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Factors associated with bat mortality at wind energy facilities in the United States

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Abstract

Hundreds of thousands of bats are killed annually by colliding with wind turbines in the U.S., yet little is known about factors causing variation in mortality across wind energy facilities. We conducted a quantitative synthesis of bat collision mortality with wind turbines by reviewing 218 North American studies representing 100 wind energy facilities. This data set, the largest compiled for bats to date, provides further support that collision mortality is greatest for migratory tree-roosting species (Hoary Bat [*Lasiurus cinereus*], Eastern Red Bat [*Lasiurus borealis*], Silver-haired Bat [*Lasionycteris noctivagans*]) and from July to October. Based on 40 U.S. studies meeting inclusion criteria and analyzed under a common statistical framework to account for methodological variation, we found support for an inverse relationship between bat mortality and percent grassland cover surrounding wind energy facilities. At a national scale, grassland cover may best reflect openness of the landscape, a factor generally associated with reduced bat activity and abundance that may also reduce turbine collisions. Further representative sampling of wind energy facilities is required to validate this broad pattern. Ecologically informed decisions regarding placement of wind energy facilities involves multiple considerations, including not only factors associated with bat mortality, but also factors associated with bird collision mortality, indirect habitat-related impacts to all species, and overall ecosystem impacts.

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Supplementary Material
A detailed description of methods (Appendix A); monthly mortality proportions used to estimate annual mortality (Appendix B); R script for simulations used to assess bias in statistical estimators (Appendix C) and implement the selected statistical estimator (Appendix D); and total bats killed by month (Appendix E) and species (Appendix F) are online.

Keywords

anthropogenic wildlife mortality; bats; systematic review; wind energy; wind turbine

1. Introduction

A global increase in renewable energy generation has helped offset some of the environmental impacts of fossil fuels. In 2017, the 84 gigawatts of U.S. installed wind energy capacity represented 8% of the nation's total electricity generating capacity (EIA 2017), and wind energy has increased in generation capacity more than any other U.S. energy source in recent years (EIA 2016). Although wind energy is renewable, wind energy facilities can adversely affect wildlife, both indirectly due to habitat loss, disturbance and displacement, and creation of movement barriers (Kunz et al. 2007b; Arnett et al. 2008), and directly due to collisions of wildlife with wind turbines, a phenomenon recorded worldwide (Arnett et al. 2016).

Wind turbine collisions annually kill hundreds of thousands of bats in the U.S. (Arnett & Baerwald 2013; Smallwood 2013). These fatalities have sparked conservation concern because bats have low reproductive rates and require high adult survivorship to avoid population decline (Barclay & Harder 2003). Additionally, bats face an increasing variety of anthropogenic threats, including habitat loss and white-nose syndrome. As a result, populations of many species are in decline (e.g., Eastern red bat [*Lasiurus borealis*], Northern long-eared bat [*Myotis septentrionalis*], and Little brown bat [*Myotis lucifugus*]) (Winhold et al. 2008; Jones et al. 2009; Frick et al. 2010). Determining cumulative effects of wind energy facilities on bats is difficult because there is limited information about bat population abundance and trends (Cryan 2011). However, wind turbine collisions may threaten population viability for some frequently killed species, such as the Hoary Bat (*Lasiurus cinereus*) (Frick et al. 2017).

National-scale information about drivers of bat-turbine collision mortality is required to inform bat conservation and wind facility siting. Although research has assessed factors influencing bird-turbine collision mortality at a national scale (Barclay et al. 2007; Loss et al. 2013), drivers of bat collision rates remain unclear even though more bats than birds appear to be killed (Smallwood 2013). In the U.S., most bat fatalities appear to occur between late-July and mid-September and to affect migratory tree-roosting species (e.g., Hoary bat, Eastern red bat, and Silver-haired bat [*Lasionycteris noctivagans*]) (Johnson 2005; Kunz 2007a; Arnett & Baerwald 2013). Studies at individual wind energy facilities suggest that proximity to hibernacula, ravines, and wetlands influences mortality (Piorkowski & O'Connell 2010; Ferreira et al. 2015). Comparisons of bat mortality among North American wind energy facilities illustrate a positive relationship between bat mortality and turbine height (Barclay et al. 2007) and mortality variation among different regions and vegetation cover types (Arnett et al. 2008; Arnett & Baerwald 2013).

Although this research has increased understanding of bat-turbine collisions, studies comparing bat mortality among wind energy facilities are limited due to their largely qualitative approach and unaddressed methodological variation that limits cross-facility comparisons (Huso et al. 2016). We conducted a quantitative synthesis of bat collision mortality with wind turbines by reviewing 218 North American studies representing 100 wind energy facilities. Using a subset of 40 U.S. studies meeting rigorous inclusion criteria—and implementing a common statistical framework to account for methodological variation—we assessed factors associated with variation in bat collision mortality across U.S. wind energy facilities.

2. Materials and Methods

Detailed methods are in Appendix A. We conducted a literature search resulting in compilation of 218 published and unpublished studies from the U.S. and Canada (Fig. 1). To minimize bias, we applied several inclusion criteria, such as only including studies of monopole turbines and those accounting for surveyor detection and scavenger removal of carcasses. This resulted in acceptance of 40 studies/wind facilities from which we extracted mortality data and values of potential facility-scale predictor variables. Although we reviewed and screened studies from Canada and included these in summaries of bat mortality by species and month, only U.S. studies met inclusion criteria for the analysis of mortality correlates. We therefore limit the scope of our conclusions about factors associated with bat mortality to the U.S.

Predictor variables included factors documented or hypothesized to cause variation in bat mortality within or among facilities: turbine hub height, number of turbines in the facility, topography (represented by mean elevation and elevation range), and the proportion of different land cover types surrounding facilities (Barclay et al. 2007; Kunz et al. 2007b; Arnett et al. 2008; Baerwald & Barclay 2009; Arnett & Baerwald 2013). We also assessed the effect of geographic region using categories in Arnett & Baerwald (2013) representing broad habitat characterizations (e.g., Northeastern Deciduous Forest, Great Plains). For land cover variables, we used ArcGIS 10.3 (ESRI 2014) and the National Land Cover Database (Homer et al. 2015) to calculate percent cover of four reclassified cover types (forest, shrubland, grassland, agriculture) in 500 m and 1 km buffers around facilities. These buffers correspond to scales beyond the search radius of bat mortality surveys but within distances we hypothesized land cover would most influence bat activity and mortality. We were unable to consider other variables (e.g., weather, turbine lighting system) due to limited resolution of mortality data and/or inconsistent reporting in original studies.

For facilities sampled less than a calendar year, we estimated annual mortality using monthly mortality proportions calculated from year-round studies (Appendix B). We ran all mortality data through a statistical estimator (Etterson 2013) that incorporates information about mortality surveys and searcher detection and scavenger removal trials to estimate the proportion of bat carcasses found at each facility (Appendices C and D). These proportions were combined with annual carcass counts and numbers of turbines and megawatts (MW) of installed generating capacity to estimate per turbine and per MW annual mortality rates at each facility. For both estimated mortality rates, we ran a null model and single-variable linear regression for each predictor variable (using ln+1-transformed mortality). Model support was determined using Akaike’s Information Criterion, corrected for small sample sizes (Burnham & Anderson 2002). We did not assess multiple-variable models due to the limited sample size of included studies and because we found clear support for the top models in each analysis.

3. Results

The reviewed data spanned 39 years (1976 to 2014), 26 U.S. states, and 2 Canadian provinces, representing the largest bat mortality database compiled to date (12,532 total fatalities). Within this data set, 82% of mortality occurred from late summer to early fall (July-October) (Appendix E), and 19 species were reported, with 3 composing the majority of mortality: Hoary Bat (35%), Eastern Red Bat (27%), and Silver-haired Bat (17%) (Appendix F).

Based on the 40 U.S. studies meeting inclusion criteria, percent grassland within 500 m of wind facilities was overwhelmingly the most strongly supported factor for explaining per MW mortality (ΔAIC_c >11 above next best model; ω_i=0.99; Table 1). Across observed grassland cover values (0.0–98.6%), mortality decreased by 7.8% (coefficient±95% CI = −1.76±1.12; R^2=0.21; Fig. 2). For mortality per turbine, two models received strong support, those containing grassland cover within 1 km (ω_i=0.49) and 500 m (ω_i=0.36; Table 1). Across observed cover values at the 1 km scale, mortality per turbine decreased by 7.64% (coefficient±95% CI = −1.33±0.97; R^2=0.20; Fig. 3a); at the 500-m scale, mortality decreased by 6.23% across cover values (coefficient±95% CI = −1.39±0.97; R^2=0.18; Fig. 3b).

4. Discussion

We found that bat mortality was inversely related to grassland cover surrounding wind facilities, and we provide additional evidence that most U.S. bat fatalities occur between July and October with migratory tree-roosting species most affected. There are several potential explanations for the relationship between mortality and grassland cover. First, tree-roosting bat species are generally less abundant and/or concentrated in grasslands and other open areas, especially during migration (Johnson et al. 2004; Baerwald and Barclay 2009), and this may result in less collision mortality. However, exceptions to this pattern exist (Jain 2005; Arnett and Baerwald 2013), and as described below, a lack of data may limit the generality of this finding to all regions. Second, the relationship could indirectly reflect a positive relationship between forest cover and bat mortality. Qualitative studies have suggested such an association (Johnson 2005; Arnett et al. 2008); however, our quantitative analysis indicated no support for the forest cover model, and recent research documenting significant bat mortality at some wind facilities in non-forested areas of the Great Plains and Midwest suggests a more complex relationship between bat mortality and land cover (Arnett & Baerwald 2013). Third, the relationship could have an underlying geographic explanation with facilities in extensive grasslands tending to occur in regions characterized by other factors influencing mortality. Although we found no support for a region model based on broad vegetation characterizations, other regional factors that potentially co-vary with grassland cover (e.g., seasonal bat abundance, migratory patterns, food abundance, and both local airflow and large-scale weather patterns; Arnett & Baerwald 2013; Cryan et al. 2014) may partly explain this relationship and should be explored with further research. Fourth, at

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a national scale, grassland cover may better reflect openness of the landscape surrounding wind facilities (a factor associated with bat activity/abundance, as discussed above) than other factors that reflect openness in certain regions (e.g., agricultural cover in the Midwest, a region with relatively little remaining grassland cover). Regardless of the explanation, additional a priori research across a large number of representative wind facilities would further clarify predictors of bat mortality (Huso et al. 2016).

Percent grassland cover was the most strongly supported variable for both per turbine and per MW mortality, supporting the robustness of this relationship. However, cumulative bat mortality may actually be higher in some regions with substantial grassland cover, such as the Great Plains, due to the large amount of installed wind generating capacity (NREL 2016). Furthermore, the data meeting inclusion criteria underrepresented top wind energy producing regions that are experiencing rapid energy growth and have substantial grassland (e.g., Texas, Oklahoma, and Iowa). Additional research in under-studied regions is required to validate the pattern documented here. Even if the relationship between mortality and grassland cover applies broadly, placing turbines in intact grasslands may not be advisable due to adverse impacts to biodiversity. Siting wind energy facilities involves multiple considerations, including not only factors associated with bat mortality, but also factors associated with bird collision mortality, indirect habitat-related impacts to all species, and overall ecosystem impacts. Notably, achievement of national renewable energy development goals appears possible by avoiding grasslands and instead placing turbines in disturbed agricultural areas (Kiesecker et al. 2011).

Other wind facility characteristics have been suggested to influence bat mortality. For example, Barclay et al. (2007) found that taller turbines killed more bats, a pattern also shown for birds (Loss et al. 2013). Although tall turbines reach into airspace used by large numbers of migrating bats (Mabee & Cooper 2004; Plissner et al. 2006), we found no evidence that turbine height influences bat mortality. The earlier study included data from shorter lattice turbines that we excluded, and this may partially explain these contradictory findings (see also Loss et al. 2013). We recommend further research into the relationship between turbine height and bat mortality because turbines are expected to eventually reach 140 m in height (Zayas et al. 2015).

Our results are limited by availability and quality of bat mortality data, and the issues of data standardization and transparency have been repeatedly discussed in the context of wind energy impacts on wildlife (Huso et al. 2016). We applied inclusion criteria that excluded studies lacking clear methods or experimental trials accounting for major survey-related biases, and we also accounted for substantial methodological variation by analyzing all mortality data with a common statistical estimator. The large number of excluded studies (178 of 218 studies reviewed) indicates substantial effort is required to improve rigor and standardization in data collection, as well as clarity and transparency of data reporting.

Wind energy avoids many environmental impacts of nonrenewable energy sources; however, adverse impacts of wind energy on wildlife, including bat collisions with wind turbines, remain a significant conservation issue. Populations of many bat species are experiencing long-term declines due to numerous anthropogenic impacts, and bat mortality at turbines raises additional concerns due to the rapid expansion of wind energy in North America. Additionally, turbines are becoming larger to allow for more efficient wind energy generation in previously undeveloped regions (e.g., the southeastern U.S.) and at lower wind speeds (Zayas et al. 2015). Continued research will be needed to document correlates of bat mortality and impacts to bat populations as the wind energy industry evolves.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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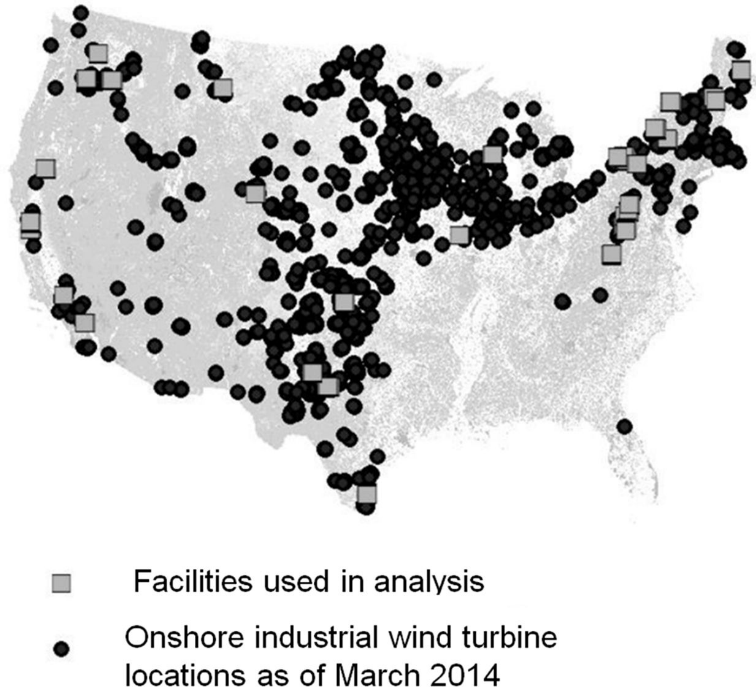

Figure 1.

Map of all U.S. wind energy facilities as of March 2014 (Diffendorfer et al. 2014), including sites meeting inclusion criteria that were used in the current analysis of factors influencing bat mortality rates at U.S. wind energy facilities.

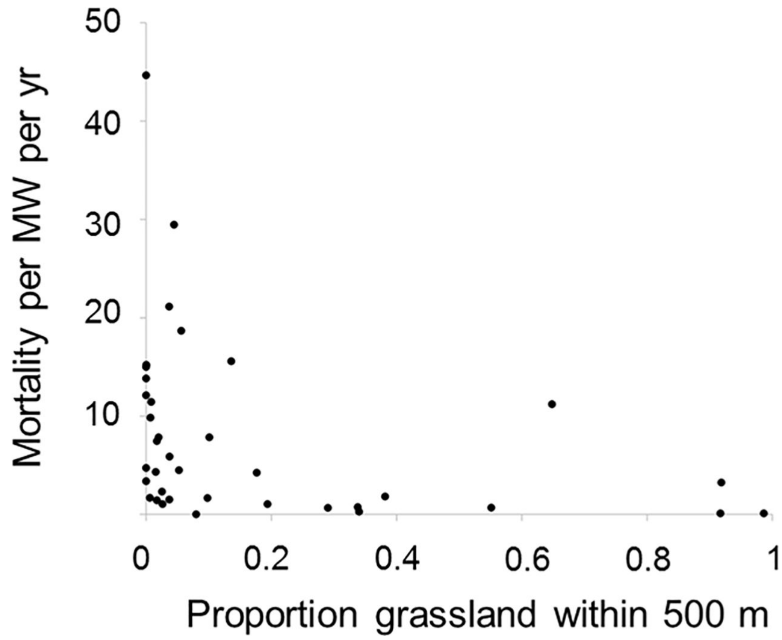

Figure 2.
Relationship between bat mortality (per megawatt per year) and grassland cover within 500 m of wind facilities.

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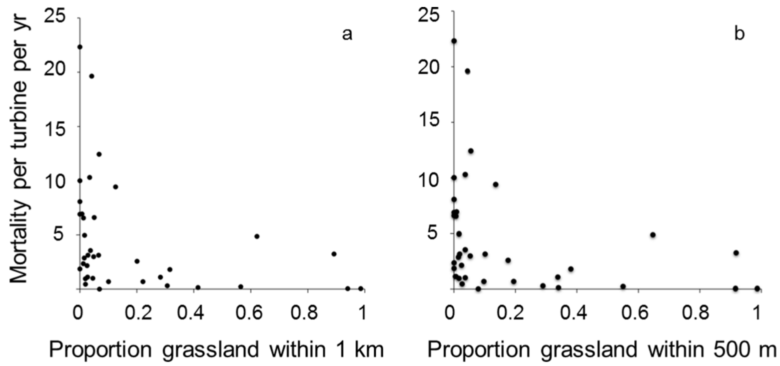

Figure 3.

Relationship between bat mortality (per turbine per year) and grassland cover within (a) 1 km, and (b) 500 m of wind facilities.

Table 1.

Model selection results for analysis of factors associated with bat collision mortality per megawatt (MW) per year (left) and per turbine per year (right) as derived from Akaike's Information criteria, corrected for small sample size (AIC_c).

Model (Mortality per MW per yr)	K[a]	ΔAIC_c[b]	ω_i[c]	Model (Mortality per turbine per yr)	K[a]	ΔAIC_c[b]	ω_i[c]
Grassland cover within 500 m	2	0.00	0.989	Grassland cover within 1km	2	0.00	0.493
Grassland cover within 1 km	2	11.004	0.004	Grassland cover within 500 m	2	0.617	0.362
Mean elevation	2	11.765	0.003	Forest cover within 1 km	2	4.208	0.060
Region	2	11.866	0.003	Forest cover within 500 m	2	4.642	0.048
Elevation range	2	15.265	0.000	Shrub cover within 500 m	2	7.906	0.009
Forest cover within 1 km	2	16.065	0.000	Shrub cover within 1 km	2	7.946	0.009
Forest cover within 500 m	2	16.391	0.000	Agriculture cover within 500 m	2	7.998	0.009
Shrub cover within 500 m	2	20.303	0.000	Agriculture cover within 1 km	2	8.005	0.009
Shrub cover within 1 km	2	20.325	0.000	Mean elevation	2	18.888	0.000
Agriculture cover within 1 km	2	20.366	0.000	Elevation range	2	21.617	0.000
Agriculture cover within 500 m	2	20.373	0.000	Region	2	21.739	0.000
Turbine hub height	2	35.577	0.000	Turbine hub height	2	21.862	0.000
Null model	2	37.187	0.000	Number of turbines	2	25.206	0.000
Number of turbines	2	37.550	0.000	Null model	2	25.479	0.000

[a] Number of parameters in the model

[b] Difference in AIC_C value between model and the most strongly supported model

[c] AIC_C weight – relative support for model