczak 2008). As an additional complication, bats exhibit considerable plasticity in their vocalizations and can produce call variants that overlap in many parameters with those emitted by other species (Thomas et al. 1987, Obrist 1995, Barclay 1999).

Despite these challenges and limitations, the basic time-frequency characteristics rendered by zero-crossing (Anabat) processed data generally provides sufficient information to recognize acoustically distinctive species (e.g., eastern red bat [*Lasiurus borealis*] and hoary bat (*Lasiurus cinereus*]) and at the minimum place bats into groups having similar acoustic characteristics (e.g., big brown [*Eptesicus fuscus*] and silver-haired bats [*Lasionycteris noctivagans*], and *Myotis* species, respectively).

High-resolution sonograms processed from full-spectrum data reveal subtle attributes and significantly improve species discrimination of bat echolocation calls (Fig. 16; Parsons and Jones 2000, Fenton et al. 2001, Szewczak 2004). The greater information content inherent in full-spectrum data also supports objective species discrimination using automated computer processing. Parsons and Jones (2000) developed an artificial neural network that correctly identified 87% of the 12 most acoustically difficult bat species in the United Kingdom including a suite of *Myotis* species, compared with the performance of discriminant function analysis on the same data set that gave a correct classification rate of 79%. More recent research applying increased extraction of acoustic parameter and ensembles of computer learning systems have boosted the correct automated classification rate of this same data set to 97% (S. Parsons, University of Auckland, personal communication). Systems applying this methodology to North American bats are currently under development. Our understanding of bat behavior continues to improve with advances in detection technology. For example, ultrasonic microphone arrays and video images could be used to determine the 3-dimensional use of space by bats around turbines (Holderied and von Helversen 2003, Holderied et al. 2005).

Predicting bat fatalities.—The preliminary report of an ongoing preconstruction survey by Arnett et al. (2006) provides the first example of a thoroughly designed study involving acoustic monitoring. The study was initiated in mid-summer 2005 as part of a 5-year study to determine patterns of bat activity and evaluate the use of acoustic

Table 5. Fatality and bat activity indices at 5 wind-energy facilities in the United States.

Study area	Inclusive dates of study[a]	Bat mortality (no./turbine/yr)	Bat activity (no./detector/night)	Total detector nights	Source
Mountaineer, WV	31 Aug–11 Sep 2004	38.0	38.2	33	E. B. Arnett, Bat Conservation International, unpublished data
Buffalo Mountain, TN	1 Sep 2000–30 Sep 2003	20.8	23.7	149	Fiedler 2004
Top of Iowa, IA	15 Mar–15 Dec 2003, 2004	10.2	34.9	42	Jain 2005
Buffalo Ridge, MN	15 Mar–15 Nov 2001, 2002	2.2	2.1	216	Johnson et al. 2004
Foote Creek Rim, WY	1 Nov 1998–31 Dec 2000	1.3	2.2	39	Gruver 2002

[a] Sample periods and duration of sampling varied among studies, with no fatality assessments conducted or bat activity monitored in winter months.

monitoring to predict fatalities of bats at a proposed wind-energy facility in south-central Pennsylvania. The primary objectives were to 1) determine level and patterns of activity of different species groups of bats using the proposed wind facility prior to and after construction of turbines, 2) evaluate relationships between bat activity, weather, and other environmental variables, and 3) determine if indices of preconstruction bat activity can be used to predict postconstruction bat fatalities.

The study plan relied on long-term recording of echolocation calls using Anabat zero-crossing ultrasonic detectors (Fig. 17) with spot-sampling using mist-net captures and full-spectrum acoustic recording. This study used a rotation of temporary towers to sample at a large number of proposed turbine sites. Results from the study will be combined with numerous studies currently underway throughout North America that have deployed acoustic detectors to quantify preconstruction bat activity and will later conduct postconstruction searches to estimate bat fatality. The analysis will evaluate possible relationships between bat activity with postconstruction fatality rates from each facility to determine if fatalities can be predicted from preconstruction acoustic data and at what level of precision.

Bat fatality and activity indices.—Five studies have reported on postconstruction surveys using Anabat zero-crossing ultrasonic detectors to support and interpret carcass surveys at operating wind-energy facilities (Table 5). The estimated total number of bat calls per night for each site was positively correlated with estimated fatalities per turbine per year ($r = 0.79$). However, there are several limitations of this type of analysis. The data on echolocation calls reported in these studies did not distinguish among species. Moreover, echolocation calls were recorded at different altitudes at some sites and only at ground level at others. In addition, echolocation call data were all collected after the wind-energy facilities were constructed. Thus, it is unclear whether preconstruction call data would have shown a different pattern. If modifications to forested habitats (thereby creating linear landscapes) or the turbines themselves attract bats, the relationship between preconstruction call rates and fatality rates may not exist or may not be as strong.

Radiotelemetry

Radiotracking (following animals) or radiotelemetry (transmitting other information in addition to an audio signal with miniature VHS transmitters (Millspaugh and Marzluff 2001, Fuller et al. 2005) has the potential to follow the dispersal and migratory paths of known individual birds or bats for long distances. Radiotracking was pioneered with birds weighing about 35 g in the 1960s (Graber 1965, Cochran et al. 1967) and has been used to 1) study the flight of nocturnal passerine migrants with respect to wind and land features (Cochran and Wikelski 2005), 2) recapture birds for measurements of metabolic rate during flight (Wikelski et al. 2003), and 3) transmit wing-beat information (Diehl and Larkin 1998). Where ground-tracking is impractical (e.g., highly mountainous regions), radiotracking from small aircraft holds promise for determining nightly dispersal patterns and migratory routes of some species. Radiotracking of small bats and birds weighing $\geq$15 g over long distances is currently limited by the size of radiotransmitters (e.g., type of signal, and signal strength and duration, which are limited by battery size). A rule of thumb for radiotracking birds and bats is that radiotransmitters should not exceed 5% of the animal's body mass (Aldridge and Brigham 1988).

Global Positioning System (GPS) receivers and transmitters used with Argos satellites are currently too large to be used on passerine birds and small bats (Aldridge and Brigham 1988, Cryan and Diehl 2008). Although radiotracking has been widely employed to follow movements of bats (e.g., Williams and Williams 1970, Wilkinson and Bradbury 1988, Bontadina et al. 2002, Lacki et al. 2007, Amelon et al. 2008), we are unaware of published accounts of long-range migrations of small, migratory bats determined by radiotracking. Large Old World fruit bats (*Pteropus* spp.) have been radiotracked long distances by aircraft (Eby 1991, Spencer et al. 1991), and by satellite (Olival and Higuchi 2006), and ongoing studies in New York and Pennsylvania have been routinely radiotracking Indiana bats (*Myotis sodalis*) with aircraft as they migrate from their hibernacula to maternity sites (A. Hicks, New York Department of Natural Resources, personal communication; C. Butchkoski, Pennsylvania Game Commission, unpublished data; Fig. 18).

Radiotracking by aircraft is an attractive technique for investigating how known individuals of different species of nocturnal birds and bats use the landscape (e.g., Cochran and Wikelski 2005, Holland et al. 2006). Birds and bats have been followed with vehicles (use of vehicles is limited when roads are poor and when a signal is obstructed by terrain), by fixed-base Yagi antennae placed on ridges, and

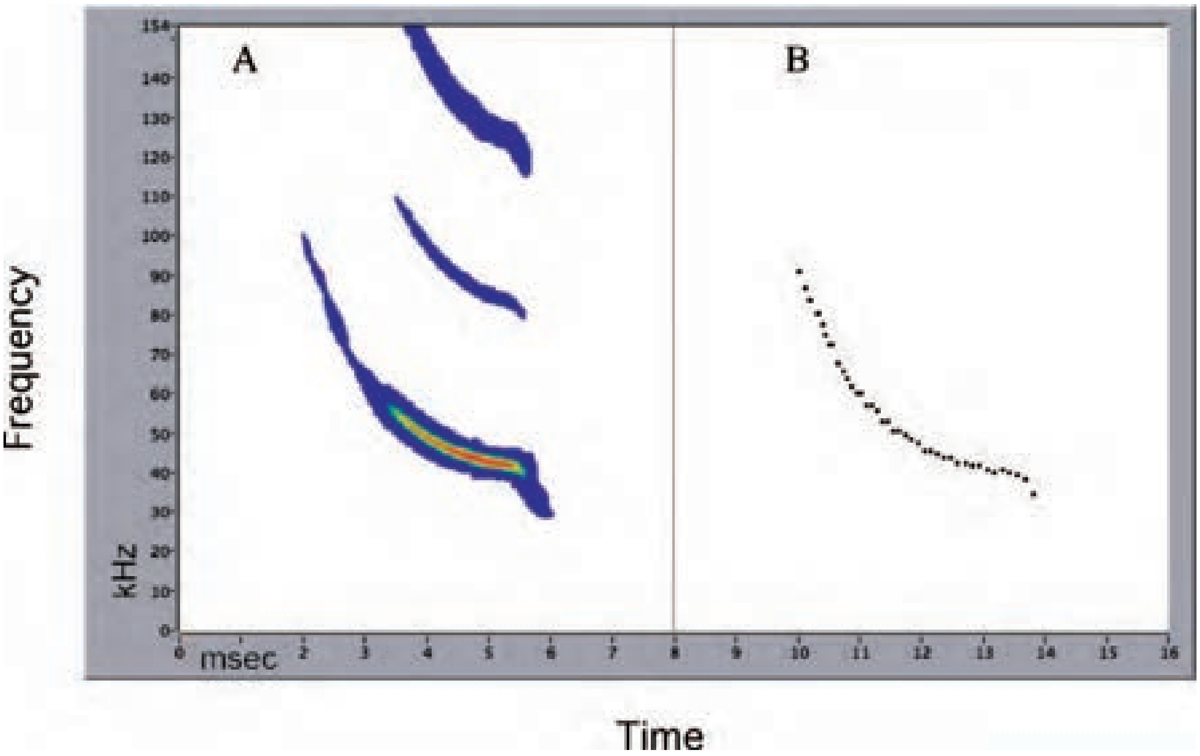


Figure 16. Echolocation call recorded from a western small-footed myotis (*Myotis ciliolabrum*) processed from full-spectrum data (A) and rendered with zero-crossing data reduction in the manner of Anabat (B), Birchim Canyon, near Bishop, California, 11 June 2001. The distribution of amplitude with the call, as mapped by color, can aid in discriminating this species from other *Myotis* species with calls in this frequency range. The presence of harmonics is a useful indicator that can aid in discriminating some species such as silver-haired bats (*Lasionycteris noctivagans*) and big brown bats (*Eptesicus fuscus*; J. Szewczak, Humboldt State University, unpublished data).

with aircraft but with high hourly expense and limitations due to Federal Aviation Administration regulations and public safety. In some situations, it may be possible to track nocturnally active birds and bats from fixed-base Yagi antennae positioned on high places in the area under study (Larkin et al. 1996; R. P. Larkin, Illinois Natural History Survey, unpublished data). Such stations arranged in a picket line (string of stations) could be used to follow flight paths of several migrating bats (known individuals and species) across areas such as mountain ridges. A recent proposal to develop a global small-animal satellite tracking system (Wikelski et al. 2007) holds considerable promise for investigating movements of small birds and bats over large temporal and spatial scales. The scientific framework for this project is outlined in the International Cooperation for Animal Research Using Space initiative. If satellite tracking of birds and bats with miniature transmitters becomes possible (Cochran and Wikelski 2005), this will open a new era of logistical feasibility for following nightly and seasonal movements of bats and birds.

METHODS AND METRICS FOR COLLECTING ADDITIONAL DATA ON NOCTURNALLY ACTIVE BIRDS AND BATS

Capture Methods

Captures of nocturnally active birds and bats may provide valuable information for assessing and confirming the presence of both resident and migrating species, but special training of personnel is required to capture and remove birds and bats from mist nets. Resident bird and bat species are easiest to capture when they forage near the ground, over bodies of water, or within and beneath the canopy of forests (e.g., Kunz 1973, Kurta 1982, Lloyd-Evans and Atwood 2004). Capturing migrating birds and bats during migratory stopovers can provide valuable demographic information (e.g., relative abundance, condition, age, and sex) needed for assessing population status provided that long-term, consistent, efforts are made (Lloyd-Evans and Atwood 2004, Weller and Lee 2007; T. Lloyd-Evans, Manomet Center for Conservation Sciences, personal communication).

Because many bats fly above the height of ground-based mist nets, surveys should employ both ground-level and stacked canopy nets, especially in forested landscapes and in riparian communities or over water holes (e.g., cattle tanks and ponds) located in agricultural and other open landscapes. Developing a capture history that can be used to estimate probabilities of detection and occupancy (e.g., program PRESENCE; MacKenzie et al. 2001, U.S. Geological Survey 2006) requires multiple visits. A single season, even with multiple visits, does not reliably sample bat assemblages or presence of a single species (Weller and Lee 2007; E. B. Arnett, Oregon State University, unpublished data). Unless multiple capture efforts over multiple years are undertaken, species of bats should not be considered absent or to have low relative abundance at a proposed site. Mist

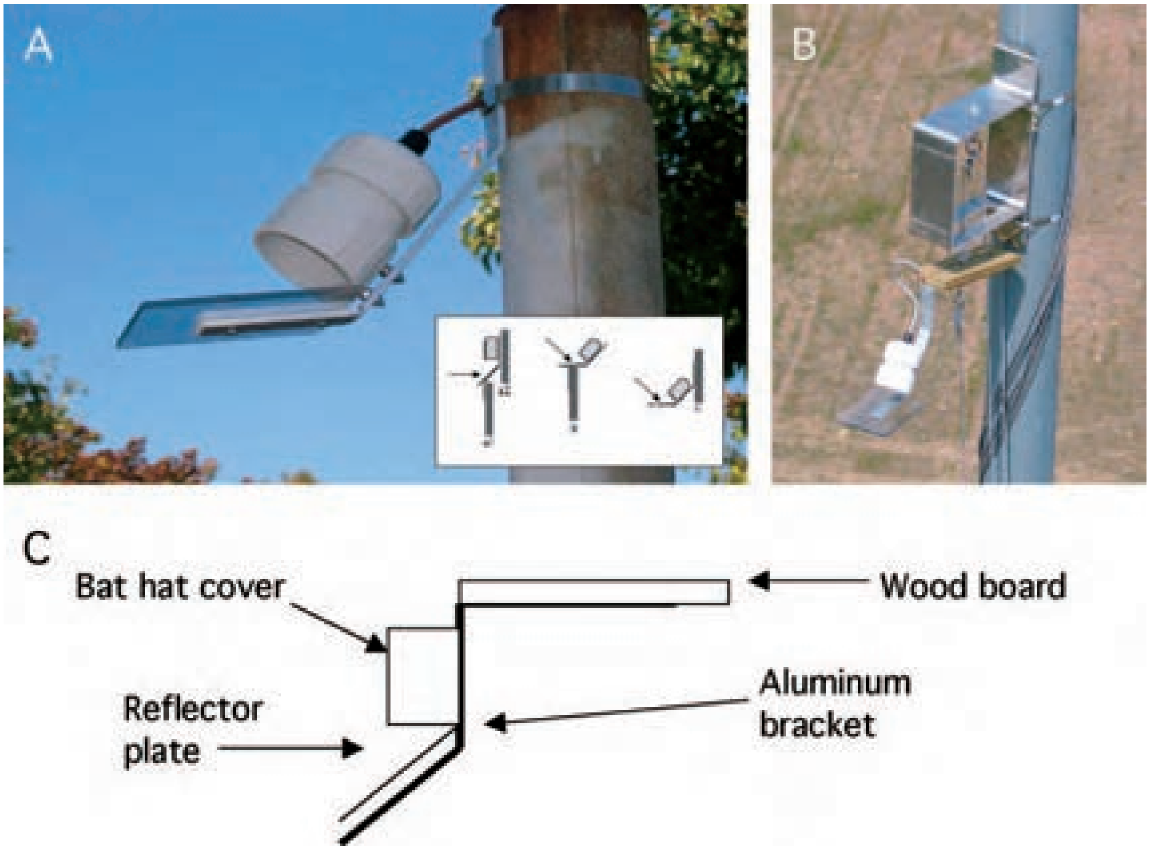


Figure 17. A) Anabat microphones protected by a weather-proof bat hats can be deployed and linked by cables to ground-based data-logging units. When installed, the microphone points downward and receives signals from a clear Lucite or Plexiglas reflector. Three optional designs of brackets are shown for mounting bat hats (see inset). B) Remote microphones protected by weather-proof bat hats are mounted on a carriage that is part of a pulley system. When attached to a tethered pole, this configuration enables retrieval and deployment of microphones (using a crane) from the ground following initial installation. C) Schematic diagram of bracket used to mount a bat hat on the pulley system shown in A (E. B. Arnett, Bat Conservation International, unpublished data).

netting used in conjunction with acoustic detectors (Kuenzi and Morrison 1998) may offer a more complete approach to evaluating presence of species at a site.

Devices and methods used to capture birds and bats have been thoroughly discussed elsewhere (see reviews in Kunz and Kurta 1988, Kunz et al. 1996, Braun 2005, Kunz et al. 2008*a*), so only a brief overview of methods is provided here. Although no single capture method is suitable for all species, mist nets for birds and mist nets and harp traps for bats are the devices used most commonly because they are relatively easily deployed and can be used in a variety of situations.

The choice of capture device for bats should be dictated by numbers of animals present or expected at a particular site or expected to emerge from a roost located near proposed or operational wind-energy facilities. In situations during preconstruction surveys at proposed wind-energy facilities, where the local bat fauna and roost sites are unknown, trapping efforts should focus on expected or potential commuting, foraging, drinking, and roosting sites. Prior assessment of local topography, habitat structure (e.g., foliage density), and visual or acoustic surveys using ultrasonic detectors can often aid in the selection of potential capture sites and deployment of appropriate capture devices. Many of the methods used to capture birds and bats are similar—although some differences exist. For example, if bats are to be captured at roost sites to assess the species present in the vicinity of wind-energy facilities, or to monitor changes in colony size, harp traps are preferable to mist nets (Kunz et al. 2008*a*). Most importantly, efforts should be made to minimize disturbance to bat colonies or colonial-nesting birds.

Mist nets.—A mist net consists of a nylon mesh supported by a variable number of taut, horizontal trammel lines, or shelf strings. Bats and birds are captured after they become entangled in the mesh of the nets. Mist nets are properly deployed when the horizontal shelf strings that support the net are taut horizontally. The netting material should not be extended to its full extent, but should allow some slack between the shelf strings, to allow the formation of bags (or pockets) into which the bird or bats fall upon encountering the net. A bird or bat is captured in a mist net when it flies into the mesh between the shelf strings, and falls into a net bag from which it generally is unable to escape (Braun 2005, Kunz et al. 2008*a*, *b*).

The type and number of nets, and the manner in which they are deployed, can greatly influence capture success. For most applications, ground-level nets are easiest to deploy, but they may bias the sample of captured birds or bats if some species fly (e.g., commute or forage) high in or above the forest canopy. Use of canopy nets can provide researchers access to the aerial space in forested regions where some bats and birds may forage or roost during migratory stopovers (Fig. 19). Compared to ground-level nets, canopy nets may take longer to deploy, but they have the advantage of covering a larger area of vertical space within or beneath a forest canopy, including areas near the ground (Mease and Mease 1980, Hodgkison et al. 2002).

For detailed information on types and sizes of mist nets, preparation of nets for field use, deployment strategies in different environments, types of net poles, removing bats and birds from nets, and methods for dismantling nets, consult published descriptions (Kunz and Kurta 1988, Ralph et al. 1993, Kunz et al. 1996, Braun 2005, Kunz et al. 2008*a*).

Harp traps.—Harp traps are recommended for assessing presence and relative abundance of bats in situations where opportunities for mist netting are ill advised or limited, especially where bats are present in relatively high densities or roost in caves, mines, or buildings near proposed or operational wind-energy facilities. Harp traps have proven successful for capturing bats as they emerge from such roost sites during evening emergence and throughout the night as they periodically return and emerge during intermittent feeding bouts (Fig. 20). These traps consist of one or more rectangular frames, strung with a series of vertical wires or monofilament lines usually spaced about 2.5 cm apart. When a bat hits the bank of wires or lines, it falls into a bag beneath the trap. In situations during preconstruction surveys where the local bat fauna and possible colonies sizes are unknown, harp-trapping efforts should focus on expected or potential commuting, foraging, drinking, and roosting sites.

Personnel assigned to capture bats at wind-energy projects also must secure state and Federal permits to capture and handle birds and bats, especially endangered species. In the case of handling, personnel must be immunized against rabies and wear proper gloves to avoid being bitten. Nets must be tended regularly to avoid injury to captured animals and to prevent damage to nets if too many bats are captured simultaneously. Nocturnally active birds and bats captured at ground level, near roost sites, or in the forest canopy, may not reflect the same composition of species that fly within the rotor-swept area or that are killed during migration.

Pre- and postconstruction surveys.—Capture surveys for bats are frequently employed and often required by government agencies, particularly to assess presence of endangered species. However, not all proposed or operational wind-energy facilities offer conditions conducive to capturing bats and often the number of suitable sampling points is minimal. Sometimes netting efforts occur at water sources off-site or harp trapping at nearby roosts, which may not reflect species presence at or use of the actual site where turbines are to be installed.

Mist netting alone may be inadequate for assessing bat activity at proposed and operational wind-energy facilities and, thus, should be considered a low priority in open landscapes such as grassland and agricultural fields (except when birds or bats are active over and near water tanks and reservoirs). Notwithstanding, mist-netting and harp-trapping are the only available methods that can provide reliable information on sex, age, and reproductive condition, and when possible these techniques should be employed as part of pre- and postconstruction surveys. Captures of birds and bats near roost sites and in habitats below and adjacent to wind turbines can provide valuable information on population variables before and following construction of wind turbines, especially for the collection of tissue samples for DNA and stable isotopes, and for assessing demographic population size, genetic diversity, and geographic origins of bats and birds present during resident and migratory periods.

Estimating Population Size and Genetic Variation Using Molecular Markers

Estimates of population structure, genetic diversity, and demographic and effective population size are important parameters for assessing the dynamics of endangered, threatened, and species of special concern (DeYoung and Honeycutt 2005, Dinsmore and Johnson 2005, Lancia et al. 2005). Estimates of these parameters for both resident and migrating birds and bats are needed to better understand how populations respond to naturally occurring perturbations and anthropogenic factors such as climate change, deforestation, and habitat alteration. Wind-energy development, along with other anthropogenic activities, may have adverse effects on some bird and bat populations by directly causing fatalities and indirectly altering critical nesting, roosting, and foraging habitats. To adequately assess whether fatalities or altered habitats are of biological significance to resident and migrating birds and bats, knowledge of baseline population levels, population structure, and genetic variation are needed. These parameters can be expected to differ among species that are subject to different risks from local and regional environmental factors.

Estimating demographic population size.—Historically, estimates of population size of birds and bats have been derived using a variety of methods, including direct counts, point counts, and other estimating procedures such as capture–mark–recapture methods, photographic sampling, probability sampling, maximum likelihood models, and Bayesian methods (e.g., Bibby et al. 2000, Thompson 2004, Braun 2005, Kunz et al. 2008*b*). Notwithstanding, few statistically defensible estimates of population size for birds and bats have been published, especially for migratory tree-roosting bat species (O'Shea and Bogan 2003; O'Shea et al. 2003, 2004). Direct counts often are not practical for most nocturnally active bird or bat species, in part because these animals are typically small, cryptic, or otherwise difficult to visually census using most existing technologies during 1) daily or nightly emergences from roosts, 2) migratory or foraging flights, or 3) migratory stopovers.

Visual census methods at bat roosts.—When bat colonies are relatively small <1,000), visual censusing may be practical and potentially less disturbing to the colony than other methods (Kunz and Anthony 1996, Kunz 2003, Kunz et al. 2008*b*). Where large numbers of bats are present at roost sites, censusing protocols using thermal infrared imaging cameras can provide reliable estimates of number of bats present (Sabol and Hudson 1995; Frank et al. 2003; Kunz 2003; Betke et al. 2007, 2008) although repeated sampling is required to assess seasonal changes in abundance and colony composition.

Genetic sampling.—Noninvasive genetic sampling can provide valuable information for assessing population parameters of birds and bats at potential risk from wind-energy facilities and other anthropogenic influences. The DNA extracted from skin, hair, feathers, or feces may be used to identify individuals and species, estimate population size, determine sex, identify dietary items, and evaluate genetic diversity and population structure (Thompson 2004, Waits and Paetkau 2005).

Identification of individuals should be the first step when assessing levels of genetic variation within populations. At least 30 individuals from a study population should be genotyped, with 10–25 microsatellite loci. Individual identification based on genetic samples can be used to obtain population estimates based on the minimum known alive or estimates based on mark–recapture methods. Waits and Paetkau (2005) provide technical advice for accurate and efficient collection of genetic data for identification of species, sex, and individuals. Hair and wing tissue (for bats) and feathers and blood (for birds) are the most commonly used sources for noninvasive sampling.

Analysis of mitochrondial DNA (mtDNA) is used for species identification and nuclear DNA (nDNA) is used for individual and sex identification. The DNA extracted from feather samples can be derived from cells attached to the roots of feathers (Smith et al. 2003). Wing biopsies are the most common source of DNA for bats (Worthington Wilmer and Barratt 1992). In these situations, samples for DNA analysis can be collected from live or recently killed birds or bats. Extraction of host DNA from fecal samples is more challenging, and there is no consensus on the most appropriate method to use (Waits and Peatkau 2005).

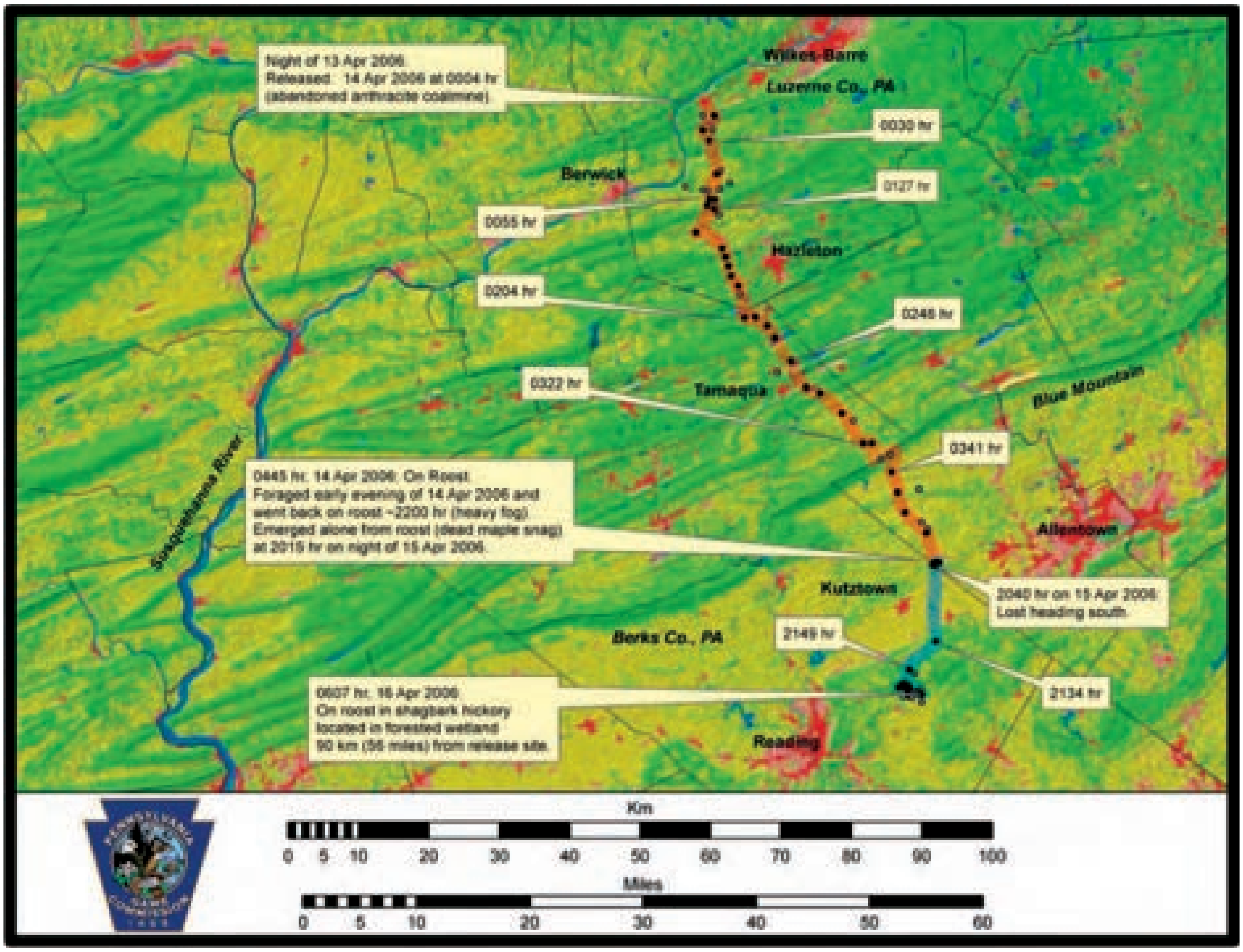
Capture–mark–recapture models have been used to estimate population sizes derived from genetic samples (Waits 2004, DeYoung and Honeycutt 2005). Using this approach, Puechmaille and Petit (2007) compared estimates of colony sizes of the lesser horseshoe bat (*Rhinolophus hipposideros*) based on DNA extracted from feces with independent estimates of colony size derived from nightly emergence counts. Their results indicate that analysis of DNA can provide accurate estimates of colony size even when feces are collected during a single sampling session.

Estimating effective population size.—Estimates of effective population size (N_e) also can be derived from genetic markers. Effective population size provides information on how fast genetic variation is being lost or relatedness is increasing in a population of interest (Leberg 2005). Knowledge of N_e is critical for assessing and managing threatened and endangered species or those of special concern because it provides information on how rapidly a population is losing genetic diversity. Thus, reductions in N_e also are related to reduced population variability. Comparisons of historic and contemporary N_e can be used to assess whether a population is declining (Leberg 2005) and, thus, impacts of anthropogenic-related factors (e.g., fatalities at wind-energy facilities) on the genetic future of populations can be assessed (Lande and Barrowclough 1987).

Large populations typically accumulate more genetic diversity and retain this diversity longer than do small populations (DeYoung and Honeycutt 2005). Because these effects are predictable, it is possible to estimate long-term effective population size based solely on observed patterns of DNA diversity. If a population changes in size, predictable effects on patterns of diversity occur, and these effects are proportional to that change. Thus, significant declines in population size through time can be documented, although there is some time lag between changes in population size and observable effects on genetic diversity. A conceptual description of the coalescent process that results in these effects is provided below. More detailed descriptions and applications are found in Luikart et al. (1998), Roman and Palumbi (2003), Avise (2004), Russell et al. (2005), DeYoung and Honeycutt (2005), and references cited therein.

The genetic variation at any particular gene in a population can be illustrated as a topology or gene tree reflecting the historical relationships or genealogy of the gene copies found in different individuals. The number of mutations (i.e., nucleotide substitutions) separating these variable DNA sequences is a function of the demographic history of the population. Because mutations accumulate through time, sequences that diverged longer ago will be separated by a larger number of mutations than those that diverged more recently. If a historically large population remains large, its gene trees will have many branches of varying lengths that reflect the accumulation and retention of older and younger mutations. If a large population is reduced in size, its gene tree will be pruned. That is, genes reflecting both long and short branches will be lost with the result of less overall diversity. Short branches also will be proportionately fewer in the reduced population because fewer recent mutations occur and they are less likely to be retained because of the smaller population size. Correspondingly, if a population that was historically small expands in size, its gene tree will consist mostly of short branches reflecting the increased occurrence and retention of more recent mutations.

It is important to understand the extent of population-level structuring because it can differ markedly among species (DeYoung and Honeycutt 2005). For example, population genetic studies on the Brazilian free-tailed bat (*Tadarida brasiliensis*) show high levels of genetic diversity and little population-level structuring (Russell and McCracken 2006), whereas other species, such as the lesser long-nosed bat (*Leptonycteris curasoae*), show relatively low levels of genetic diversity and high population structuring.



Night of 13 Apr 2006.
Released: 14 Apr 2006 at 0004 hr
(abandoned anthracite coalmine)

0445 hr: 14 Apr 2006: On Roost.
Foraged early evening of 14 Apr 2006 and
went back on roost ~2200 hr (heavy fog).
Emerged alone from roost (dead maple snag)
at 2015 hr on night of 15 Apr 2006.

2040 hr on 15 Apr 2006:
Lost heading south.

0607 hr, 16 Apr 2006.
On roost in shagbark hickory
located in forested wetland
90 km (56 miles) from release site.

Figure 18. Migration route of an Indiana bat (*Myotis sodalis*) over forested ridge tops in western Pennsylvania, USA. This bat was captured and released at an abandoned coal mine at 0004 hours on 14 April 2006. It was tracked by aircraft traveling in a southeasterly direction, settling in a dead maple snag at 0445 hours. In the early evening of 14 April it foraged briefly and returned to its roost at 2000 hours (due to heavy fog). It emerged from its roost tree at 2015 hours on night of 15 April, but at 2040 hours it was temporarily lost while traveling south (near Kutztown, Berks County). On 16 April it was located roosting in a shagbark hickory (*Carya ovata*) tree in forested wetland 90 km from its release site (C. M. Butchkoski and G. Turner, Pennsylvania Game and Fish Commission, unpublished data).

The implications of these and other studies using molecular markers (Avise 1992, 2004) indicate that different species are subject to different risks from anthropogenic influences and should be studied to assess whether a given species is more or less at risk from changing environments. Sex ratios, effective population size, and genetic diversity are intimately linked. Changes in sex ratios in populations can cause changes in effective population size, and when effective population size decreases, populations tend to lose genetic diversity. Loss of genetic diversity can lead to loss of fitness (DeYoung and Honeycutt 2005).

Estimates of effective population size based on genetic diversity have been applied to a variety of birds and mammals to investigate patterns of change caused by human intervention (DeYoung and Honeycutt 2005). For example, the historical population sizes of humpback (*Megaptera novaengliae*) and fin whales (*Balaenoptera physalus*) prior to hunting by humans were estimated to consist of approximately 240,000 and 360,000 whales, respectively, contrasted to modern population sizes of 10,000 and 56,000 individuals, respectively (Roman and Palumbi 2003). The historical estimate of the effective population size of the gray wolf (*Canus lupus*) prior to human settlement of North America was estimated at approximately 5,000,000, as compared to the current estimate of 173,000 (Vilà et al. 1999). For bats, coalescent analysis indicates an expansion of migratory populations of Brazilian free-tailed bats approximately 3,000 years ago, a date that corresponds with the development of a wetter climate and increased insect availability (Russell et al. 2005, Russell and McCracken 2006). This was apparently followed by an approximately 16-fold decline in estimated population size in more recent times, postulated as a consequence of human activity (Russell et al. 2005, Russell and McCracken 2006).

For the lesser long-nosed bat, the most recent estimate of effective population size was 159,000 individuals (Wilkinson and Fleming 1996). These and other estimates of effective population size reflect the current distributional range of a given species. However, census data on populations also are needed when evaluating cumulative impacts resulting from anthropogenic changes. For example, current estimates of colony sizes for Brazilian free-tailed bat,

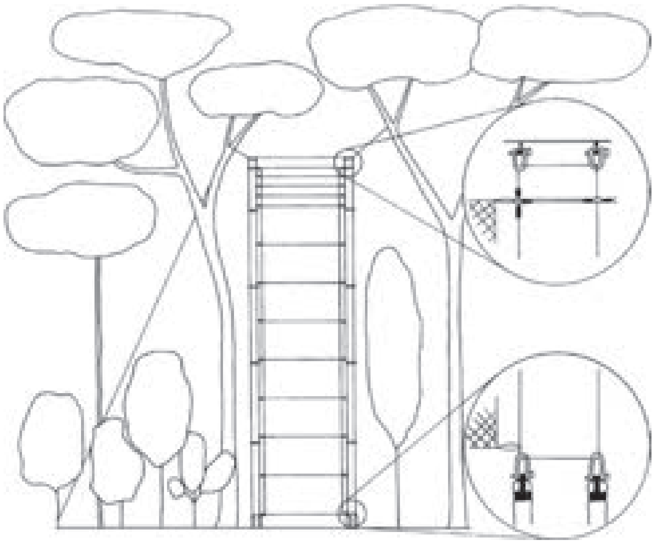


Figure 19. Multiple stacked horizontal mist nets used for capturing bats and birds from ground level into the forest sub-canopy (from Hodgkison et al. 2002).

based on thermal infrared imaging and computer vision technologies, emphasize the importance of establishing baseline levels and for conducting long-term studies for assessing real and projected impacts on local and regional populations (Betke et al. 2008; N. I. Hristov and T. H. Kunz, Boston University, unpublished data).

Migratory tree-roosting bats are especially challenging organisms to census, largely because they are solitary and roost in foliage (eastern red bats and hoary bats) or tree cavities (silver-haired bats; Carter and Menzel 2007). Instead of using traditional marking methods, molecular markers could be used to estimate population sizes after identifying individuals from the DNA obtained noninvasively from samples of feces, hair, or skin tissue. As with traditional methods, the reliability of population estimates based on molecular methods makes certain assumptions (DeYoung and Honeycutt 2005). For example, population size can be under- or overestimated if scoring errors are made when the alleles of heterozygous individuals are not amplified during a positive polymerase chain reaction (PCR), or PCR-generated alleles create a slippage artifact during the first cycles of the reaction (Waits and Leberg 2000). Errors of this type can be corrected by repeating the process of genotyping and comparing genotypes to each other (Paetkau 2003).

There are several potential limitations in using genetic sampling to estimate population parameters from both mtDNA and nDNA markers, including contamination of field samples, identifying enough loci to establish adequate resolution sufficient to distinguish individuals, and genotyping errors. If sufficient data are not collected for an adequate number of loci, then the number of individuals in the population will be underestimated. Increasing the number of loci, with improved resolution, also increases the probability of observing genotying errors.

Figure 20. Harp traps can be used to successfully capture bats as they emerge from or return to roosts such as buildings, caves, and other similar structures (J. Chenger, Bat Conservation and Management, Inc., unpublished data).

Assessing Geographic Origins of Resident and Migrating Birds and Bats Using DNA and Stable Isotopes

Knowledge of geographic patterns of stable isotopes of hydrogen (deuterium [D]: hydrogen [H]) has proven valuable for assessing patterns of migration for some bird and bat species (e.g., Meehan et al. 2001, Cryan et al. 2004, Rubenstein and Hobson 2004, Hobson 2005, Cryan and Diehl 2008). This knowledge is made possible because isotopic signatures present in precipitation are transferred directly or indirectly from green plants to consumers (e.g., insects, birds, and bats).

No other element (except oxygen, which is highly correlated with hydrogen) exhibits such consistent patterns of geographic distribution. The stable isotope ratio of hydrogen, δD ($\delta D = \left[\frac{(D/H)\text{sample}}{(D/H)\text{reference}}\right] \times 10^3$), in precipitation is inversely related to latitude, elevation, and distance from the coast across all continents (Rozanski et al. 1993, Cryan and Diehl 2008). Following shifts in δD between precipitation and primary producers, isotopic signatures typically change systematically across trophic levels (Birchall et al. 2005). Thus, during postnatal growth and molt, δD values of animal tissues are correlated with the hydrogen isotope ratios of local precipitation (δD_p; Hobson and Wassenaar 1997). The relationship between δD_p and the δD values in animal tissues has made it possible for researchers to infer the geographic origins of migratory animals by comparing tissues collected at different seasons and in different parts of their range (Chamberlain et al. 1997, Hobson and Wassenaar 2001, Meehan et al. 2001, Cryan and Diehl 2008).

Kelly et al. (2002) used stable isotopes of hydrogen extracted from the feathers of breeding, migrating, and wintering Wilson's warblers (*Wilsonia pusilla*), and found that δD values were positively and significantly correlated with latitude of collection, indicating that δD values in feathers provided a good descriptor of the breeding latitude. Cryan et al. (2004) also used stable isotopes of hydrogen to infer migratory movements of hoary bats in North America. Using data collected from feather samples, several studies have used both stable isotope and genetic markers to evaluate migratory habits of birds (Clegg et al. 2003, Royle and Rubenstein 2004, Hobson 2005, Kelly et al. 2005, Smith et al. 2005).

The primary limitations of using stable isotopes for assessing migration of birds and bats is that the stable isotope of hydrogen can vary locally, based on differences in precipitation and ground water. Thus, when tissues are collected from birds or bats, samples of precipitation and ground water should be collected at the same time to improve the geographic resolution of isotopic ratios (L. I. Wassenar and K. A. Hobson, Environment Canada, personal communication). Currently, the resolution of isotope ratios of hydrogen in precipitation is relatively crude with respect to latitude, longitude, and altitude, and it may not be possible to precisely identify source areas of breeding birds or bats within a small geographic region. Gannes et al. (1997) appropriately pointed out the importance of validating assumptions when using stable isotopes and calling for laboratory experiments to validate methods.

Collecting tissue samples for DNA and stable isotope analysis.—Living or dead bats collected at or in the vicinity of wind-energy facilities can provide invaluable data for advancing knowledge about the geographic source and abundance of resident and migratory populations. Tissue (via wing biopsies) collected from bats (Worthington Wilmer and Barratt 1996) and blood or feathers from birds (Smith et al. 2003, Waits and Paetkau 2005) can be used for analysis of genetic variation, population structure, for potentially assessing population size using DNA markers, and for assessing the geographic origin of migrants based on stable isotope and genetic analysis. Date, location, species, sex, age, reproductive condition, and standard external measurements for each live, dead, or moribund bird and bat captured or recovered should be recorded.

Use of mtDNA and nDNA sequence data derived from birds and bats killed by wind turbines also offer the potential for identifying closely related or cryptic species. For example, many species of *Myotis* are difficult to identify from either external morphological characters or echolocation calls, yet they can be identified using unique DNA markers (e.g., Bickham et al. 2004, Stadelmann et al. 2007).

Developing collaborations.—Collaborations with researchers experienced in genetic and stable isotope analyses are highly recommended. Carcasses should be collected in part or in their entirety and deposited as voucher specimens in research laboratories associated with universities and natural history museums. In the United States, the American Museum of Natural History, New York, serves as a repository for tissues collected from dead or living bats recovered from beneath wind turbines or collected alive (http://research.amnh.org/mammalogy/batgenetics/; contact N. B. Simmons, American Museum of Natural History). The Conservation Genetics Research Center, Center for Tropical Research, University of California, Los Angeles serves as a repository for feather samples from which stable isotope and genetic analysis of birds can be conducted (http://ioe.uclla.edu/CTR/cgrc.html; contact J. Pollinger, University of California, Los Angeles).

CONDUCTING PRE- AND POSTCONSTRUCTION MONITORING

Many of the methods and metrics summarized above for monitoring nocturnally active birds and bats have been applied during pre- and postconstruction monitoring and research efforts. In this section, we describe basic approaches and protocols to perform pre- and postconstruction monitoring and research, discuss factors influencing and limiting protocol development and implementation, and offer considerations for future monitoring and research.

Preconstruction Studies

Preconstruction assessments at proposed wind-energy facilities generally are initiated from early project evaluations in consultation with state or Federal agencies with respect to wildlife, including potential direct impacts to bird and bat species, especially nocturnal migrants, and threatened and endangered species or species of special concern. Agencies generally request that data be used to characterize wildlife resources in the context of a proposed development, to evaluate the potential impacts from such development, and to the greatest extent possible, determine the location of turbines that will minimize risk to birds and bats. Although these objectives may provide useful information for designing a facility and siting specific turbines, or perhaps aiding in the decision to abandon a project altogether, each project may require a different sampling design, level of sampling intensity, and volume of data to be collected.

Multiple factors may influence preconstruction monitoring and confidence of the data collected as outlined in the original "Methods and Metrics" document (Anderson et al. 1999), as well as other works (e.g., Skalski 1994, MacKenzie et al. 2001, Morrison et al. 2001, Pollock 1991, Pollock et al. 2002). Designing a preconstruction study protocol should begin with clearly defined questions. Thus, a clear understanding of the relevant questions should dictate the sampling design and methods. An inappropriate protocol may result in low power to detect differences (Steidl et al. 1997), failure to account for spatial and temporal variation (Hayes 1997), and pseudoreplication (Hurlbert 1984), all of which can lead to unreliable statistical and deductive inferences. Ultimately, when assessing risks to nocturnally active birds or bats at a proposed wind-energy site, failure to design an appropriate sampling protocol and account for the aforementioned factors may increase the likelihood of a Type II error (i.e., failing to reject a false null hypothesis and concluding no effect when, in fact, there is one).

A fundamental gap in our current knowledge of preconstruction assessment of risk is that no linkages exist between preconstruction assessments and postconstruction fatalities for nocturnal wildlife. Although intensive studies are underway (Arnett et al. 2006), it may be several years before methods described in this document can be used to predict fatalities with an acceptable level of precision, accuracy, and degree of confidence.

In the case of Federally endangered species, the course of action for decision-making is reasonably well-defined. For example, a developer who finds Indiana myotis (*Myotis sodalis*) during mist-net surveys on a project area may enter into voluntary negotiations with the United States Fish and Wildlife Service (USFWS) to receive an incidental take permit under the auspices of a Habitat Conservation Plan under Section 10 (a)(1)(B) of the Endangered Species Act or may chose to abandon the project due to high risk of taking additional endangered species (U.S. Fish and Wildlife Service 2003).

Currently, there is neither a framework nor empirically driven guidelines for agencies or developers to know what 39.7 (±3.1 SD) bat calls per night gathered with acoustic detectors or a passage rate of 116.9 (±8.6) targets/km/hour collected from radar actually mean compared to 119.1 (±26.2) bat calls per night or 350.7 (±77.1) targets/km/hour, except that the activity and variance is about 3 times higher in both cases. Thus, establishing linkages between preconstruction metrics and postconstruction fatality estimates is a vital next step toward being able to predict impacts and, thus, provide the context needed for decision-making. Until additional empirical data are gathered and a relationship between independent variables and the number of fatalities, establishing decision-making criteria will be far more challenging, controversial, and politically charged than improving the sampling designs and quality of information gathered. Considerable uncertainty and risk reside in existing decision-making frameworks, but to best utilize the information gathered during the preconstruction period, such frameworks are needed for stakeholders to agree upon and implement. Established quantitative criteria for decision-making should be based on the best available scientific information and subject to change as new information is gathered, following the fundamental principles of adaptive management (Holling 1978, Walters 1986).

Postconstruction Studies

Many of the methods and metrics described for preconstruction surveys may be used effectively during the postconstruction period, including visual, acoustic, radar, and capture methods. In addition, postconstruction studies require estimates of actual bird and bat fatalities.

Estimating presence and activity.—With few exceptions, postconstruction monitoring has centered on fatality searches. Five postconstruction studies have deployed ultrasonic detectors to record bat activity at operating wind facilities (Gruver 2002, Johnson et al. 2003, Fielder 2004, Jain 2005, Arnett et al. 2006). However, only one study in North America has used thermal imaging cameras to observe bat behavior and interactions with turbines (Horn et al. 2008). Efforts to deploy multiple tools (e.g., acoustic detectors, radar, and thermal imaging cameras) at proposed wind facilities, or those currently operating, are underway in an attempt to test various methods for evaluating preconstruction activity of birds and bats and establishing relationships between flight activity and fatalities (D. Redell, Wisconsin Department of Natural Resources, unpublished data; R. M. R. Barclay and E. Baerwald, University of Calgary, personal communication; A. Kelly, personal communication).

Postconstruction studies using multiple tools (e.g., acoustic detectors, radar, night-vision devices, and thermal infrared cameras) are needed to determine the context and relative exposure of nocturnal animals using the airspace in relation to observed fatalities. Numerous reports and environmental impact statements argue that fatalities of bats at wind-energy facilities are lower in the western United States and within agricultural regions, for example, compared to forested ridge tops in the eastern United States. However, fatalities could be proportionally the same in relation to regional populations or simply the numbers of animals using the airspace at the time fatalities occur. Until this context is established, we suggest that comparisons and extrapolations among regions, especially when varying methods are employed, be viewed cautiously.

Fatality assessment.—Experimental designs and methods for conducting postconstruction fatality searches are well-established (Anderson et al. 1999, Morrison et al. 2001). Although the statistical properties for at least some common estimators have been evaluated and suggested to be unbiased or close to unbiased under the assumptions of the simulations (W. P. Erickson, WEST, Inc., unpublished data), important sources of field-sampling bias should be accounted for to correct estimates of fatalities. Important sources of bias include 1) fatalities that occur on a highly periodic basis, 2) carcass removal by scavengers, 3) searcher efficiency, 4) failure to account for the influence of site conditions (e.g., vegetation) in relation to carcass removal and searcher efficiency (Wobeser and Wobeser 1992, Philibert et al. 1993, Anderson et al. 1999, Morrison 2002), and 5) fatalities or injured bats that may land or move outside search plots.

Temporal distribution of fatalities.—Most estimators assume that fatalities are uniformly distributed, and at independent random times between search days. However, if the distribution of fatalities is highly clustered, then estimates may be biased, especially if carcass removal rates are high. Most estimators apply an average daily rate of carcass removal expected during the study. If most fatalities

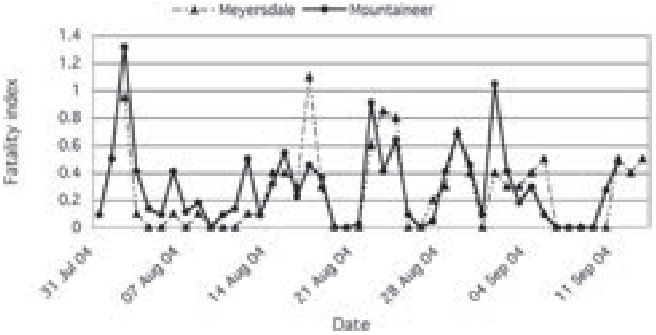


Figure 21. Comparison of daily fatalities (no. of fresh bat fatalities/no. of turbines searched) of hoary bats (*Lasiurus cinereus*) and eastern red bats (*L. borealis*) from the Mountaineer Wind Energy Center, Tucker County, West Virginia, USA (31 Jul–11 Sep 2004) and the Meyersdale Wind Energy Center, Somerset County, Pennsylvania, USA (2 Aug–13 Sep 2004). Fatality index is the total number of fresh bats found on a given day divided by the number of turbines searched that day (Kerns et al. 2005).

occur immediately after a search, they would have a longer time to be removed before the next search, resulting in higher scavenging rates than the average rate used in the estimates. This would lead to an underestimate of fatalities. On the other hand, if most fatalities occur before but close to the next search, the fatalities may be overestimated. Potential biases are minimized by ensuring that some searches are conducted most evenings during the survey period and that they are well-distributed throughout the area of interest (Fig. 21).

Scavenging rates.—The second source of bias in fatality estimation relates to assessing carcass removal rates by scavengers. All wind-energy facilities will be inhabited by a variety of potential avian (e.g., cervids [Corvidae], vultures [Ciconiidae]), mammalian (e.g., skunks [Mephitidae], raccoons [*Procyon lotor*], and coyotes [*Canis latrans*]), and insect (e.g., burying beetles and ants) scavengers, and searches, especially those conducted at less-frequent intervals, may result in highly biased estimates of fatality (Morrison 2002). Past experiments that have assessed carcass removal using small birds as surrogates for bats may not be representative of scavenging for bat carcasses. Two studies conducted by Erickson et al. (2003) and Johnson et al. (2003) used bat carcasses (estimated to be killed the previous night when found) and found similar or lower scavenging rates on bat carcasses compared to small bird carcasses. However, small sample sizes may have biased estimates and limited the scope of inference of these 2 studies. Fiedler (2004) and Fiedler et al. (2007) conducted 6 bias trials during the first phase of development at the Buffalo Mountain Energy Center in Tennessee and found no difference between bird and bat carcasses for searcher efficiency or scavenging time. Notwithstanding, Kerns et al. (2005), however, reported significantly lower scavenging rates on birds compared to both fresh and frozen bat carcasses at the Mountaineer Wind Energy Center in West Virginia. Scavenging should be expected to vary temporally (e.g., seasonally) and spatially from site to site and among both macroscale habitats (e.g., forests vs. grasslands or agricultural landscapes) and microscale vegetation conditions at any given turbine (e.g., bare ground compared to short grass or agricultural stubble).

Searcher efficiency.—It is well-known that searcher efficiency or observer detection (i.e., the rates at which searchers detect carcasses) varies among individuals (Morrison et al. 2001). Searcher efficiency also can be biased by other factors including topography, vegetation, condition of carcasses (e.g., decomposed remains compared to fresh, intact carcasses), weather, and lighting conditions. Searcher efficiency and carcass scavenging should be expected to vary considerably within and among different vegetation cover conditions (Wobeser and Wobeser 1992, Philibert et al. 1993, Anderson et al. 1999, Morrison 2002, Arnett et al. 2008). The use of trained dogs can increase the recovery rate of carcasses, especially in heavy vegetation cover, and offers promise for addressing many questions surrounding bat fatality at wind facilities (Arnett 2006), although dogs undoubtedly vary in their ability to detect carcasses.

Size of search plots.—Sizes of plots have varied among studies. Many recent studies used rectangular search plots with edges of plots a minimum distance from the turbine equal to the maximum tip height of the turbine. Observed spatial distributions of fatalities suggest that most, but not all, fatalities occur in this general area. However, topography, maturity of vegetation, size of carcass, wind direction, and other factors likely affect the distribution. This distribution can be used to approximate the number of fatalities missed (Kerns et al. 2005; Arnett et al. 2008; W. P. Erickson, personal communication). Most studies have shown a tighter distribution of bat fatalities around the turbine compared to birds (Kerns et al. 2005). Additional factors affecting the precision and accuracy of fatality estimates include search effort, including the number of turbines searched, intensity of searches within search plots, and the experience of observers (Anderson et al. 1999).

Search protocols.—Fatality search protocols have varied considerably among studies. Sampling methods and duration for 21 postconstruction studies conducted in North America are summarized by Arnett et al. (2008). Fatality searches usually are conducted on a systematic schedule of days (e.g., every 1 d, 3 d, 7 d, or 14 d) but rarely have daily searches been employed (Kerns et al. 2005). More intensive searches often are performed during the spring and autumn migratory periods, whereas summer breeding surveys sometimes are less frequent or not conducted at all. By contrast, when they are conducted, most spring and autumn postconstruction carcass searches at communication towers are performed nightly (Manville 2005).

Although there are multiple approaches to performing searches (e.g., line transects, circular plots), any protocol that is used must thoroughly quantify the aforementioned sampling biases to obtain reliable estimates. Most fatality studies to date have poorly accounted for searcher efficiency and removal by scavengers, especially for bats (NRC 2007, Arnett et al. 2008). Some studies adjusted fatality estimates based on a single trial for searcher efficiency and scavenger removal using small samples of bird and bat carcasses, and on ≥2 occasions these trials occurred outside of the migratory periods.

There is a clear need for rigorous implementation of search protocols that can yield reliable estimates of bird and bat fatalities. We recommend that all postconstruction monitoring be designed to address ≥2 common objectives. First, search protocols should be conducted so that estimates of fatalities can be compared across different landscapes and habitats both within and among regions. By standardizing protocols for fatality searches, comparable estimates can be achieved and will be useful for understanding different levels of risk. Search intervals could vary from 3 days to 7 days, as long as standard search methods (we suggest line-transect sampling) are employed and sampling biases (e.g., search efficiency and scavenger removal) are adequately accounted for. The total area searched also should be accounted for and similar visibility classes need to be established (see Kerns et al. 2005).

Second, establishing patterns of fatalities in relation to weather variables, turbine characteristics (e.g., revolutions/min) and other environmental factors is fundamental to understanding wildlife fatality and developing solutions (Kunz et al. 2007). Thus, more intensive (nightly) postconstruction sampling should be conducted at sites where relatively high bat fatalities are expected for ≥33% of all turbines, to gather data required to meet this objective. Specific methods and suggestions for establishing and conducting sampling protocols are summarized in Kerns et al. (2005) and Arnett et al. (2008).

MANAGEMENT IMPLICATIONS

Requirements and implementation of preconstruction monitoring are far less consistent than postconstruction fatality-monitoring protocols. Some states have no requirements for preconstruction surveys, whereas others have minimum requirements to survey for threatened, endangered, or species of concern. However, most available guidelines for assessing potential impacts of wind-energy development on wildlife are voluntary (U.S. Fish and Wildlife Service 2003). With few exceptions, preconstruction studies have been conducted for less than a full year or active season, and some postconstruction surveys have only included a few days or weeks during assumed times of the year when risks may be highest (e.g., migratory periods). Below we provide an overview of methods that we consider important for the study of impacts of wind-energy facilities on nocturnally active birds and bats (Table 6).

Visual Methods

Night vision goggles and scopes, video cameras, and thermal infrared cameras are valuable tools for monitoring for the presence and activity of nocturnally active birds and bats at wind-energy facilities. Results derived from these tools, combined with appropriate metrics, are important for characterizing activity of birds and bats in both pre- and postconstruction studies associated with wind-energy projects. Deployment of these tools requires adequate knowledge and training of individuals charged with their use and maintenance, the need for periodic calibration, and a full understanding of the limits of detection.

Proper planning and reliable monitoring using visual methods can provide important information about the abundance, frequency, and duration of bat activity in both proposed and operational wind-energy facilities. We recommend that future monitoring studies of nocturnally active birds and bats deploy thermal infrared cameras in concert with acoustic studies to address questions about the postulated causes of bat fatalities at wind turbines. Results from these studies could then be compared with results from other types of monitoring (e.g., radar) to evaluate potential risks to both resident and migrating birds and bats in the vicinity of wind-energy facilities. In particular, thermal infrared imaging holds considerable promise for evaluating the hypothesis that turbines attract bats or insects. For this approach, ≥2 synchronized high-resolution thermal infrared cameras should be used to record the interaction of bats and birds in finer spatial and temporal scales. Such imaging could help researchers visualize, for example, when and how bats interact with stationary and operational wind turbines and, thus, inform owners, operators, and decision-makers how best to develop mitigation strategies.

Chemilumnescent and LEDs have been used successfully for observing the foraging behavior of bats and for validating echolocation calls from different species. Light tags can be used most effectively to observe bats when they fly in open areas, in flyways, and along forest edges and, thus, they may be particularly valuable for assessing bat activity in the vicinity of many wind-energy facilities and for observing responses of flying bats to both stationary and operational wind turbines.

Radar

Radar is a powerful tool for studying the movement of flying animals. Weather surveillance radars (e.g., NEXRAD) can provide valuable information on broad-scale patterns of migration, colony locations of birds and bats, nightly dispersal behavior, and location of stopover sites for migrating species. However, to obtain passage rates of birds or bats within turbine height (i.e., no. of birds [or bats]/km/hr that are below approx. 125 m agl), we recommend using a marine radar system (to provide passage rates, flight directions, flight path, and altitude information) in tandem with visual techniques (to help distinguish birds from bats). To determine if comparisons can be made among studies from different radars, parallel studies are needed to compare and calibrate the various radar systems, settings, and sampling regimes. Postconstruction studies at wind-energy facilities using carcass searches conducted concurrently with assessments of passage rates using visual and acoustic methods are needed to determine the relationships among passage rates in the rotor-swept zone, weather conditions, and bird and bat fatalities. Limitations of NEXRAD and marine radar include 1) inability to consistently separate migratory birds, bats, and fast-flying insects, 2) inability to determine species identity of most targets, 3) echoes from

Table 6. Tools for detecting, tracking, and assessing presence and activity of flying birds, bats, and insects (modified from Larkin 2005).

Equipment	Range	Identification[a]	Passage rates	Ht information	Cost
Moon watching	Observer-dependent	+ Skilled observers can identify many types of birds and discriminate birds from bats + Insect contamination rare; butterflies and moths can be identified	2 d before and 2 d after full moon and with no cloud cover	Very crude	A good telescope of ≥20× is required. Labor-intensive; $2,000/unit
Ceilometer (spotlight)	<400 m	− Poor for small targets − Insects can sometimes be confused with birds and bats	Yes, but light may affect flying animals	Very crude	Inexpensive but labor-intensive
Night vision (image intensifier)	Good equipment: small birds at 400 m Inexpensive equipment: shorter range	− Inexpensive equipment: poor + Good equipment: better + Discriminate birds, bats vs. insects nearby	Yes	Very crude	Relatively expensive if high-quality equipment used: $1,500/unit
Thermal infrared imaging cameras	Depends on equipment; can detect some birds at 3 km	Size but not species + Discriminates birds, insects, and foraging bats + Migrating birds and bats	Excellent when altitude of target is known	Coarse when calibrated with vertically pointing radar and then used alone	Expensive if high-quality equipment used: >$75,000/unit
NEXRAD, Doppler weather surveillance radar	10–200 km	+ Can discriminate targets by speed if winds are known + Waterfowl and raptors vs. other birds and bats + Insects slower than songbirds	Good in the infrequent cases where a radar siting is opportune	Very coarse with poor low-altitude coverage	Data are available at no cost; skilled labor for analysis
Marine (X-band) radar	30 m–6 km with proper siting of unit	+ Bird and bats vs. insects − Birds vs. bats straight flight: unknown	Good to excellent	Unmodified marine radar antenna in vertical surveillance: yes Parabolic antenna: yes	Specialized; expensive if done correctly Skilled labor for analysis
Tracking radar	100 m–20 km	Vertebrates vs. insects; birds vs. bats in development excellent (stationary beam mode)	Excellent		
Audio microphones for birds	400 m; depends on ambient noise	+ Some nocturnal songbird species + Data include no insects	Only some species call and quantification is assumption-ridden	Microphones: single: no; arrays: possible	Recording equipment inexpensive, analysis expensive
Ultrasound microphones for bats	<30 m; depends on humidity	− Bats may or may not emit sounds + If they do, may be species-specific	No, only presence–absence Many unknowns at current state of knowledge	Some; depends on microphones and placement	Moderate costs: $2,500/unit
Radiotracking	0–4 km	Excellent	Poor	Crude	High

[a] + indicates capability, − indicates a lack of capability.

surrounding objects can obscure large parts of the screen, 4) inability to find suitable marine (mobile) radar sampling sites, and 5) difficulty of detecting small birds and bats aloft during periods of heavy precipitation.

Acoustic Monitoring of Nocturnal Migrating Songbirds

Recording calls of birds that migrate at night permits identification of many species and similar-sounding groups of species by experienced listeners, but this method does not give a direct indication of numbers or rates of passage. Because the rate of calling varies greatly from night to night, extended sampling periods are needed. To obtain data pertinent to the altitude of birds flying near wind turbines, ≥ 2 microphones are needed to localize the source of calls. The most important practical limitation in assessing bird calls will likely involve interference from ambient sounds at field sites. Advances are being made in sound localization and what determines which species are calling and how often they do so.

Acoustic Monitoring of Echolocating Bats

Acoustic detection of bats provides an effective method for assessing bat presence and activity. Because ultrasonic sounds are produced above the range of human hearing, it is important to sample the ultrasound environment prior to establishing a detector placement. A 10-m shift in microphone placement can often make the difference between acquiring useful and useless acoustic data. The ideal recording environment includes anechoic conditions that are thermally homogeneous, without wind, and free from ambient sounds of rustling leaves, falling water, or calling insects. Unfortunately, these conditions are rarely encountered outside of a sound studio and, thus, field-acquired data may be compromised. Successful acoustic monitoring of echolocating bats during pre- and postconstruction periods depend on instrumentation that provides high-quality, distortion-free data. Owing to the limited range of existing ultrasonic detectors, placement of ultrasonic detectors both below and at the height of the turbine rotors will be required to reliably detect presence and activity of bats at proposed and operational wind-energy facilities. Postconstruction studies at wind-energy facilities that include concurrent acoustics monitoring and carcass sampling are needed to determine the relationship among passage rates in the rotor-swept zone, weather conditions, and bat fatalities.

Radiotracking

Radiotracking of small, nocturnally active birds and bats using aircraft promises to provide the most valuable information for assessing regional movements and long-distance migration in relation to assessing impacts of wind-energy facilities. Knowing when and where nocturnally active birds and bats navigate over and within natural and human-altered landscapes promises to provide important information that could help guide decision-makers with respect to the siting of wind-energy facilities in order to avoid or minimize risks to both resident and migrating species.

Capturing Birds and Bats

At times, it will be necessary to capture birds and bats in the vicinity of wind-energy facilities to confirm the presence of species that cannot be detected by other means. Knowledge obtained from capturing birds and bats in the vicinity of proposed or operational wind-energy facilities, during summer resident periods or migratory stopovers, can provide valuable demographic information needed to assess long-term population trends including possible changes in sex and age ratios, breeding condition, population size, and genetic variation in response to possible adverse impacts of wind turbines. Choice of capture device will be dictated by the taxa of interest, landscape characteristics, and numbers of animals expected at a particular site or expected to return to or emerge from a roost located near proposed or operational wind-energy facilities.

Collecting Tissue Samples for DNA and Stable Isotope Analyses

Knowledge of geographic patterns of stable isotopes of hydrogen makes it possible to identify the geographic source of birds in temperate regions by comparing the isotope ratios in precipitation with those found in animals captured or recovered during migratory stopover areas or in over-wintering sites. Dead and injured birds and bats collected at or in the vicinity of wind-energy facilities can potentially provide valuable data for assessing demographic and effective population sizes, genetic variation, and the geographic origin of resident and migratory populations. Carcasses should be collected in part or in their entirety and deposited as voucher specimens in research laboratories associated with universities and natural history museums. Information about carcasses found beneath wind turbines should be recorded with respect to date, location, species, condition, sex, age, and reproductive status. Collaborations with researchers experienced in genetic and stable isotope analyses are strongly recommended.

Pre- and Postconstruction Monitoring Protocols

The methods and metrics summarized above provide guidance for monitoring and researching nocturnally active birds and bats at wind-energy projects. Preconstruction assessments should be conducted in consultation with State and Federal agencies, including potential direct and indirect impacts on both resident and migrating birds and bats. Depending upon location, topography, type of vegetation and number of proposed wind turbines, each project will quite likely require a different sampling design, level of sampling, and amount of data collected. A clear understanding of the potential influence of topographic variation, altered land cover, local weather conditions, and other relevant variables will dictate the sampling design and methods used at each proposed or operational wind-energy facility.

At present, a fundamental gap exists between preconstruction activity of nocturnally active birds and bats and postconstruction fatalities. Given this knowledge gap, quantitative studies on both the presence and activity of nocturnally active bird and bats are needed, including estimates of population size and variation, to provide the best scientific information available to confidently inform decision-makers and other stakeholders concerning risks posed by wind-energy facilities. Rigorous assessments of fatalities reported during the postconstruction periods are needed that incorporate corrections for both searcher efficiency and scavenging biases so that reliable estimates of cumulative impacts can be made. Pre- and postconstruction monitoring protocols are needed that consider both natural variation in population size and seasonal and nightly activity levels. Without a clear understanding of this natural variation, reliable interpretation of risks and actual effects of wind turbine facilities to nocturnally active bird and bat populations will remain elusive.

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