# Chapter 21
# Impacts of Wind Energy Development on Bats: Implications for Conservation

**Edward B. Arnett and Erin F. Baerwald**

**Abstract** At a time of growing concern over the rising costs and long-term environmental impacts from the use of fossil fuels, wind energy has become an increasingly important sector of the electrical power industry. However, large numbers of bats are being killed at utility-scale wind energy facilities, and these fatalities raise important concerns about cumulative impacts of proposed wind energy development on bat populations. We discuss our current state of knowledge on patterns of bat fatalities at wind facilities, present new information on cumulative fatalities in the USA and Canada, and present findings from mitigation studies. Given the magnitude and extent of fatalities of bats worldwide, the conservation implications of understanding and mitigating bat fatalities at wind energy facilities are critically important.

## 21.1 Introduction

Given a changing climate (Inkley et al. 2004; Schlesinger and Mitchell 1987) and rising costs and long-term environmental impacts from use of fossil fuels, the world is increasingly exploring alternatives to supply emission-free energy (Bernstein et al. 2006; Kunz et al. 2007; McLeish 2002). Wind power is one of the fastest growing renewable energy sources (Fig. 21.1), in part due to recent cost competitiveness with conventional energy sources, technological advances, and tax incentives (Bernstein et al. 2006). At regional to global scales, the effects of wind energy on

E.B. Arnett (✉)
Theodore Roosevelt Conservation Partnership, 3604 Canter Ln., Loveland, CO 80537, USA
e-mail: earnett@trcp.org

E.F. Baerwald
Department of Biological Sciences, University of Calgary,
2500 University Drive N.W., Calgary, AB T2N 1N4, Canada
e-mail: efbaerwa@ucalgary.ca

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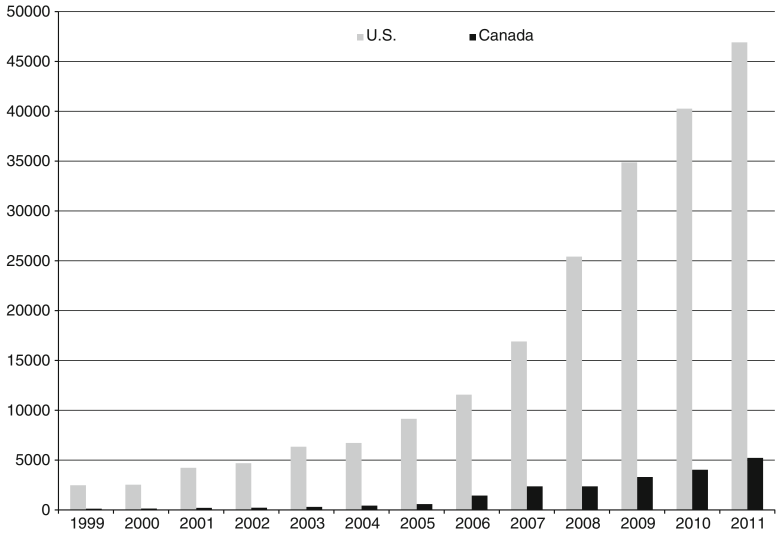


**Fig. 21.1** Installed wind energy capacity (MW) from 1999 to 2011 in the USA and Canada (from the Energy Information Administration 2011, http://www.eia.gov/forecasts/aeo; and the Canadian Wind Energy Association, http://www.canwea.ca/farms/wind-farms_e.php)

the environment are positive, owing to reductions in mining activities, air pollution, and greenhouse gas emissions associated with nonrenewable energy sources (NRC 2007). However, wind energy development is not environmentally neutral and impacts on wildlife and their habitats are of increasing concern (Arnett 2012; Arnett et al. 2007; Kunz et al. 2007).

Fatalities of bats (Fig. 21.2) occur at wind energy facilities worldwide but generally received little attention until 2003 when high fatalities were documented at the Mountaineer Wind Energy Center, West Virginia (Arnett et al. 2008), followed by numerous other studies documenting similar losses (e.g., Arnett et al. 2008; Baerwald and Barclay 2009; Dürr and Bach 2004; Rydell et al. 2010). These fatalities raise concerns about population-level impacts (Frick et al. 2010; Racey and Entwistle 2003; Winhold et al. 2008) with wind energy development cited to increase worldwide (Energy Information Administration 2011). Bats are long lived and have exceptionally low reproductive rates, and their population growth is relatively slow, which limits their ability to recover from declines and maintain sustainable populations (Barclay and Harder 2003). The high mortality caused by wind facilities poses a serious threat to bats unless solutions are developed and implemented.

### *21.1.1 Background*

Arnett et al. (2008) reviewed 21 post-construction fatality studies conducted at 19 facilities in the USA and Canada. In this chapter we further synthesized information

**Fig. 21.2** A hoary bat found dead at a wind energy facility in the Northeastern Deciduous Forest region (Photo by E.B. Arnett, Bat Conservation International)

from 122 post-construction fatality studies (2000–2011) from 73 regional facilities using only data from studies published in scientific journals or unpublished reports made publicly available through an organization, agency, or online sources. We do not focus extensively on characteristics of surrounding habitat, turbines used, duration of studies, methods employed, and how field sampling biases were accounted for, as did Arnett et al. (2008), but rather focus on patterns of fatality, unifying themes, estimates of fatality and potential cumulative impacts, mitigation, and future research needs.

We categorized regions based on broad habitat characterizations (e.g., forest, shrub-steppe habitats) that potentially influence how bats may generally use an area and considered features that would serve as migration corridors (i.e., topography, geographic landscape, riparian corridors) or affect bat behavior relative to the amount of installed wind capacity. This resulted in 12 regions across the USA (including Alaska and Hawaii) and Canada (Table 21.1). We only present information for five regions because publically available studies were not available from remaining regions or no wind energy facilities have yet been constructed.

We did not have access to data required for quantitative meta-analysis to develop estimates using the published techniques and estimator (Huso 2011). Therefore, we compiled empirical results but only included reported estimates of fatalities where bias corrections (e.g., searcher efficiency and carcass removal) were quantified and used to adjust estimates (Strickland et al. 2011). We report estimated fatalities per turbine and per megawatt (MW, number of fatalities per turbine/megawatt capacity of each turbine type). We caution that studies had varying levels of effort, used different estimators (Huso 2011), and different methods to quantify bias (Arnett et al. 2008).

**Table 21.1** Regions of the USA and Canada defined for establishing fatality rates of bats at wind facilities and their installed capacity (MW) as of 31 December 2011

| Region | Installed MW (as of 9/30/2011) | States/provinces |
|---|---|---|
| Great Basin/Southwest Open Range-Desert | 10,037 | Southern California and Central Valley; west Texas Pecos region; non-forested Arizona and New Mexico; Nevada; eastern Oregon, Washington, and Idaho; western Utah and Colorado |
| Great Plains | 19,033 | Southern Alberta, Saskatchewan, and Manitoba; eastern Montana; North and South Dakota; Nebraska; Kansas; Oklahoma; North and Central Texas; eastern Colorado; unforested portions of Wyoming |
| Gulf Coast | 1,217 | Coastal Texas and Louisiana (inland 200 km) |
| Midwestern Deciduous Forest-Agricultural | 13,361 | Southern Ontario, Minnesota, Wisconsin, Iowa, Michigan, Illinois, Missouri, Indiana, Ohio |
| Northern Boreal-Taiga | <1 | Central Alaska; most of Northwest and Yukon Territories; northern portions of British Columbia, Alberta, Ontario, Saskatchewan, Manitoba, and Quebec; most of Newfoundland; southern portion of Nunavut |
| Northeastern Deciduous Forest | 4,872 | Delaware; Maine; Maryland; Massachusetts; New Hampshire; New Jersey; New York; Pennsylvania; Rhode Island; Vermont; West Virginia; New Brunswick; southern portions of Newfoundland, Ontario, and Quebec; Prince Edward Island; and Nova Scotia |
| Northern Tundra | 10 | Northern portions of Alaska, Northwest Territories, Yukon Territory, Nunavut, Quebec, and Newfoundland |
| Southeastern Mixed Forest | 29 | Tennessee, Kentucky, Virginia, East Texas, North and South Carolina, Georgia, central and north Louisiana, Arkansas, Mississippi, Alabama, and Florida |
| Tropical Forest | 93 | Hawaii |
| Tropical Open Range-Grassland | 0 | Hawaii |
| Western Temperate Forest | 247.5 | Forested portions of eastern Oregon, Washington, and British Columbia; Idaho; Montana; Wyoming; Colorado; Utah; New Mexico; Arizona |
| Coastal Temperate Forest | 0 | West Cascades Oregon and Washington, coastal British Columbia and Alaska, northern California redwood forests |

## 21.2 Reasons for Bat Mortalities

Kunz et al. (2007) proposed several hypotheses relating to potential attraction factors (e.g., insects, heat, visual, sound, roosting opportunities) of turbine arrays. Cryan and Barclay (2009) proposed proximate (how bats were being killed) and ultimate (why bats were being killed) causes of bat fatalities that included random chance events, coincidental fatality during migration, and attraction factors.

Thermal imaging studies confirm that bats are attracted to turbines (Horn et al. 2008). Kunz et al. (2007) proposed a roost attraction hypothesis that seemed potentially plausible. However, Cryan (2008) noted that *Lasiurus* species may use the tallest trees in a landscape as rendezvous points or possibly lekking sites during the migration/mating period and therefore may mistake turbines for trees, resulting in a bias toward fatalities of migratory species (Cryan and Barclay 2009). Baerwald and Barclay (2011) suggested that if the mating behavior hypothesis is correct, then we would expect correlation between timing of adult male/female migration; however, they reported asynchronous migration between sexes of hoary bats (*Lasiurus cinereus*) in southwestern Alberta, suggesting that mating behavior was not likely causative of wind turbine mortality in that region. Baerwald and Barclay (2011) did report concurrent timing of adult male/female silver-haired bats during (*Lasionycteris noctivagans*) migration and that mating behaviors could be associated with fatalities. As is, the roost tree and mating hypotheses may account for mortality in some species, but clearly does not explain fatalities of other species such as the Brazilian free-tailed bats (*Tadarida brasiliensis*) (Miller 2008; Piorkowski and O'Connell 2010) whose mortality may be a coincidental outcome of migration (Cryan and Barclay 2009) or be due to periodic insect aggregations. Although testing hypotheses regarding causation of large-scale bat kills by wind turbines is challenging, it is paramount for preventing future fatalities, especially during early planning and risk assessment phases of development (Cryan and Barclay 2009).

Baerwald et al. (2008) found that the cause of death in many bats at turbines was due to barotrauma, resulting from sudden decompression due to low-pressure air pockets produced by rotating turbine blades (Kunz et al. 2007). Approximately 90 % of dead bats found had no visible signs of injury (Fig. 21.3), but had internal hemorrhaging consistent with barotrauma, whereas direct contact with turbine blades accounted for about half of the fatalities (Baerwald et al. 2008). Grodsky et al. (2011) found that 74 % of 23 bat carcasses examined using radiology had bone fractures, primarily in wing bones, but that using visual inspection only resulted in 33 % fewer detected bone fractures. They also reported that more than half of the specimens had mild to severe hemorrhaging in the middle and/or inner ears, and thus, it is difficult to attribute individual fatalities exclusively to either direct collision or barotrauma. Rollins et al. (2012) found that 73 % of bats they examined had lesions consistent with traumatic injury by physical contact with turbine blades but that 20 % had ruptured tympana, likely from barotrauma (Rollins et al. 2012).

In order to fully account for bat mortality at turbines, we must consider possible crippling effects resulting from inner ear damage and thus echolocation ability due to barotrauma or bone fractures that may cause death far from the offending site. Although Grodsky et al. (2011) suggested that delayed lethal effects could result in underestimating fatalities, they found that 71 % of bat carcasses found were within 30 m of turbines, and the majority of those having the fewest broken bones were found within 40 m of turbines. This finding is consistent with a unifying pattern in all regions we reviewed. Approximately 85 % of bats grounded but still alive found by Klug and Baerwald (2010) were discovered within 35 m of the turbine base, and 69 % of these had no obvious external injuries but fell rapidly to the ground after nonlethal encounters with only a minor number falling outside search plots. While individuals experiencing delayed lethal effects might bias fatality estimates, the

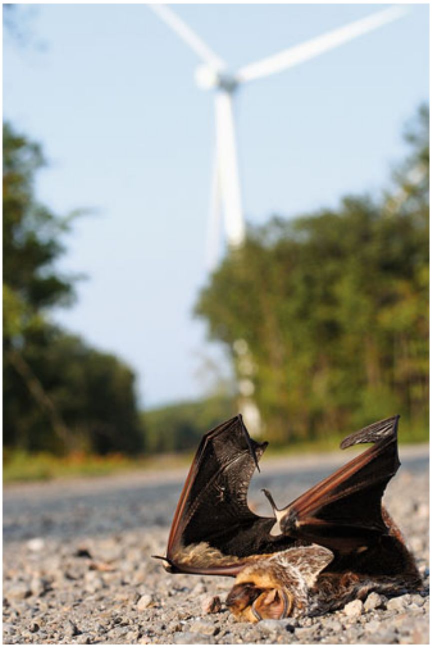

**Fig. 21.3** A dead hoary bat found beneath a turbine showing no visible sign of injury (Photo by M.R. Schirmacher, Bat Conservation International)

only feasible method to test this is by using trained dogs (Arnett 2006; Fig. 21.4) to search excessively large plots around turbines (Strickland et al. 2011). However, even dogs cannot search entire landscapes and certain habitats (e.g., forests), so while we do not feel that delayed lethal effects contribute greatly to underestimating fatalities, the true influence may never be known.

## 21.3 Estimates of Bat Fatalities

We again caution that patterns and estimates of fatalities reported here are affected by many factors (Arnett et al. 2008), but for regions having multiple studies, estimates of bat fatalities were highest at facilities located in the Northeastern Deciduous Forest (Fig. 21.5) and Midwestern Deciduous Forest-Agricultural regions (Table 21.2). The Midwestern region generally had been considered to have low–moderate fatality rates relative to the eastern USA and Canada (Arnett et al. 2008; Johnson 2005); however, this is no longer the case. The Great Plains region (Fig. 21.6) has highly variable (0.16–21.6 individuals/MW) but moderately high fatality rates on average (Table 21.2). While several studies included in this region had low fatality rates, our stratification of this region also included the southern part of the Canadian prairie provinces and facilities in northern Texas, which have reported high fatality rates. The Great Basin/Southwest Open Range-Desert region consistently has reported the least variable and lowest fatality rates for bats (Arnett et al. 2008; Johnson 2005). Wind energy facilities in this region occur in habitats generally offering few if any

**Fig. 21.4** The senior author with his chocolate Labrador retriever, Sage, after discovering a tricolored bat at a wind energy facility. Trained dogs can find more than 80 % of bats during searcher efficiency trials and are especially effective in dense, low-visibility vegetation (Photo by M.D. Tuttle, Bat Conservation International)

**Fig. 21.5** Wind energy facilities on forested ridges in the eastern USA have consistently documented high fatality rates of bats (Photo by M.D. Tuttle, Bat Conservation International)

**Table 21.2** Number of sites and studies and estimates of bat fatality (mean and 95 % confidence limits) for each region in the USA and Canada, 2000–2011

| Region | No. sites w/data | No. studies | Mean fatalities | Lower 95 % CL | Upper 95 % CL |
|---|---|---|---|---|---|
| Coastal Temperate Forest | – | – | – | – | – |
| Great Basin/Southwest Open Range-Desert | 17 | 24 | 1.39 | 1.02 | 1.76 |
| Great Plains | 20 | 32 | 6.04 | 3.98 | 8.10 |
| Gulf Coast | – | – | – | – | – |
| Midwestern Deciduous Forest-Agricultural | 14 | 23 | 7.94 | 4.92 | 10.96 |
| Northern Boreal-Taiga | – | – | – | – | – |
| Northeastern Deciduous Forest | 21 | 44 | 8.30 | 6.08 | 10.52 |
| Northern Tundra | – | – | – | – | – |
| Southeastern Mixed Forest | 1 | 2 | 41.17 | 28.61 | 53.73 |
| Tropical Forest | – | – | – | – | – |
| Tropical Open Range-Grassland | – | – | – | – | – |
| Western Temperate Forest | – | – | – | – | – |

**Fig. 21.6** Wind energy facilities in shrub-steppe habitats in the western USA consistently document fatalities of bats, but rates are usually considerably lower than other regions (Photo by E.B. Arnett, Bat Conservation International)

roosting resources, possibly (but untested) poor foraging opportunities, and may not be in migratory pathways, thus rendering these sites less risky to bats. However, we caution that this pattern could change as development increases and if facilities are poorly sited in areas with higher use and densities of bats.

## 21.4 Bat Fatalities and Cumulative Impacts

The context of fatalities remains a mystery, in part because little population data exist for most species of bats (O'Shea et al. 2003) and has hindered understanding of population-level impacts, as well as effectiveness of mitigation measures. Estimating exposure risk of bats to collisions with turbine blades is problematic but necessary to understand the context of fatalities. The role of abundance, relative to exposure of bats to collisions, may be modified by behavior within and among species and likely varies across locations, although avoidance behavior is complicated by possible attraction to turbines (Cryan and Barclay 2009; Horn et al. 2008). Studies using radar, thermal imaging, acoustic monitoring, and other technologies simultaneously and concurrent with fatality studies would help determine exposure risk. Model-based analysis is also helpful, but empirical data are generally lacking for developing such models (Arnett et al. 2007), but high bat fatalities at some wind energy facilities raise concern about biologically significant additive mortality (Kunz et al. 2007). At the end of 2011, there was 5,265 MW of wind energy installed in Canada and 46,919 MW in the USA, for a total of 52,184 MW (Table 21.1, Fig. 21.1). We calculated mean bat fatalities and 95 % confidence intervals for each region (Table 21.1) and then calculated a weighted mean and confidence interval (based on regional means and weighted by installed capacity) for each year from 1999 to 2010 in the USA and Canada that was multiplied by the total installed MW for each year. The total estimated fatalities for each year were then summed to determine cumulative fatalities between 2000 and 2011 (data from the prior year were used to develop the weighted means and estimates for the following year; no estimate of kills for 1999, but studies from that year were used to derive estimates for the following year in 2000, based on 1999 data and installed capacity). Assuming fatality rates are (1) representative of all regional sites, and (2) consistent from year to year without behavioral modification or mitigation, cumulative bat fatalities in the USA and Canada ranged from 650,104 to 1,308,378 over the past 12 years (Table 21.3). This estimate is projected to increase by 196,190–395,886 bats in 2012. Three species of migratory tree bats (hoary, eastern red (*Lasiurus borealis*), and silver-haired bats) accounted for 78 % of cumulative fatalities, ranging from 538,902 to 1,229,547 individuals killed since 2000. Eastern red bat populations are already thought to be in decline (Winhold et al. 2008), and almost nothing is known about population status and mortality factors affecting this species or populations of hoary and silver-haired bats.

However, some evidence suggests significant population declines of migratory tree bats. Historical accounts of large flocks (>100 individuals) of migrating eastern red bats and hoary bats no longer occur (Winhold et al. 2008). Furthermore, capture rates of lasiurine bats (although perhaps somewhat biased by capture probability) have declined across North America (Carter et al. 2003). Finally, although also biased, the number of lasiurine bats submitted for rabies testing across the USA has decreased; in Arkansas from 1938 to 1998, the number of eastern red bats submitted for rabies testing has fallen by approximately 3 bats per year (Carter et al. 2003); in Michigan a tenfold decrease occurred over 38 years (Winhold et al. 2008); in Indiana, the proportion of eastern red bats submitted has declined 7 % between

**Table 21.3** Estimates of cumulative fatalities of each species of bat from 2000 to 2011 for all regions combined in the USA and Canada

| Scientific name | Common name | % of total fatalities | Lower range | Upper range |
|---|---|---|---|---|
| *Eptesicus fuscus* | Big brown bat | 4 | 26,004 | 52,255 |
| *Lasiurus blossevillii* | Western red bat | <0.01 | 69 | 143 |
| *Lasiurus borealis* | Eastern red bat | 22 | 143,023 | 287,403 |
| *Lasiurus cinereus* | Hoary bat | 38 | 247,040 | 633,822 |
| *Lasiurus cinereus semotus* | Hawaiian hoary bat | <0.001 | 4 | 8 |
| *Lasiurus ega* | Southern yellow bat | <0.01 | 69 | 143 |
| *Lasiurus intermedius* | Northern yellow bat | <0.01 | 553 | 1,145 |
| *Lasionycteris noctivagans* | Silver-haired bat | 18 | 148,839 | 308,322 |
| *Lasiurus seminolus* | Seminole bat | <0.01 | 1,106 | 2,290 |
| *Lasiurus xanthinus* | Western yellow bat | <0.01 | 622 | 1,288 |
| *Myotis evotis* | Long-eared myotis | <0.01 | 3,731 | 7,730 |
| *Myotis lucifugus* | Little brown myotis | 6 | 51,617 | 106,925 |
| *Myotis septentrionalis* | Northern myotis | <0.01 | 1,175 | 2,433 |
| *Myotis sodalis* | Indiana bat | <0.01 | 69 | 143 |
| *Myotis velifer* | Cave myotis | <0.01 | 69 | 143 |
| *Myotis volans* | Long-legged myotis | <0.01 | 69 | 143 |
| *Nyctinomops femorosacca* | Pocketed free-tailed bat | <0.01 | 69 | 143 |
| *Nycticeius humeralis* | Evening bat | <0.01 | 1,589 | 3,292 |
| *Perimyotis subflavus* | Tricolored bat | 6 | 45,260 | 93,756 |
| *Parastrellus hesperus* | Canyon bat | <0.01 | 69 | 143 |
| *Tadarida brasiliensis* | Brazilian free-tailed bat | 3 | 21,282 | 44,087 |
| Unknown spp. | Unknown spp. | 2 | 20,036 | 41,505 |
| Total | Total | | 650,104 | 1,306,378 |

1990 and 2000, and hoary bat submissions declined from 3.8 to 1.8 % during the same period (Whitaker et al. 2002).

Turbine fatalities for little brown bats (*Myotis lucifugus*) were estimated to be between 51,617 and 106,925 since 2000 (Table 21.3), and while these estimates are low relative to migratory tree bats, the cumulative impact for cave-hibernating bats is significant and important in light of massive fatalities from white-nose syndrome (WNS; Frick et al. 2010; Turner et al. 2011). Although estimated wind turbine-related fatalities occurred over a longer period than calculated for WNS bat fatalities (Turner et al. 2011), continued wind turbine effects may further compound population declines. Furthermore, wind-related fatalities are skewed toward migratory tree bats, whereas WNS affects hibernating species.

## 21.5 Composition of Fatalities

Of the 47 species of bats known to occur north of Mexico, individuals of 21 have been reportedly killed at wind energy facilities (Table 21.3) and, as mentioned, fatalities are skewed toward migratory, foliage-roosting species including hoary bats (38 %), eastern red bats (22 %), and silver-haired bats (18.4 %) that comprised a total of 78.4 % of all bat turbine fatalities (Table 21.4). Hoary bats constituted the highest proportion at most facilities (range = 12–51 %; Table 21.44), whereas tricolored bats constituted nearly 25 % of fatalities at some facilities in the eastern USA but only 5.6 % across all fatalities (Table 21.4). Similarly, at some facilities in the Northeastern Deciduous Forest and Midwestern Deciduous-Agricultural regions, the little brown bat comprised up to 60 % of fatalities but only about 6 % of total fatalities. Brazilian free-tailed bats encompass up to 90 % of fatalities at some facilities in Texas (Miller 2008) and Oklahoma (Piorkowski and O'Connell 2010), and at five sites in California, they constituted 31–57 %. Since 2007 when Arnett et al. (2008) reported that 10 species of bats had been found killed at wind facilities, 11 new species have been documented: long-eared myotis (*Myotis evotis*), long-legged myotis (*Myotis volans*), southern yellow bat (*Lasiurus ega*), northern yellow bat (*Lasiurus intermedius*), western yellow bat (*Lasiurus xanthinus*), evening bat (*Nycticeius humeralis*), cave myotis (*Myotis velifer*), canyon bat (*Parastrellus hesperus*), pocketed free-tailed bat (*Nyctinomops femorosacca*), and the US federally endangered Indiana bat (*Myotis sodalis*; Good et al. 2011) and Hawaiian hoary bat (*Lasiurus cinereus semotus*, two fatalities; R. Roy, First Wind, personal communication). Recent reports of Indiana bat fatalities precipitated the development of site-specific habitat conservation plans (HCPs) at the US Fish and Wildlife Service's Midwest region under Section 10 of the US Endangered Species Act (T.J. Miller, US Fish and Wildlife Service, personal communication). Site-specific HCPs have been developed for the Hawaiian hoary bat. Although no other federally threatened or endangered species has been found killed at a wind facility in the USA, anticipated facility expansion within the range of listed species such as the lesser long-nosed bat (*Leptonycteris yerbabuenae*) may yield fatalities. Several of the species found killed at wind facilities have either state of federal agency management status or both, although such status rarely provides a nexus for mandatory survey or mitigation requirements. In Canada, three species (hoary, silver-haired, and eastern red bats) found killed at wind facilities are considered to be of special management concern provincially. Additionally, the Committee on the Status of Endangered Wildlife in Canada recently announced that WNS poses a serious and imminent threat to the survival of bats and recommended that the Federal Environment Minister issue an "emergency order," placing the tricolored bat, little brown myotis, and northern myotis on Canada's list of endangered species.

## 21.6 Temporal and Spatial Patterns

### *21.6.1 Seasonal Timing of Fatality*

Consistently, the highest bat fatalities occur during late summer and early fall (Arnett et al. 2008; Rydell et al. 2010) which coincide with autumn migration (Cryan 2003; Fleming and Eby 2003), although some fatalities during spring migration have also been reported (Arnett et al. 2008). One hypothesis explaining different seasonal fatality rates is that migratory tree bats may exhibit different behaviors and follow alternate migration routes in each season (Cryan 2003). Baerwald and Barclay (2011) found that fatalities of hoary bats began in late July and early August and were followed by silver-haired bats in mid- to late August, implying that variation in timing of migration is due to different geographic distributions of populations during summer. Piorkowski and O'Connell (2010) reported spring-summer fatalities of Mexican free-tailed bats that included pregnant females during searches conducted in May and June, whereas Miller (2008) reported highest kills of Mexican free-tailed bats in fall with peaks in September and October, indicating that the number of fatalities reported by Piorkowski and O'Connell (2010) was low.

### *21.6.2 Spatial Patterns*

The spatial context of bat kills, both among turbines within a facility and among different facilities, could be useful for developing mitigation strategies. If, for example, kills were concentrated at specific turbines, then curtailment, removal, or relocating that turbine may reduce bat deaths. However, if fatalities are broadly distributed, then facility-wide mitigation strategies would be necessary (Arnett et al. 2008). Although most studies indicate that fatalities generally are distributed across a facility, Piorkowski and O'Connell (2010) found a cluster of turbines to be a hot spot of collision mortality. Baerwald and Barclay (2011) found no differences in fatalities on the east vs. west side of a facility in southern Alberta, but the fatality rate was higher at the north end. Fielder et al. (2007) also observed a general north–south trend of bat fatalities, and Gruver et al. (2009) found slightly higher mortality in the northern portion of their study area for both migratory and nonmigratory species. Baerwald and Barclay (2011) hypothesized that because fall migrations are from north to south, higher fatality rates could be expected at the more northerly turbines first encountered by migrating bats. This pattern likely varies from site to site depending on the facility's location relative to the direction of fall bat migrations.

In addition, Baerwald and Barclay (2009) documented higher activity and fatality rates of bats at wind facilities near the foothills of the Rocky Mountains as compared to eastward prairie grasslands. They hypothesized that turbine proximity to stopover and roost sites in foothills habitat significantly increased fatality rates assuming that geographical landmarks are used for navigating migration routes and that bats judge nightly travel distances between suitable diurnal roosting sites (Baerwald and Barclay 2009; Cryan and Veilleux 2007; Fleming and Eby 2003). There also appears to be a pattern of latitudinal decline in bats fatalities in the Northeastern Deciduous Forest region from the Mid-Atlantic area in Pennsylvania and West Virginia (highest fatalities) northward to Maine and the eastern Canadian provinces (lowest fatalities). It seems plausible that seasonal abundance, distributions, and migratory patterns, any of which may be influenced by climatic conditions and food availability, could impact mortality rates resulting in a pattern of declining kills with increasing latitude in this region.

If fatalities are related to habitat or topographic characteristics, then understanding these relationships may help in developing mitigation strategies (e.g., avoiding placement of turbines near open water sources or known roosts; Arnett et al. 2008). Many wind energy facilities occur in settings with too little habitat or topographic variation among turbines to allow an evaluation of landscape relationships with bat fatalities. However, Johnson et al. (2004) did not find a significant relationship between the number of bat fatalities and any of the 10 cover types within 100 m of turbines at facilities in Minnesota or any relationship between fatalities and distance to nearest wetland or woodlot. Distance to wooded area, regardless of woodlot size, did not predict number of fatalities at wind turbines in Wisconsin either (Gruver et al. 2009). In Oklahoma, Piorkowski and O'Connell (2010) found no consistent pattern in bat fatalities relative to ground cover or topographic position, but did find that fatalities were higher at several individual turbines, all of which were located near the heads of eroded ravines. In New York, Jain et al. (2007) found no significant relationship between bat fatalities and distance to wetlands using daily and 3-day carcass searches, but did find moderate evidence of higher fatalities in proximity to wetlands when using 7-day searches. Conversely, they found no relationship with proximity to woodlands at a different facility in New York. Interestingly, Grodsky (2010) found a significant relationship between fatalities and distance to the Horicon Marsh, but fatalities were actually lower near the marsh.

Piorkowski and O'Connell (2010) documented the first evidence of collision mortality of Mexican free-tailed bats at a North American wind farm that could be attributed to the site's proximity (~15 km) to a large maternity colony. In Wisconsin, Grodsky (2010) found no relationship between distance of turbines from a large hibernaculum (Neda Mine). Given that the majority of bat fatalities appear to be active during migrations, it may not be enough to consider the proximity of a facility to a maternity or hibernation site, but rather where it is located relative to movement corridors between these important sites.

## 21.7 Effects of Turbine Size

Barclay et al. (2007) reported that taller turbines had significantly higher fatalities on bats than did smaller ones. However, the sites used in this analysis were not sampled simultaneously during the same years, and the reported difference could have resulted from annual variation, increased survey effort at sites with taller turbines, or some other factor. Notwithstanding, Arnett et al. (2008) reported that height and dimensions of the rotor-swept area of turbines appeared to influence bat fatalities. During the second phase of study at Buffalo Mountain, Tennessee, 0.66-MW turbines with 65-m-tall towers and 1,735-$m^2$ rotor-swept area killed fewer bats per turbine but more bats per MW than adjacent 1.8-MW turbines with 78-m towers and nearly three times the total rotor-swept area (Arnett et al. 2008; Fielder et al. 2007). At the Buffalo Ridge site in Minnesota, taller turbines with greater rotor-swept areas killed more bats per turbine and per MW compared to smaller ones

(Arnett et al. 2008:63). Baerwald and Barclay (2009) found that bat fatality rates varied in part due to differences in turbine height, with taller turbines yielding higher fatalities.

## 21.8 Fatalities in Relation to Weather Variables

Arnett (2005) employed daily carcass searches and related them to weather variables and found that most bats were killed on low-wind nights when power production appeared insubstantial, but turbine blades were still moving (often times at or close to full operational speed at 17 revolutions/min [rpm]). In addition, 82–85 % of bat fatalities at two facilities in the eastern USA were estimated to have occurred on nights with median nightly wind speeds of <6 m/s (Arnett et al. 2008).

In Iowa, Jain et al. (2011) found that maximum wind speeds when bat collisions likely occurred ranged from 2.4 to 5.3 m/s, and Good et al. (2011) demonstrated for every 1 m/s increase in wind speed, bat fatalities decreased by 14 %. Grodsky (2010) used weekly power output as a surrogate for wind speed and found a significant negative relationship between fatalities and power, indicating lower wind speeds yield higher bat fatalities. Indeed, fatalities are typically highest during lower wind speeds, usually <6.0 m/s (Arnett 2005; Rydell et al. 2010; Young et al. 2010, 2011). In addition, fatalities increased as ambient temperature rose to some threshold (Grodsky 2010; Young et al. 2011), and Baerwald and Barclay (2011) reported that species-specific fatalities were affected by greater moon illumination. They also observed that falling barometric pressure and the number of deaths were correlated and that whereas fatalities of silver-haired bats increased with increased activity, moon illumination, and southeasterly winds, hoary bat mortality increased most significantly with falling barometric pressure. Interestingly, neither hoary bat activity nor fatality was influenced by any measured variables other than falling barometric pressure, possibly because migrating bats are less selective of environmental conditions at the northern end of their migration (Baerwald and Barclay 2011).

## 21.9 Offshore Wind Facilities

Offshore wind facilities occur throughout Europe, but few studies have determined impacts on animals, and although virtually these relate only to birds (Arnett et al. 2007), observations in Europe and anecdotal accounts of bats occurring offshore suggest probable impacts. Ahlen et al. (2009) recorded 11 species of bats flying over the ocean up to 14 km from shore. They observed both migrant and resident bats foraging over water on abundant insects and observed these bats rapidly changing altitude to forage around turbine blades at an offshore facility. Cryan and Brown (2007) observed hoary bats readily migrating over open ocean between islands that are stopping points along the migratory route. Johnson et al. (2011) recorded five species of bats, including eastern red bats, big brown bats (*Eptesicus fuscus*), hoary bats, tricolored bats, and silver-haired bats, on a barrier island off the coast of Maryland along their migratory route. Use of such islands would have implications for wind energy development near- and offshore.

We suggest that impacts of the first several offshore wind energy facilities proposed and built in North America, including those on inland waters such as the Great Lakes, be evaluated extensively for both fatalities and displacement effects, although finding and retrieving dead birds and bats from water bodies will be a considerable challenge (Arnett 2012; Arnett et al. 2007).

## 21.10 Mitigating Bat Mortality

### *21.10.1 Operational Mitigation*

As mentioned, most bat fatalities occur during relatively low-wind conditions over a relatively short period of time during bat migration periods (Arnett et al. 2008). Operational adjustments under these conditions and during this time period have long been proposed as a possible means of reducing impacts to bats (Arnett 2005; Arnett et al. 2008; Kunz et al. 2007). In southern Alberta, Baerwald et al. (2009) reported that raising turbine cut-in speeds (i.e., wind speed at which wind-generated electricity enters the power grid) above the manufactured speed (usually 3.5–4.0 m/s for modern turbines) and altering blade angles to either stop or slow rotor movement in low wind speeds significantly reduced mortality by up to 60.0 %. Arnett et al. (2011a) found that nightly reductions in bat fatality ranged from 44 to 93 % when turbine cut-in speed was raised from 3.5 m/s to either 5.0 or 6.5 m/s. The resulting economic loss was less than 1 % of the total annual energy output for the facility. In Indiana, Good et al. (2011) slightly modified the Arnett et al. (2011a) study design and reported an approximate 50 % reduction in overall bat fatalities when turbine cut-in speed was raised from 3.5 to 5.0 m/s and approximately 78 % fewer fatalities when cut-in speed was raised from 3.5 to 6.5 m/s.

Interestingly, some turbine models actually spin, sometimes at full rotational speed, below the turbine's cut-in speed, which can kill bats even when no electricity is being generated. Young et al. (2010) found that by simply pitching turbine blades parallel to the wind and stopping turbine blades from spinning below the manufacturer's cut-in speed (4.0 m/s; Baerwald et al. 2009), fatalities were reduced significantly, and by excluding nights that treatments were not in effect, the odds of a bat casualty was 3.69 times less likely at curtailed turbines during the first 5 h past sunset and approximately two times less likely at turbines curtailed during 5 h prior to sunrise than under normal operations. This represented 50–72 % fewer bat kills at curtailed turbines with little financial cost beyond operational time to implement treatments. Such operational costs could be minimized if turbine computer systems are reconfigured to account for such adjustments and automatically implemented on turbines. While costs of lost power due to mitigation can be factored into the economics, financing, and power purchase agreements of new projects, altering turbine operations even on a limited-term basis potentially poses difficulties on existing projects, so there is considerable interest in developing other solutions that do not involve turbine shutdowns.

### 21.10.2 Turbine Color

Insect attraction to and activity near wind turbines remains a valid, but untested, hypothesis (Cryan and Barclay 2009; Kunz et al. 2007). Long et al. (2010) found that, at ground level, common turbine colors, white and light grey, attracted significantly more insects than other colors tested; however, tests at hub height and/or at operating wind facilities have not been conducted to date.

### 21.10.3 Electromagnetic Signals

Studies in Scotland suggest that bat activity may be deterred by electromagnetic signals from small, portable radar units. Nicholls and Racey (2009) reported that bat activity and foraging effort per unit time were significantly reduced during experimental trials when their radar antenna was fixed to produce a unidirectional signal that maximized exposure to foraging bats. The effectiveness of radar as a potential deterrent has not been tested at an operating wind facility; thus, it remains unclear if electromagnetic signals would deter bats that are migrating as effectively as those that are foraging. Moreover, the effective range of electromagnetic signals as well as the number of radar units needed to affect the most airspace has not been determined, but must be to fully evaluate effectiveness and the cost-benefit analysis relative to other potential deterrents (Arnett et al. 2011a; Baerwald et al. 2009).

### 21.10.4 Ultrasonic Broadcasts

Griffin et al. (1963) showed that broadband random ultrasonic noise could partially mask bat echolocation, and Mackey and Barclay (1989) concluded that ultrasound broadcasts reduced bat activity by increasing the difficulty for bats to hear and interpret the echoes from insects. Arnett et al. (2011b) tested a newly designed ultrasonic broadcasting device and found that, after accounting for inherent variation among sample turbines, bat fatalities were reduced up to 64 % at turbines with deterrent devices relative to control turbines (see http://www.batsandwind.org) and that broadband, ultrasound broadcasts may discourage bats from approaching a sound source that interferes with their echolocation. However, effectiveness is limited by the distance and area that ultrasound can be broadcast. Ultrasound attenuates quickly and is heavily influenced by humidity, and thus ultrasonic deterrent devices are still in the experimental and modifications phase. Future studies should attempt to optimize both placement and number of devices on each turbine that would affect the greatest amount of airspace in the rotor-swept area and evaluate the cost-effectiveness of deterrents in relation to different operational strategies.

## 21.11 Implications for Conservation

The negative effects of turbines on bats are troubling because in a larger context assaults on bat welfare are many, and most importantly WNS is rapidly spreading and decimating populations of several cave-hibernating species of bats (Frick et al. 2010; Turner et al. 2011). If taken cumulatively, the overall impact on bat communities is predictably devastating and will have profound ecological and economic impacts (Boyles et al. 2011). Animals that migrate tend to be more vulnerable to extinction than those that do not (Fleming and Eby 2003; Pimm et al. 1988) and also require appropriate habitat in several, spatially disjunct locations including breeding/summering sites, hibernation/overwintering sites, stopover sites, and linked migratory corridors. Although the distributions, genetic structure, and migratory routes of bats are mostly unknown, if certain routes have an increased risk of mortality at wind facilities, then this may lead to genetic isolation and endangerment of specific subpopulations. Migratory tree-roosting species killed most frequently by turbines in North America are not protected under federal, state, or provincial laws (Arnett 2012; Cryan 2011). Further, while bats may be protected under state laws pertaining to “nongame” animals, most states do not enforce the killing of bats by wind turbines (Arnett 2012).

## 21.12 Conclusions

Whereas predicting patterns of fatality based on habitat types and other covariates is confounding, it may be possible to predict high-risk facility locations based on possible migratory pathways (Baerwald and Barclay 2009). As such, we strongly encourage future research efforts that identify migratory pathways and stopover sites and the establishment of buffers where turbines may not be constructed near maternity roosts, hibernacula, and other important areas.

Population data are lacking for most species of bats (O’Shea et al. 2003) and particularly migratory tree bats (Carter et al. 2003). Not only does this impede our understanding of the true impacts of wind turbines but also makes it difficult to determine if, for example, a 50 % reduction in bat fatalities from changing turbine cut-in speed is an adequate mitigation strategy or is simply delaying inevitable population-level impacts. The lack of population data also make it difficult to set triggers for mitigation (i.e., number of bats killed per turbine or MW that requires mitigation). However, such data are not likely to be available for most bats species in the near future, and thus, wind operators should practice the precautionary principle and implement operational mitigation at sites where bat fatalities are high, even in the absence of population data.

Future mitigation experiments should be designed to determine which factors (e.g., temperature, wind, humidity, moon illumination) or combination of factors will best improve predictability of bat fatalities while minimizing economic costs (Weller and Baldwin 2012). Developers must avoid building wind energy facilities in high-risk areas based upon pre-construction activity data, even though analyses linking pre-construction activity with post-construction fatality data are still lacking. More detailed meta-analyses of existing data may yield important relationships, but lack of data disclosure from many sites by some companies hinders such analyses.

We encourage developers to follow guidelines (Strickland et al. 2011) consistently when implementing pre- and post-construction monitoring and allow for these data to be published in refereed journals or placed into the public domain to avoid unnecessary skepticism regarding the quality of such efforts. There have been relatively few studies of wind energy effects on wildlife in peer-reviewed scientific journals (Arnett et al. 2007), although this trend is changing (Arnett 2012), allowing for decision-making based on solid science (Kunz et al. 2007; NRC 2007). Research partnerships among diverse players help generate common goals and to provide adequate funding for research [Arnett and Haufler 2003; Bats and Wind Energy Cooperative (http://www.batsandwind.org), American Wind and Wildlife Institute (http://www.awwi.org)] as well as garner support from government agencies, industry, NGOs, and academia that can leverage dollars and logistical support needed and provide peer-review, dissemination processes, and transparency that yield credibility (Arnett 2012).

The Canadian Wind Energy Association is calling for wind energy to provide 20 % of Canada's electricity, an additional 50,000 MW by 2025 (http://www.canwea.ca/images/uploads/File/Windvision_summary_e.pdf). The US Department of Energy (2008) estimated that 241 GW of land-based wind energy development on approximately five million hectares will be needed to reach 20 % electricity production for the USA by 2030. Kiesecker et al. (2011), however, estimated that there is 3,500 GW of potential wind energy that could be developed across the USA on already disturbed lands which would avert development of 2.3 million hectares on undisturbed lands while generating the same amount of energy. While we agree with this strategy, we caution that development in disturbed landscapes may not alleviate bats fatalities because high bat fatalities are already reported in agricultural settings in the Midwestern Deciduous Forest-Agricultural region (Grodsky 2010) and Great Plains (Baerwald and Barclay 2009). Thus, operational mitigation may be required at facilities constructed in disturbed landscapes.

There are a number of policies, regulatory, and communication challenges we face in protecting bats while developing wind energy responsibly (Arnett 2012). Unless there is a federal, state, or provincial nexus, most research, siting, and mitigation efforts by wind energy developers and operating companies will be voluntary, likely without regard for cumulative effects. Sites that do trigger a regulatory nexus will be driven by endangered species issues, and associated operational mitigation may also benefit other bat species. We encourage continuing cooperation with stakeholders, gathering needed information, avoiding construction in high-risk sites, considering cumulative effects, and implementing mitigation where needed even when no regulatory process is triggered. We do, however, recognize that companies must be treated fairly and consistently to ensure proactive measures are implemented. That some companies may choose to cooperate while others may not (Arnett 2012) creates unnecessary angst and deters resolving wildlife impacts and other issues. Decision-making based on the best available science, consistent policy, accountability, effective siting and mitigation strategies, and a "level-playing field" for the industry (i.e., consistent requirements and incentives for all companies) is fundamental for successfully developing wind energy that protects bats and other wildlife.

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## References

Ahlen I, Baagoe HJ, Bach L (2009) Behavior of Scandinavian bats during migration and foraging at sea. J Mammal 90:1318–1323

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

Arnett EB (2006) A preliminary evaluation on the use of dogs to recover bat fatalities at wind energy facilities. Wildl Soc Bull 34:1440–1445

Arnett EB (2012) Impacts of wind energy development on wildlife: challenges and opportunities for integrating science, management, and policy. In: Sands JP, DeMaso SJ, Brennan LA, Schnupp MJ (eds) Wildlife science: connecting research with management. Taylor and Francis, New York

Arnett EB, Brown WK, Erickson WP, Fiedler JK, Hamilton BL, Henry TH, Jain A, Johnson GD, Kern J, Koford RR, Nicholson CP, O'Connell TJ, Piorkowski MD, Tankersley Jr. RD (2008) Patterns of bat fatalities at wind energy facilities in North America. J Wildl Manage 72:61–78

Arnett EB, Haufler JB (2003) A customer-based framework for funding priority research on bats and their habitats. Wildl Soc Bull 31:98–103

Arnett EB, Inkley DB, Larkin RP, Manes S, Manville AM, Mason JR, Morrison ML, Strickland MD, Thresher R (2007) Impacts of wind energy facilities on wildlife and wildlife habitat. Wildlife Society Technical Review 07-2. The Wildlife Society, Bethesda, MD

Arnett EB, Huso MMP, Schirmacher MR, Hayes JP (2011a) Changing wind turbine cut-in speed reduces bat fatalities at wind facilities. Front Ecol Environ 9:209–214. doi:10.1890/100103

Arnett EB, Hein CD, Schirmacher MR, Baker M, Huso MMP, Szewczak JM (2011b) Evaluating the effectiveness of an ultrasonic acoustic deterrent for reducing bat fatalities at wind turbines. A final report submitted to the Bats and Wind Energy Cooperative. Bat Conservation International. Austin, TX

Baerwald EF, Barclay RMR (2009) Geographic variation in activity and fatality of migratory bats at wind energy facilities. J Mammal 90:1341–1349

Baerwald EF, Barclay RMR (2011) Patterns of activity and fatality of migratory bats at a wind energy facility in Alberta, Canada. J Wildl Manage 75:1103–1114

Baerwald EF, D'Amours GH, Klug BJ, Barclay RMR (2008) Barotrauma is a significant cause of bat fatalities at wind turbines. Curr Biol 18:R695–R696

Baerwald EF, Edworthy J, Holder M, Barclay RMR (2009) A large-scale mitigation experiment to reduce bat fatalities at wind energy facilities. J Wildl Manage 73:1077–1081

Barclay RMR, Harder LM (2003) Life histories of bats: life in the slow lane. In: Kunz TH, Fenton MB (eds) Bat ecology. University of Chicago Press, Chicago, IL

Barclay RMR, Baerwald EF, Gruver JC (2007) Variation in bat fatalities at wind energy facilities: assessing the effects of rotor size and tower height. Can J Zool 85:381–387

Bernstein MA, Griffin J, Lempert R (2006) Impacts on U.S. energy expenditures of increasing renewable energy use. Technical report prepared for the Energy Future Coalition. RAND Corporation, Santa Monica, CA

Boyles JG, Cryan PM, McCracken GF, Kunz TH (2011) Economic importance of bats in agriculture. Science 332:41–42

Carter TC, Menzel MA, Saugey DA (2003) Population trends of solitary foliage-roosting bats. In: O'Shea TJ, Bogan MA (eds) Monitoring trends in bat populations of the United States and Territories: problems and prospects. U.S. Geological Survey, Biological Resources Discipline, Information and Technology Report USGS/BRD/ITR-2003-0003, Washington, DC

Cryan PM (2003) Seasonal distribution of migratory tree bats (*Lasiurus* and *Lasionycteris*) in North America. J Mammal 84:579–593

Cryan PM (2008) Mating behavior as a possible cause of bat fatalities at wind turbines. J Wildl Manage 72:845–849

Cryan PM (2011) Wind turbines as landscape impediments to the migratory connectivity of bats. Environ Law 41:355–370

Cryan PM, Barclay RMR (2009) Causes of bat fatalities at wind turbines: hypotheses and predictions. J Mammal 90:1330–1340

Cryan PM, Brown AC (2007) Migration of bats past a remote island offers clues toward the problem of bat fatalities at wind turbines. Biol Conserv 139:1–11

Cryan PM, Veilleux JP (2007) Migration and use of autumn, winter, and spring roosts by tree bats. In: Lacki MJ, Kurta A, Hayes JP (eds) Conservation and management of bats in forests. John Hopkins University Press, Baltimore, MD

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

Energy Information Administration [EIA] (2011) Annual energy outlook 2011 with projections to 2035. http://www.eia.gov/forecasts/aeo. Accessed 15 Aug 2011

Fielder JK, Henry TH, Tankersley RD, Nicholson CP (2007) Results of bat and bird mortality monitoring at the expanded Buffalo Mountain Windfarm, 2005. Knoxville, Tennessee: Tennessee Valley Authority. doi: org/10.3996/032012-JFWM-024.S2

Fleming TH, Eby P (2003) Ecology of bat migration. In: Kunz TH, Fenton MB (eds) Bat ecology. University of Chicago Press, Chicago, IL

Frick WF, Pollock JF, Hicks AC, Langwig KE, Reynolds DS, Turner GG, Butchkoski CM, Kunz TH (2010) An emerging disease causes regional population collapse of a common North American bat species. Science 329:679–682

Good RW, Erickson WP, Merrill A, Simon S, Murray K, Bay K, Fritchman C (2011) Bat monitoring studies at the Fowler Ridge Wind Energy Facility Benton County, Indiana. A report prepared for Fowler Ridge Wind Farm. Western Eco Systems Technology, Inc., 2003 Central Avenue, Cheyenne, Wyoming

Griffin DR, McCue JJG, Grinnell AD (1963) The resistance of bats to jamming. J Exp Zool 152:229–250

Grodsky SM (2010) Aspects of bird and bat mortality at a wind energy facility in southeastern Wisconsin: impacts, relationships, and cause of death. Thesis, University of Wisconsin, Madison, WI

Grodsky SM, Behr MJ, Gendler A, Drake D, Dieterle BD, Rudd RJ, Walrath NL (2011) Investigating the causes of death for wind turbine-associated bat fatalities. J Mammal 92:917–925

Gruver J, Bay K, Erickson W (2009) Post-construction bat abd bird fatality study, Bly Sky Green Field Wind Resource Area, Fond du Lac County, Wisconsin. Interim report prepared for WE Energies. Western EcoSystems Technology, Inc., Cheyenne, Wyoming, USA

Horn J, Arnett EB, Kunz TH (2008) Behavioral responses of bats to operating wind turbines. J Wildl Manage 72:123–132

Huso MMP (2011) An estimator of wildlife fatality from observed carcasses. Environmetrics 22:318–329. doi:10.1002/env.1052

Inkley DB, Anderson MG, Blaustein AR, Burkett VR, Felzer B, Griffith B, Price J, Root TL (2004) Global climate change and wildlife in North America. Wildlife Society Technical Review 04-1. The Wildlife Society, Bethesda, MD

Jain AA, Koford RR, Hancock AW, Zenner GG (2011) Bat mortality and activity at a northern Iowa wind resource area. Am Midl Nat 165:185–200

Jain A, Kerlinger P, Curry R, Slobodnik L (2007) Annual report for the Maple Ridge wind power project post-construction bird and bat fatality study – 2006. Annual report prepared for PPM Energy and Horizon Energy, Curry and Kerlinger LLC, Cape May Point, New Jersey, USA

Johnson GD (2005) A review of bat mortality at wind-energy developments in the United States. Bat Res News 46:45–49

Johnson GD, Perlik MK, Erickson WP, Strickland MD (2004) Bat activity, composition, and collision mortality at a large wind plant in Minnesota. Wildl Soc Bull 32:1278–1288

Johnson JB, Gates JE, Zegre NP (2011) Monitoring seasonal bat activity on a coastal barrier island in Maryland, USA. Environ Monit Assess 173:685–699

Kiesecker JM, Evans JS, Fargione J, Doherty K, Foresman KR, Kunz TH, Naugle D, Nibbelink NP, Niemuth ND (2011) Win-win for wind and wildlife: a vision to facilitate sustainable development. PLoS One 6:e17566. doi:10.1371/journal.pone.0017566

Klug BJ, Baerwald EF (2010) Incidence and management of live and injured bats at wind energy facilities. J Wildl Rehab 30:11–16

Kunz TH, Arnett EB, Erickson WP, Hoar AR, Johnson GD, Larkin RP, Strickland MD, Thresher RW, Tuttle MD (2007) Ecological impacts of wind energy development on bats: questions, research needs, and hypotheses. Front Ecol Environ 5:315–324

Long CV, Flint JA, Lepper PA (2010) Insect attraction to wind turbines: does colour play a role? Eur J Wildl Res 57:323–331 doi:10.1007/s10344-010-0432-7

Mackey RL, Barclay RMR (1989) The influence of physical clutter and noise on the activity of bats over water. Can J Zool 67:1167–1170

McLeish T (2002) Wind power. Nat New England 11:60–65

Miller A (2008) Patterns of avian and bat mortality at a utility-scaled wind farm on the southern High Plains. Thesis, Texas Tech University, Lubbock, TX

National Research Council [NRC] (2007) Ecological impacts of wind-energy projects. National Academies Press, Washington, DC

Nicholls B, Racey PA (2009) The aversive effect of electromagnetic radiation on foraging bats—a possible means of discouraging bats from approaching wind turbines. PLoS One 4(7):e6246. doi:10.1371/journal.pone.0006246

O'Shea TJ, Bogan MA, Ellison LE (2003) Monitoring trends in bat populations of the United States and Territories: status of the science and recommendations for the future. Wild Soc Bull 31:16–29

Pimm SL, Jones HL, Diamond J (1988) On the risk of extinction. Am Nat 132:757–785

Piorkowski MD, O'Connell TJ (2010) Spatial pattern of summer bat mortality from collisions with wind turbines in mixed-grass prairie. Am Midl Nat 164:260–269

Racey PA, Entwistle AC (2003) Conservation ecology of bats. In: Kunz TH, Fenton MB (eds) Bat ecology. University of Chicago Press, Chicago, IL

Rollins KE, Meyerholz DK, Johnson GD, Capparella AP, Loew SS (2012) A forensic investigation into the etiology of bat mortality at a wind farm: barotrauma or traumatic injury? Vet Pathol 49:362–371. doi:10.1177/0300985812436745

Rydell J, Bach L, Dubourg-Savage M, Green M, Rodrigues L, Hedenstrom A (2010) Bat mortality at wind turbines in northwestern Europe. Acta Chirop 12:261–274

Schlesinger ME, Mitchell JFB (1987) Climate model simulations of the equilibrium climate response to increased carbon dioxide. Rev Geophys 25:760–798

Strickland MD, Arnett EB, Erickson WP, Johnson DH, Johnson GD, Morrison ML, Shaffer JA, Warren-Hicks W (2011) Comprehensive guide to studying wind energy/wildlife interactions. Prepared for the National Wind Coordinating Collaborative, Washington, DC

Turner GG, Reeder DM, Coleman JTH (2011) A five-year assessment of mortality and geographic spread of white-nosed syndrome in North American bats and a look to the future. Bat Res News 52:13–27

U.S. Department of Energy (2008) 20% wind energy by 2030: Increasing wind energy's contribution to U.S. electricity supply. DOE/GO-102008-2567. U.S. Department of Energy, U.S. Department of Energy, Office of Scientific and Technical Information, Oak Ridge, TN

Weller TJ, Baldwin JA (2012) Using echolocation monitoring to model bat occupancy and inform mitigations at wind energy facilities. J Wildl Manage 76:619–631

Whitaker JO, Brack V, Cope JB (2002) Are bats in Indiana declining? Proc Indiana Acad Sci 111:95–106

Winhold L, Kurta A, Foster R (2008) Long-term change in an assemblage of North American bats: are eastern red bats declining? Acta Chiropr 10:359–366

Young DP, Bay K, Nomani S, Tidhar WL (2010) Nedpower Mount Storm Wind Energy Facility post-construction avian and bat monitoring. Report prepared for NedPower Mount Storm, LLC, Houston, Texas, USA. Western Ecosystems Technology, Inc., Cheyenne, Wyoming, USA

Young DP, Nomani S, Tidhar WL, Bay K (2011) Nedpower Mount Storm Wind Energy Facility post-construction avian and bat monitoring. Report prepared for NedPower Mount Storm, LLC, Houston, Texas, USA. Western Ecosystems Technology, Inc., Cheyenne, Wyoming, USA