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Impact of wind energy on bats: a summary of our current knowledge

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Abstract: Since 2003, when it was discovered that large numbers of bats were being killed at wind turbines in the eastern United States, our understanding of the impact of wind energy development on bats has increased and consistent patterns of fatality, including seasonality and species composition have become evident. Yet, many questions remain despite the wealth of data collected across numerous post-construction monitoring studies. We synthesized the recent literature to provide an overview of our current understanding of patterns of bat fatalities at wind energy facilities in the United States and Canada. Our understanding of the impact of wind energy development on bats continues to be hindered by inconsistencies among studies and lack of publicly available data. It will be difficult to fully address this complex issue and develop sustainable strategies to reduce the impact of wind turbines on bats and generate wind energy without standardized protocols for field methods, estimation of fatality, and greater cooperation among stakeholders.

Key words: bat behavior, bat fatality patterns, human–wildlife conflicts, wind energy, wind turbines

Bat fatalities at wind energy facilities were first reported from Australia >40 years ago (Hall and Richards 1972). In the United States, observations of bat carcasses beneath wind turbines were reported in the late 1990s (Johnson et al. 2003), but it was not until 2003, when a series of alarming fatality events were reported, that efforts to quantify the extent and magnitude of wind turbine-related fatality of bats began in earnest (Arnett 2005). Since then, our understanding of the impact of wind energy development on bats has increased, and consistent patterns of fatality, including seasonality and species composition, have been identified. Yet, many questions remain, despite the wealth of data collected during numerous post-construction monitoring studies at individual wind energy facilities,.

Here, we synthesize recent literature, including peer-reviewed journal articles, book chapters, and selected unpublished reports that are publicly available, to provide an overview of our current understanding of patterns of bat fatalities at wind energy facilities in the United States and Canada. We also identify the gaps in our knowledge and suggest additional research needs to address this complex issue.

Reasons for bat fatality at wind turbines

Although our understanding of the interactions between bats and wind turbines has increased over the years, many questions remain as to why unexpectedly high bat fatalities occur at operational wind energy facilities. Kunz et al. (2007) presented several plausible hypotheses regarding the potential attraction of bats to turbines that range in scale (e.g., landscape-level versus turbine-level attraction) or are based on the bats' perception of the structure (e.g., acoustic or visual attraction). Subsequently, Cryan and Barclay (2009) discussed hypotheses on proximate (i.e., direct means by which bats die at turbines) and ultimate (i.e., why bats come close to turbines) causes of bat fatalities, partitioned ultimate factors into random collisions, coincidental collision, and collisions resulting from attraction to turbines, and summarized existing data relevant to each factor.

Data collected prior to the advent of wind turbine-related fatalities indicates that bat collisions with stationary anthropogenic structures were rarely observed (see Cryan and Barclay 2009). Additionally, no fatalities at stationary wind turbines or meteorological towers have been reported, and altering operations of turbines such that blades are stationary or only slightly moving during periods when bat fatalities are known to be high has been a successful strategy in reducing bat fatalities (Arnett et al. 2013). There is some suggestion that, at least in part, collisions are coincidental events associated with certain life history characteristics of bats (e.g., migration), primarily because fatalities tend to be clustered in late summer and fall (Arnett and Baerwald 2013). This may be an artifact of how bats migrate across the landscape in space and time, concentrating at stopover sites or along migratory corridors, or how weather variables influence flight behavior (Cryan and Barclay 2009). Yet, migration alone cannot explain the interaction between bats and wind turbines. Relatively few fatalities are observed during spring, and non-migratory species can comprise a high proportion of fatalities at some wind energy facilities (Arnett et al. 2008, Cryan and Barclay 2009, Arnett and Baerwald 2013). Thus, observed patterns in fatality presumably are influenced by other factors.

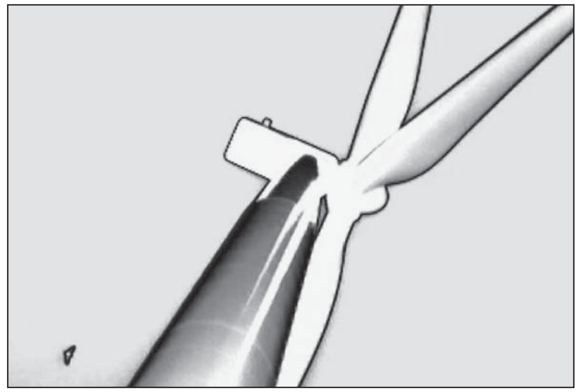

Figure 1. Still image of a bat (lower left corner) flying near a wind turbine captured in thermal-infrared video footage. (*Photo courtesy Paul Cryan, U.S. Geological Survey*)

Growing evidence indicates that some species of bats are attracted to wind energy facilities or wind turbines (Horn et al. 2008, Cryan et al. 2014). Horn et al. (2008) first documented bat behavior near wind turbines using thermal imaging cameras. They observed bats approaching rotating and non-rotating blades, investigating various parts of the turbine with some individuals attempting to land on the blades and towers, and, in the process, colliding with turbine blades. Their findings also indicated that bats actively forage near wind turbines, and that activity is positively correlated with insect abundance. Cryan et al. (2014), using thermal imaging cameras (Figure 1), detected bats more frequently at lesser wind speeds and greater moon illumination. During these conditions, bats typically approached from the leeward side of the turbine, suggesting bats may orient toward turbines by sensing air currents and using vision expecting resources normally associated with large trees (e.g., potential roosts, conspecifics, insect prey).

Although data suggest that certain species of bats are attracted to wind turbines, it is still unclear as to what the attractor(s) might be. It is important to note that multiple attractors may act synergistically and that the influence of attractors may vary by species. Bats commonly use forest gaps and edge, and may be attracted at a landscape-scale by creation of these features during construction (Hein et al. 2009). In addition, wind turbines may further attract bats once close to the structure. Differences in behavioral response toward wind turbines may exist between tree- and cave-roosting species. Perception of turbines as tree-like structures may attract species evolved to use trees, including hoary bats (*Lasiurus cinereus*), for roosting, mating, and foraging (Cryan and Brown 2007, Cryan et al. 2014), but may not influence behavior of cave-roosting bats that are vulnerable to wind energy development, such as the Brazilian free-tailed bat (*Tadarida brasiliensis*).

Estimates of impacts

With only a fraction of individual studies available, it is difficult to place impact of wind energy development on bats into context. Several attempts to develop cumulative estimates for a given region or year have been made, each using different assumptions and datasets. Kunz et al. (2007) estimated cumulative bat fatalities for the Mid-Atlantic Highlands would range from 33,000 to 62,000 or 59,000 to 111,000, depending on the projected installed capacity in the region by the year 2020. Cryan (2011) used the average 11.6 bats/megawatt, based on data provided in Arnett et al. (2008) and multiplied it by the total installed capacity in the United States, which at the time was approximately 40,000 megawatts, to estimate >450,000 bat fatalities each year in North America.

Two recent attempts were made to estimate bat fatality in the United States for 2012. Hayes

(2013) followed a similar approach to Cryan (2011) and based his analysis primarily on the limited dataset from Arnett et al. (2008). Hayes (2013) indicated that >600,000 bats were killed at wind energy facilities in 2012 and suggested that this was a conservative estimate. Smallwood (2013) estimated up to 888,000 bats were killed in the United States in 2012. He used a larger dataset than Hayes (2013) and applied a common estimator and 3 adjustment factors to improve comparability among sites.

Arnett and Baerwald (2013) estimated cumulative bat fatalities in the United States and Canada using data from 122 post-construction fatality studies from 73 facilities. They calculated a weighted mean based on regional means and weighted by installed capacity for each year from 1999 to 2010, then calculated and multiplied by total installed megawatts for each year. Arnett and Baerwald (2013) estimated cumulative bat fatalities in the United States and Canada ranged from 0.8 to 1.7 million between 2000 and 2011. Based on their assumptions and installed wind power capacity, this estimate was projected to increase by 200,000 to 400,000 bats in 2012.

We recommend caution when using any of these estimates and to articulate the assumptions and limitations when citing these publications. Huso and Dalthorp (2013) provided a critique of the methodology used by Hayes (2013), but many of the key issues could be applied to each of these cumulative estimates. In addition, Smallwood (2013) details numerous biases associated with individual studies that make comparing and combining data problematic. Each of these studies suffers from limited datasets that were based on public availability of studies and were not a representative sample of fatality across the region of inference. Although Arnett and Baerwald (2013) had by far the most data for their analysis, this collection of studies likely was still not representative of the entire United States and Canada. Yet, theirs is the only study to weight their estimates by both region and installed wind power capacity, which may provide a more conservative and accurate estimate (Arnett et al. 2015).

Even if more data were publicly available for use, another major challenge in estimating cumulative fatalities is lack of consistency in study design among sites. This, in part, is due to changes in turbine size and advances in study protocols and fatality estimation (Huso and Dalthorp 2013, Smallwood 2013). Nevertheless, varying levels of effort (e.g., temporally and spatially), differing methods for adjusting for imperfect detection, and different estimators used among sites are so large that estimates cannot be compared or combined (Huso 2011). Piorkowski et al. (2012), recognizing the impossibility of obtaining reliable estimates of fatality from currently available data, identified development of a standardized experimental design and generalized fatality estimator as the number one issue in addressing impact of wind energy development on bats. Until this is realized, any attempt to develop cumulative estimates or project estimates of bat fatalities into the future is problematic.

We suggest that each of these be considered an order of magnitude estimate; taken together, they highlight the almost certain large number of bats being killed (i.e., on the order of hundreds of thousands per year) in the United States and Canada. Given that bats have a low reproductive rate—typically only having 1 or 2 pups/year—and require high adult survivorship to avoid population declines (Barclay and Harder 2003), this level of impact presumably puts bat populations at risk. Moreover, many species were thought to be declining prior to the onset and expansion of wind energy development, including species impacted by white-nose syndrome (Winhold et al. 2008, Frick et al. 2010). Although population data are sparse or lacking for many bat species, current and presumed future level of fatality is considered to be unsustainable, and actions to reduce impact of wind turbines on bats should be implemented immediately.

Composition of fatalities

Species

Arnett et al. (2008) reported that individuals of 10 species of bats occurring north of Mexico have been killed by wind turbines. Currently, the number of species that have been killed by wind turbines has increased to twenty-two (Arnett and Baerwald 2013, Bird Studies Canada et al. 2014). New species recovered include 2 federally endangered species, the Indiana bat (*Myotis sodalis*) and the Hawaiian hoary bat (*Lasiurus cinereus semotus*), and several species in the southwestern United States. As wind energy development continues to expand into new regions, we are likely to see number of species impacted increase.

Currently, 78% of documented fatalities are from migratory, tree-roosting bats: hoary bats (38%), eastern red bats (*Lasiurus borealis*; 22%), and silver-haired bats (*Lasionycteris noctivagans*; 19%; Arnett and Baerwald 2013; Figure 2). Few studies are available within the range of Brazilian free-tailed bats, but reports indicate that this species can comprise 90% of the observed fatalities (Arnett and Baerwald 2013). Many cave-roosting bats also are affected by wind turbines. Little brown bats (*Myotis lucifugus*) and tri-colored bats (*Perimyotis subflavus*) each comprise about 6% of fatalities in the United States and Canada; but, at specific sites, these species can comprise a high proportion of fatalities (e.g., ≤60% and 25% for little brown bats and tri-colored bats, respectively; Arnett and Baerwald 2013). Although the overall percentage of fatality rates for these species is relatively small, compared to migratory tree-roosting bats, these fatalities are not trivial, given the devastating impacts of white-nose syndrome on these and other species.

Figure 2. A hoary bat (*Lasiurus cinereus*) found dead beneath a wind turbine at a wind energy facility in Pennsylvania. *(Photo courtesy of Cris Hein*)

Gender and reproductive condition

Arnett et al. (2008) reported a significant male bias in bat fatalities across United States and Canada. In contrast, Piorkowski and O'Connell (2010) observed a strong female bias in fatalities, most of which were Brazilian free-tailed bats. Proportion of male or female carcasses recovered likely varies depending on many factors, including species and location. For example, in Piorkowski and O'Connell (2010), the wind energy facility was located close to a summer maternity colony of Brazilian free-tailed bats.

Correctly classifying gender of bat carcasses found at wind energy facilities can be difficult due to carcass decomposition and scavenging. Korstian et al. (2013) observed that field observations were male biased for hoary bats and eastern red bats, whereas molecular methods found sex ratios closer to 50:50 for both species. They speculated that a disproportionate number of females may be categorized as unknown using external morphology observations, leading to a male bias. The greater loss of female bats has greater implications for population-level impacts. Moreover, the fatality rates at sites is based on carcasses recovered and do not include unborn pups or those still reliant on their mothers for nursing when counting carcasses of reproductive females. Thus, actual fatality rates are likely greater when considering death of young dependent on their mothers for survival.

Age

Many studies report greater fatalities of adult bats than juveniles (Arnett et al. 2008), although there are exceptions. Fiedler et al. (2007) reported fewer adult than juvenile carcasses. Baerwald and Barclay (2011), found greater adult hoary bat and silver-haired bat fatalities in 2006, but observed the reverse in 2007. Jameson and Willis (2012) recorded greater juvenile fatalities of silver-haired bats than adults but found the opposite pattern for hoary bats.

The most common field method to assess relative age of bats (i.e., juveniles or adults) is to examine visually the degree of ossification in the metacarpal-phalangeal joint (Anthony 1988). This joint becomes ossified approximately 2 to 3 months after birth (Kunz and Anthony 1982). In the United States and Canada, bat fatalities are typically greatest in the mid-summer and fall (Arnett et al. 2008, Arnett and Baerwald 2013), coinciding with introduction of volant juveniles and subsequent ossification of joints, perhaps biasing age of carcasses when fatalities are greatest. It is clear that breeding-age adults comprise a large percentage of fatalities, increasing concern for population-level impacts. However, it remains unknown as to why differences between juvenile and adult fatalities are observed among species, sites, and years. Perhaps an alternative method of aging bats is required to answer this question. For example, Baerwald and Barclay (2011) confirmed a high level of accuracy comparing the degree of ossification to a technique of aging that uses the thymus gland. If this method proves to be effective and is practical for field studies, it may serve as a useful tool to age bat carcasses accurately.

Temporal fatality patterns

Bat activity patterns, as measured by acoustic detectors, vary across the night, with greater activity levels often occurring soon after sunset (Hayes 1997). Horn et al. (2008) observed similar patterns of activity near wind turbines using thermal imaging cameras; they recorded the greatest level of activity within 2 hours of sunset. However, Cryan et al. (2014) observed bats interacting with turbines throughout the night, with no distinctive pattern. Too few collisions have been observed to relate fatality to time of night.

Seasonal timing of bat fatalities has been consistent, with greatest reported fatalities occurring in late summer through fall (Arnett et al. 2008, Arnett and Baerwald 2013). This coincides when bats are migrating south and mating (Cryan 2003). Bats colliding with aircraft also are reported during this period (Peurach et al. 2009). Within this period, specific timing of mortality in different species can vary, with timing of hoary bat fatalities preceding those of silver-haired bats (Baerwald and Barclay 2011). Fatalities during other times of the year tend to be relatively low, but can also vary by species. Fatalities of silver-haired bats and Brazilian free-tailed bats have been reported in spring and early summer at several facilities (Arnett et al. 2008, Piorkowski and O'Connell (2010). Paucity of data and lack of full-year studies may contribute, in part, to the fall bias. As wind energy development expands to lower latitudes, multiseason monitoring, and perhaps year-round monitoring, will be necessary to assess the seasonality of bat fatalities in new regions.

Spatial fatality patterns

Bat fatalities tend to be distributed broadly across turbines, as opposed to concentrated at specific turbines at a given facility, although there are some exceptions (Arnett et al. 2008). A few studies have observed greater fatalities on the northern end of the facilities (Fiedler et al. 2007, Gruver et al. 2009, Baerwald and Barclay 2011). Baerwald and Barclay (2011) hypothesized that as bats migrate from north to south in fall, they encounter turbines on the northern end of facilities first. Although rarely reported, turbines near specific habitats, topographic or human-made features also may influence fatality. For example, Piorkowski and O'Connell (2010) reported greater fatalities at turbines located near wooded ravines during 1 year of their study.

There is some suggestion that large landscape features can influence fatality among wind energy facilities. Baerwald and Barclay (2009) documented greater fatality rates of bats at facilities near the foothills of the Rocky Mountains, compared to those in the prairie grasslands. Proximity of potential roosts in the foothills or use of mountains as a navigational reference by bats may have increased fatality rates. Fatality rates also vary from north to south within a region and from east to west across the country. For example, from Pennsylvania and West Virginia north to Maine, fatalities tend to decrease with higher latitudes. Variability in migratory patterns, food availability, and climate conditions may account for these differences (Arnett et al. 2008). In the United States, there tend also to be greater fatalities in eastern and midwestern states than in western states (Arnett and Baerwald 2013). Similar differences may account for these regional discrepancies, as well as differences in population size or study design.

Weather variables associated with bat fatalities

Bats suppress their activity during periods of rain, low ambient temperatures, or strong winds (Erickson and West 2002). Correlations of weather to bat fatalities is somewhat limited because exact timing of fatalities is unknown. However, wind speed consistently seems to be the primary weather variable related to bat fatalities, with lesser wind speeds (i.e., <6 m/s) correlated with greater bat fatalities (Arnett and Baerwald 2013, Cryan et al. 2014). An inverse relationship with temperature, wind direction, and falling barometric pressure also have been associated with greater fatalities, but their importance varies with site (Arnett and Baerwald 2013). Understanding the relationship between fatalities and specific weather conditions has implications for reducing fatalities and more observational data (e.g., using thermal infrared videography) is needed to determine specific conditions under which bats are most at risk.

Turbine characteristics associated with bat fatalities

Turbine operations

There is strong evidence that bat fatalities are associated with operating wind turbines and greatest during low wind conditions (Arnett 2005). Further support for this relationship has been demonstrated by significantly fewer bat fatalities at turbines with operational adjustments, such as feathering (i.e., adjusting the angle of the rotor blade parallel to the wind or by turning the whole unit out of the wind) the blades and raising cut-in speed (i.e., the wind speed at which the generator is connected to the grid and generating electricity; Arnett et al. 2013). Most modern turbines are variable pitch turbines that allow for a range of rotor speeds although a minimum rotor speed (e.g., 9 rpm [revolutions per minute] for Vestas V90) is needed to match the required generator speed to produce energy. There is limited information on the blade tip speed that is lethal to bats, but it is likely that minimum rotor speeds, and, therefore, blade-tip speed, to generate electricity exceeds the lethal limits (Arnett et al. 2013). Cryan et al. (2014) detected high levels of blade investigation by bats when turbines blades were completely feathered or free-wheeling (i.e., rotating <2 rpm). They speculated that bats may already be close to turbines and at risk when turbines begin rotating. Ramp-up speeds for some turbines seem relatively fast (e.g., free-wheeling to rotor cut-in speed in 5 to 7 seconds). Cryan et al. (2014) suggested that decreasing ramp-up speed or number of start-ups in a night might add further value to feathering and raising the cut-in speed to reduce fatalities for no additional loss of power. Another area of research is the wind speed criteria used to initiate turbine start-up, which is commonly based on a rolling 10-minute average. Hypothetically, adjusting wind speed criteria from 10 minutes to 20 or 30 minutes, may reduce bat fatalities and reduce turbine ons and offs until a sustained wind speed is detected.

Turbine height

Barclay et al. (2007) found a significant positive relationship between turbine height and bat fatalities at several wind energy facilities in United States and Canada. Yet, the studies used in the analysis were not concurrent, and differences in annual variation, survey effort, or other factors may have influenced the findings (Arnett and Baerwald 2013). Regardless, numerous studies support the hypothesis that taller turbines are associated with greater fatalities of bats (Fiedler et al. 2007, Arnett et al. 2008, Baerwald and Barclay 2009). However, turbine height alone may not account for differences in fatalities. Taller turbines are associated with larger rotor-swept areas, which presumably contribute to the greater fatality rates. Correlation between taller turbines and larger rotor-swept areas is likely related to activity of certain species at higher altitudes, including species vulnerable to wind turbines such as hoary bats, eastern red bats and Brazilian free-tailed bats. Peurach et al. (2009) reported aircraft collision with bats; approximately 36% had an average strike height of 345 m above ground level (range: 300 to 3,000 m). This suggests that if wind-turbine heights continue to increase, their impact will persist and possibly worsen, as has also been suggested for birds (Loss et al. 2012).

Turbine lighting

Turbine lighting is required by the Federal Aviation Administration (FAA), and typically, it requires synchronized red-flashing lights on multiple turbines throughout a facility. Most studies suggest consistently that FAA lighting does not increase bat fatalities, but, rather, may result in fewer fatalities. At sites in West Virginia and Pennsylvania, Arnett et al. (2005) found no relationship of bat fatality or activity at turbines with FAA lights compared to non-lit turbines. Similarly, Fielder et al. (2007) found no difference in fatalities between turbines with lights, either white strobe or red lights, compared to turbines without lights. Conversely, Bennett and Hale (2014) found fewer fatalities of eastern red bats at turbines with red FAA lights compared to non-lit turbines. If lighting can reduce bat fatalities, at least for certain species, it seems to be relatively easy to implement; yet, additional research is necessary to confirm these findings.

Management implications

Two of the larger gaps in our current understanding are the lack of population data and the cumulative effects of turbine-related fatalities (Kunz et al. 2007, Arnett et al. 2008). The former is made challenging by our basic lack of knowledge concerning the biology and behavior of bats, and it will likely not be resolved any time soon. The latter is a human-induced problem caused by a lack of consistency in sampling design and data collection among sites, fatality estimation among sites, limited long-term and broad-scale studies, and a paucity of publicly available data (Piorkowski et al. 2012). As we move forward, accurate and reliable fatality estimation procedures that are consistent among sites will enhance comparability and allow us to combine data for cumulative fatality estimates (Huso and Dalthorp 2013). Moreover, few studies are published in the scientific journals. The lack of peer-reviewed literature calls into question the validity of publicly available reports. Additional behavioral studies also are warranted to better understand timing and specific conditions that bats are interacting with wind turbines and to assess ultimate causes of collisions (Cryan and Barclay 2009). Finally, paucity of available data hinders our ability to address this complex issue. Greater cooperation among all stakeholders will undoubtedly accelerate our understanding of patterns of bat fatality at wind energy facilities and development of ecologically sound and economically feasible strategies to reduce impact to bats and generate renewable energy.

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