Bats Killed in Large Numbers at United States Wind Energy Facilities

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Bats represent a substantial contribution to mammalian species diversity and ecosystem processes in North America, including their role in performing important economic service functions. The development and expansion of wind energy facilities is a key threat to bat populations in North America. Dead bats are being found underneath wind turbines across North America, and bat fatalities have been documented at almost all of the wind facilities at which thorough bat surveys have been conducted. The results suggest that thousands of bats may be killed annually at some wind facilities, and recent estimates suggest that hundreds of thousands of bats may be killed annually in the contiguous United States. Here, I use published bat fatality information to derive estimates of the number of bats killed at wind energy facilities in the contiguous United States in 2012 and conclude that over 600,000 bats may have died as a result of interactions with wind turbines.

Keywords: bats, wind energy, United States, fatality estimates

There are 45 known bat species in the contiguous United States, and bats represent a substantial contribution to mammalian species diversity and ecosystem processes in North America (O'Shea et al. 2003, Wilson and Reeder 2005, Harvey et al. 2011, Kunz et al. 2011, Ghanem and Voigt 2012) and have important economic impacts on agricultural systems (Boyles et al. 2011). A key current threat to bats in North America is the development and expansion of wind energy facilities (Kunz et al. 2007, Cryan 2011, Smallwood 2013). Dead bats are being found underneath wind turbines across North America, and bat fatalities have been documented at almost all of the wind facilities at which thorough bat surveys have been conducted (Ellison 2012). The results of those surveys suggest that thousands of bats may be killed annually at some wind facilities, and recent estimates suggest that hundreds of thousands of bats may be killed annually in the contiguous United States (Kunz et al. 2007, Cryan 2011, Huso 2011, Ellison 2012, Smallwood 2013). Several authors have estimated the number of bats killed at wind energy facilities in the United States. The models and data used by Kunz and colleagues (2007) represent an early effort to estimate annual bat fatalities; they estimated that 33,000–111,000 bats would be killed annually at wind energy facilities. Cryan (2011) estimated that roughly 450,000 bats are killed each year in North America. Smallwood (2013) used previously unpublished data to derive an estimate of 888,000 bats killed in the United States in 2012. The purpose of this Forum essay is to help provide perspective on this topical issue by using published bat fatality information and probability-distribution-fitting analysis to derive estimates of the number of bats killed at wind energy facilities in the contiguous United States. I conclude that, in 2012, over 600,000 bats are likely to have died as a result of interactions with wind turbines.

Estimated bat fatalities due to wind energy facilities in 2012

I used information on the estimated mean number of bats killed per megawatt per year from 21 locations in the contiguous United States available in the peer-reviewed literature and academic theses (table 1; Arnett et al. 2008, Miller 2008, Piorkowski and O'Connell 2010, Grodsky 2010, Ellison 2012). I used distribution-fitting analysis to determine which of 29 nonnegative probability density functions best fit this bat fatality data using Kolmogorov–Smirnov and Anderson–Darling goodness-of-fit statistics (using EasyFit version 5.5, Mathwave Technologies, Dnepropetrovsk, Ukraine). The Kolmogorov–Smirnov and Anderson–Darling tests are commonly used to evaluate the compatibility of a sample with theoretical probability functions. I then used the highest-ranking models to estimate the mean number of bats killed per megawatt of installed wind turbine capacity per year. I estimated the total number of bats killed in the United States in 2012, assuming approximately 51,000 megawatts of installed capacity at wind energy facilities in the contiguous United States (American Wind Energy Association; *www.awea.org*). For the purposes of this analysis, I assumed that the bat fatality rates per megawatt were stable from year to year (i.e., that the fatality rates per megawatt were not decreasing) and

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Table 1. Published estimates of bat fatalities at wind facilities in the contiguous United States used in this analysis.

Location	Estimated fatalities (in bats per megawatt per year)	Reference
Buffalo Mountain, Tennessee (phase 1)	31.5	Arnett et al. 2008
Buffalo Mountain, Tennessee (phase 2)	38.7	Arnett et al. 2008
Buffalo Mountain, Tennessee (phase 2)	53.3	Arnett et al. 2008
Maple Ridge, New York	14.9	Arnett et al. 2008
Meyersdale, Pennsylvania	15.3	Arnett et al. 2008
Mountaineer 1, West Virginia	32.0	Arnett et al. 2008
Mountaineer 2, West Virginia	25.3	Arnett et al. 2008
Buffalo Ridge, Minnesota (phase 1)	0.2	Arnett et al. 2008
Buffalo Ridge, Minnesota (phase 2)	2.7	Arnett et al. 2008
Buffalo Ridge, Minnesota (phase 3)	2.7	Arnett et al. 2008
Lincoln, Wisconsin	6.5	Arnett et al. 2008
Brownsville, Wisconsin	10.0	Grodsky 2010
Top of Iowa, Iowa	8.7	Arnett et al. 2008
Woodward, Oklahoma	0.8	Piorkowski 2006
Harper County, Oklahoma	0.5	Piorkowski and O'Connell 2010
Snyder, Texas	15.3	Miller 2008
Foote Creek Rim, Wyoming	2.0	Arnett et al. 2008
Klondike, Oregon	0.8	Arnett et al. 2008
Stateline, Oregon–Washington	1.7	Arnett et al. 2008
Vansycle, Oregon	1.1	Arnett et al. 2008
Nine Canyon, Washington	2.5	Arnett et al. 2008
High Winds, California	1.9	Arnett et al. 2008

Note: For additional information, see appendix A of Arnett and colleagues (2008) and Ellison (2012). The two estimates for Buffalo Mountain (phase 2) represent estimates for two wind turbine models.

that the data used here are a representative sample of wind energy facilities in the United States.

The estimated bat fatalities per megawatt per year ranged from 0.2 to 53.3 (table 1), representing data from 13 states in the contiguous United States (figure 1). Over 80% of the wind energy sites used in this analysis had an estimated mean fatality rate of fewer than 20 bats killed per megawatt per year. The (two-parameter) Birnbaum–Saunders fatigue life distribution and the three-parameter fatigue life distribution were both ranked among the three highest-scoring distributions using the Kolmogorov–Smirnov and Anderson–Darling tests (table 2, figure 2). The lognormal (Kolmogorov–Smirnov test) and log-Pearson (Anderson–Darling test) distributions also ranked among the highest-scoring distributions. The four best-fitting distributions were all similar in their probability estimates (figure 2). The unweighted ensemble mean fatality estimate using the four highest-ranking distributions was 683,910 bats killed in 2012, with mean values for individual distributions ranging from 604,860 (fatigue life) to 912,900 (three-parameter lognormal) (table 2).

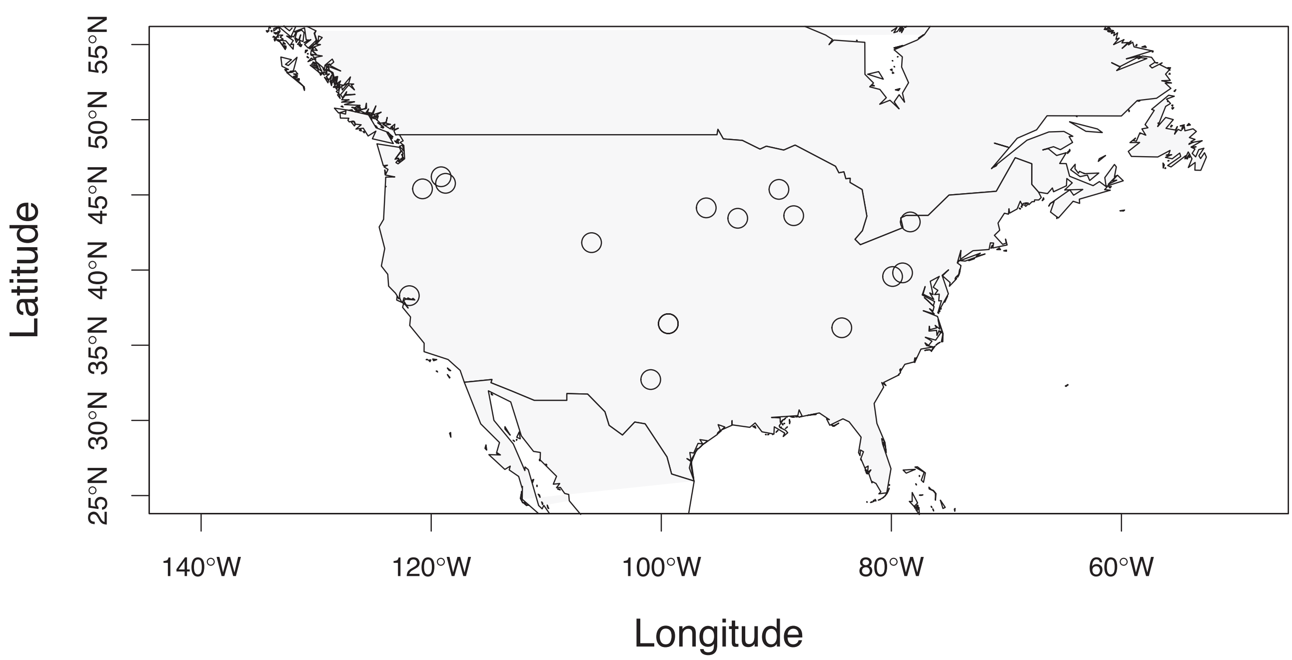

Figure 1. Map of the contiguous United States. The open circles show the locations of published bat fatality data from wind energy facilities used in this analysis.

The fatigue life, log-Pearson, and lognormal distributions are commonly used in distribution-fitting analysis. Fatigue life distributions were originally developed to model failure rates in structures and equipment (Birnbaum and Saunders 1969), not demographic or fatality rates. However, given the close agreement in shape and probability estimates of the top-ranked distributions, I concluded that the fatigue life distributions yield plausible fatality estimates, given the available data. In addition, the fatigue life distributions yield more conservative annual fatality estimates—150,000 lower than the other top-ranked distributions (table 2).

On the basis of currently available data in peer-reviewed publications and graduate theses, this analysis supports the conjecture that hundreds of thousands of bats are dying annually in the United States at wind energy facilities and suggests that well over 600,000 bats may have been killed at

Table 2. Estimates of bats killed by wind turbines in the United States in 2012 using probability-distribution-fitting analysis.

	Kolmogorov–Smirnov test		Anderson–Darling test		Fatality estimate	
Distribution	K_α (goodness of fit)	Rank	A^2 (goodness of fit)	Rank	Relative (in bats per megawatt per year)	Absolute
Fatigue life	0.115	1	0.298	1	11.86	604,860
Fatigue life[a]	0.124	2	0.327	2	11.96	609,960
Log-Pearson[a]	0.130	3	0.381	4	14.89	759,390
Lognormal[a]	0.151	12	0.379	3	17.90	912,900
Ensemble mean					13.41	683,910

Note: The bat fatality estimates are for the contiguous United States in 2012 and are based on the mean fatality estimate for each distribution, assuming 51,000 megawatts of installed wind turbine capacity. The fatigue life, log-Pearson, and lognormal distributions are commonly used in distribution-fitting analysis. The ensemble mean is an unweighted mean of the four distributions appearing in the top three models. [a]These distributions used three parameters.

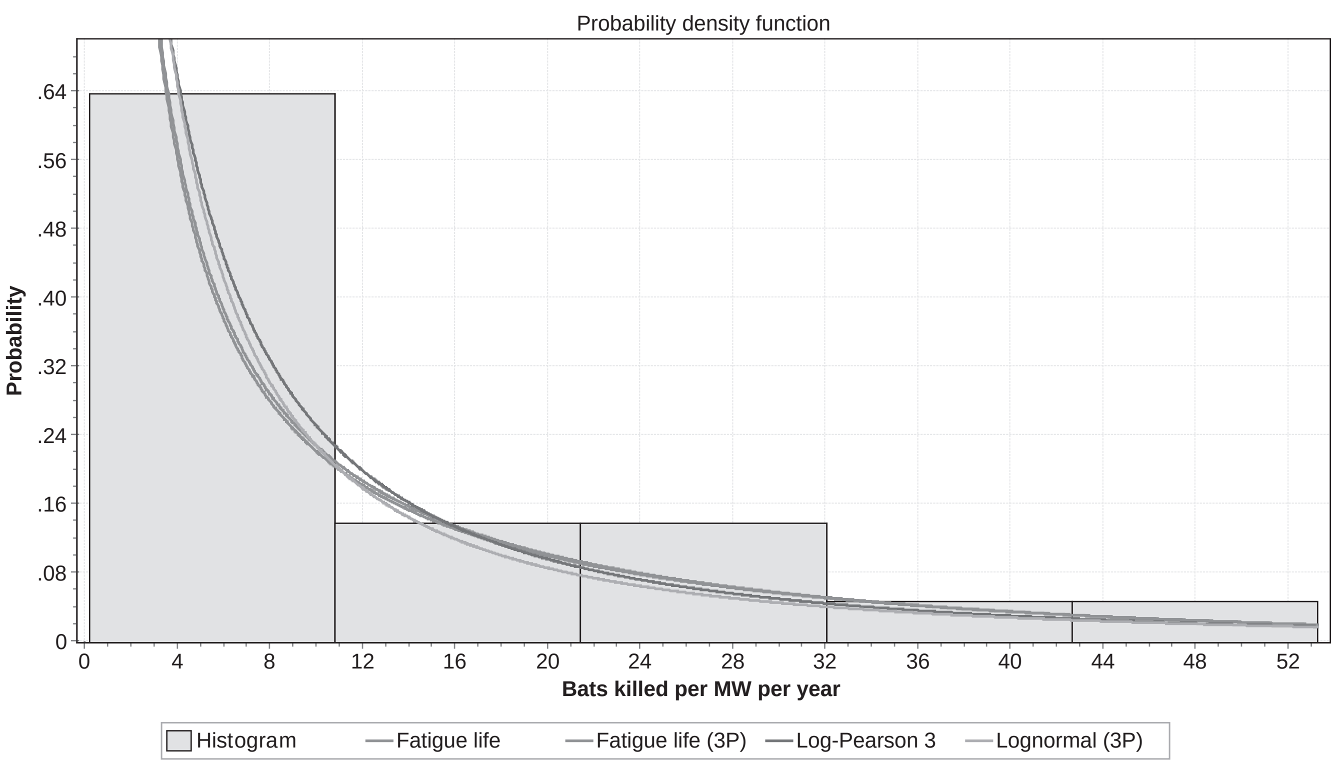

Figure 2. The four best-fitting distributions using published bat fatality data in the United States, assuming stable fatality rates per megawatt (MW) across years. The curves show the shape of the four distributions and indicate close agreement among them. The y-axis is the estimated probability that a randomly selected turbine in the contiguous United States will be associated with a given number of bat fatalities per megawatt per year. For example, the estimated probability that a turbine will result in 10 killed bats per year is approximately between .20 and .24.

such facilities in 2012. This estimate is in general agreement with other recent estimates of bat fatalities at wind energy facilities and is the first estimate to use distribution-fitting analysis to estimate bat fatality rates related to wind energy facilities in the United States. This estimate of bat fatalities in 2012 is probably conservative, (a) because, when a range of fatality estimates were reported at a facility, I used the minimum fatality estimate; (b) because, in most studies, the number of fatalities was estimated for migratory periods and all fatalities throughout the year—not just during the migratory period—were not accounted for; (c) because several areas of the United States that are known to have large bat populations and high species diversity (e.g., Texas, New Mexico, Arizona) are not well represented in this data; (d) because most estimates do not fully account for ground search efficiency, predation rates by scavengers, and other potential sources of bias (Huso 2011); and (e) because the estimate of megawatts of installed wind power in the United States in 2012 is probably low (Smallwood 2013).

These data suggest that some areas of the United States might experience relatively higher bat fatality rates at wind energy facilities than do other regions. For example, sites associated with the Appalachian Mountains (Buffalo Mountain, Tennessee, and Mountaineer, West Virginia) have the highest estimated fatality rates in this analysis. Bats are known to make seasonal movements associated with mountain ranges (Findley 1993, Jaberg and Guisan 2001), and relatively high bat fatality rates might be associated with some mountainous areas in the United States. However, little published information is available on bat fatality rates at wind energy facilities near the Rocky Mountains and Sierra Nevada ranges in the western United States. There is also a lack of published information on other areas of the United States, such as in much of the South, the Southwest, and the basins and ranges of the West. Therefore, I have not attempted to develop regional estimates of bat fatalities. I have also not attempted to develop fatality estimates based on the style or size of the wind turbines but, rather, have restricted this analysis to estimates of bat fatalities per megawatt per year. It is also likely that there are variations in bat fatalities from year to year, because bats experience differing weather patterns and prey and water resource availability, especially during the migratory period, and because bat population sizes fluctuate over long periods. As more information on bat distributions, migratory patterns, and prey use becomes available, it will be useful to develop spatially explicit fatality estimates based on species-specific distribution and migratory patterns; turbine style and size; and local topography, climate, and weather patterns. Fatality estimates would be substantially improved by using data from a randomly selected sample of active wind energy facilities in the United States.

Conclusions

Because of their small size and nocturnal habits, it is difficult to estimate the population sizes of bat species over large scales, such as that of the contiguous United States (O'Shea et al. 2003, 2004). As a result, we do not have high-quality estimates of population sizes of most North American bat species; in many cases, bat researchers would not be able to reliably estimate population sizes within an order of magnitude. This lack of reliable population estimates makes conservation and management planning challenging, especially in the face of other recently emerged threats to North American bat populations, such as diseases (e.g., white-nose syndrome; Frick et al. 2010) and a changing climate (such as in arid Western landscapes; Adams 2010). Furthermore, even under the best circumstances, temperate zone insectivorous bats usually exhibit very slow population growth rates because of the tendency of many bat species to give birth to one pup per year and high mortality rates during a bat's first year of life (O'Shea et al. 2004, Hallam and Federico 2009).

Unlike other threats to bat populations, such as disease and climate change, the impacts of wind energy development are predictable: Bats will be killed when both bats and turbines are active and when they are in close proximity to each other. Given bats' contribution to mammalian species diversity in North America and their ecological and economic importance, it will be helpful to continue research on the current and future impacts of wind energy development on bat populations. It will also be helpful to support efforts to estimate and monitor bat population sizes throughout North America.

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