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Fatalities at wind turbines may threaten population viability of a migratory bat

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ABSTRACT

Large numbers of migratory bats are killed every year at wind energy facilities. However, population-level impacts are unknown as we lack basic demographic information about these species. We investigated whether fatalities at wind turbines could impact population viability of migratory bats, focusing on the hoary bat (*Lasiurus cinereus*), the species most frequently killed by turbines in North America. Using expert elicitation and population projection models, we show that mortality from wind turbines may drastically reduce population size and increase the risk of extinction. For example, the hoary bat population could decline by as much as 90% in the next 50 years if the initial population size is near 2.5 million bats and annual population growth rate is similar to rates estimated for other bat species ($\lambda = 1.01$). Our results suggest that wind energy development may pose a substantial threat to migratory bats in North America. If viable populations are to be sustained, conservation measures to reduce mortality from turbine collisions likely need to be initiated soon. Our findings inform policy decisions regarding preventing or mitigating impacts of energy infrastructure development on wildlife.

1. Introduction

Wind energy development is growing rapidly across the globe as a renewable energy source. However, wind energy facilities are not without environmental costs (Saidur et al., 2011). For example, large numbers of bats are killed at wind energy facilities (Arnett et al., 2016; O'Shea et al., 2016). Over 300,000 bats are estimated to be killed annually at wind energy facilities in Germany (Lehnert et al., 2014; Voigt et al., 2012) and over 500,000 are estimated to be killed annually across Canada and the United States (Arnett and Baerwald, 2013; Hayes, 2013; Smallwood, 2013). Over the past decade, substantial numbers of bat fatalities and increased growth in wind energy have raised concern about the impacts of wind energy development on bat populations (Kunz et al., 2007). A critical question for conservation planning is whether these fatalities could drive populations to dangerously low levels or even extinction.

Addressing this question is challenging because bats that migrate latitudinally over long distances have the highest fatalities at wind energy facilities and are among the least studied (Kunz et al., 2007). Basic demographic parameters and even rough empirical estimates of population size do not exist (Lentini et al., 2015). In general, reproductive rates for bats are low, which can impact their ability to respond to mortality threats (Barclay and Harder, 2003). Lack of empirical demographic and population data for migratory bats, especially for non-colonial species, limits the ability to quantitatively assess the potential impact of wind energy on these species (Diffendorfer et al., 2015). The challenges associated with empirical estimation will likely remain insurmountable into the foreseeable future given the ecology of these organisms.

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Determining the threat of wind energy development on migratory bats highlights the common problem of how to assess threats to species when critical data are lacking. Data from similar species or structured elicitation of expert opinion can be used for conservation decision-making when empirical data for a focal species are unavailable (Burgman et al., 2011; Drescher et al., 2013; Martin et al., 2012). In recent decades, expert elicitation has been used for a variety of conservation problems (Donlan et al., 2010; Martin et al., 2005; Oberhauser et al., 2016; Runge et al., 2011; Smith et al., 2007), and evaluations of the elicitation method provide structured approaches to help guard against subjective biases when eliciting expert opinion (Martin et al., 2012). Deciding whether conservation measures are necessary to prevent or mitigate impacts from wind energy development on populations of migratory bats requires use of expert judgments and/or use of data from similar taxa to quantify reasonable scenarios of population growth and trajectories.

We use population projection models to explore whether fatalities from wind turbines threaten the population viability of hoary bats (*Lasiurus cinereus*), a wide-spread migratory species comprising the highest proportion of bat fatalities (38%) at wind energy facilities in North America (Arnett and Baerwald, 2013). Given the lack of empirical data on key population parameters for hoary bats, we used data from similar species as well as expert elicitation (Martin et al., 2012) to identify available data sources, provide estimates of unknown parameters, and quantify uncertainty. Our objective was to assess the likelihood that mortality from wind energy turbines poses a species-level threat to hoary bats in North America to inform conservation decision-makers about the potential impacts of energy infrastructure development on migratory bats. We hypothesized that mortality from wind energy turbines at installed capacity by 2014 was sufficiently high to substantially reduce the probability of population stability and increase the probability of extinction over the next 50 to 100 years.

2. Materials and methods

2.1. Expert elicitation

We used a structured elicitation method to obtain specific judgments or values from experts. Co-author JAS and colleagues served as eliciting facilitators and identified the conservation problem ("Does mortality from wind turbines pose a threat to population viability of hoary bats in North America?"), selected the experts, and designed the elicitation process. Nine experts (see Supporting Information) were identified based on literature review and discussions with the bat ecology and conservation community and invited to participate by JAS. Experts were chosen based on their research programs and publication records relevant to migratory bat ecology with an intent to represent a range of expertise (e.g. expertise in population dynamics, genetics, physiology, life history, and conservation). The elicitation was conducted over an introductory webinar (September 22, 2014), in-person meeting (October 21–22, 2014), and a working webinar (December 22, 2014).

Experts were instructed on the expert elicitation process and informed of the common pitfalls and biases that often impair expert judgments (Martin et al., 2012), such as anchoring and overconfidence (Speirs-Bridge et al., 2010). Anchoring happens when an expert fixes on a benchmark value and cannot adjust away from the benchmark, while overconfidence occurs when an expert believes their judgement is more accurate than is warranted (Martin et al., 2012). To help minimize anchoring and over-confidence, a four-step elicitation method was used whereby experts provided a lower bound, upper bound, and most likely estimate, and ranked their confidence level that the true value fell within the lower and upper bounds (Speirs-Bridge et al., 2010). Experts were trained on the methodology by practicing seed questions. Judgments were elicited using a modified Delphi method (Burgman et al., 2011) whereby experts provided judgments anonymously, responses were collated and discussed with the group, and then experts were allowed to adjust their estimates anonymously (Burgman et al., 2011; Martin et al., 2012). This structured approach allowed for the benefits of discussion among experts while guarding against group think (Burgman et al., 2011). Experts completed multiple rounds of elicitation until all experts were content with their responses and indicated they were at least 80% confident that the true value fell between their lowest and highest bounds.

Experts estimated the continental-wide population size of hoary bats and four vital rates: adult annual survival, first-year annual survival, adult fecundity, and first-year fecundity (Tables S1, S2). Annual survival was estimated in the absence of mortality related to wind energy. Bats typically cannot be aged after their first autumn which limits most demographic studies to two stages: young-of-the-year and adult (Lentini et al., 2015; O'Shea et al., 2004) (Fig. S1). Empirical studies on demography of other vespertilionid bats were used to inform expert opinions on vital rates because no estimates exist for hoary bats, congeneric, or ecologically equivalent species (Lentini et al., 2015; O'Shea et al., 2004). We calculated population growth rate (λ) as the dominant eigenvalue from a 2-stage Lefkovitch matrix (Caswell, 2001) using the 'most likely' vital rate estimates from each expert using function eigen.analysis in the popbio package of R (Stubben and Milligan, 2007).

2.2. Empirical estimates of bat population growth (λ)

We surveyed the literature for empirical estimates of bat population growth rates based on calculation from vital rate matrices to compare how values from expert elicitation compared to empirical studies of other bat species. We searched the 27 papers used by Lentini et al. (2015) that used vital rate estimation based on Cormack-Jolly-Seber methods for published estimates of population growth and included two additional recent studies that were published after Lentini et al. (2015) to generate 14 published estimates of population growth rate calculated from vital rate matrices for nine bat species (Table S3). There is no indication of population structure for hoary bats in Canada and the continental United States (Russell et al., 2015), so we assumed a single open population and set immigration and emigration to zero.

2.3. Estimates of mortality from wind energy turbines in North America

Arnett and Baerwald (2013) estimated the number of bats killed by wind turbines in Canada and the U.S. in 2012 (range: 196,190–395,886), of which 38% were hoary bats. We calculated fatalities per megawatt (MW) based on installed capacity in North America in 2012 (66,213 MW) and adjusted fatality estimates (F_{wind}) to the installed capacity in 2014 (75,570 MW) (American Wind Energy Association, 2016; Canadian Wind Energy Association, 2016). We kept installed capacity constant at 2014 levels to reduce uncertainty in projecting future MW capacity. We used the midpoint of the adjusted fatality estimate for hoary bats ($F_{wind} = 128.469$) to calculate the proportion of the population killed by wind turbines (F_{wind}/N_i), where N_i is initial population size, and applied that proportional mortality for each year in the simulation. We assumed that an individual bat's probability of colliding with a turbine would not depend on the density of bats, and therefore used a constant mortality rate.

2.4. Population projection model

We projected stochastic population growth with and without mortality from wind turbines across a range of mean population growth rate (λ) values and initial population sizes (N_i) to compare changes in population stability after 50 years and probability of extinction after 100 years to identify the demographic scenarios for which current levels of mortality from wind turbines results in substantial population declines or increased risk of extinction of hoary bats. We performed 100 projections (10,000 simulations per projection) using 10 sequential values of mean population growth rate (λ) from 0.94 to 1.18 and 10 sequential values of initial population size (N_i) from 1 to 10 million bats based on ranges provided by expert elicitation and informed by empirical studies of other bat species.

To account for annual variability in population growth, we used a random draw generated from a log-normal distribution where $\mu = \ln(\lambda)$ and $\sigma^2 = 0.10$ (Morris and Doak, 2002) at each time step in each simulation. We used 0.10 for σ^2 to account for environmental variation and uncertainty in λ (Morris and Doak, 2002). We fixed a ceiling on population growth at 10 times the initial population size to account for carrying capacity and to balance between unbounded and overly constrained population growth. We chose not to include additional complexity of density-dependent population growth given the limitations of available data for parameterization. We set a quasi-extinction threshold at 2500 bats.

Population stability was calculated as the proportion of the remaining population to the initial population after 50 years of projected growth (N_{50}/N_i). Probability of extinction was calculated as the fraction of simulations where the population size fell below the quasi-extinction threshold during 100 years of projected growth. We present the results as isoline contours visualizing the combinations of N_i and λ values that result in population stability or probability of extinction thresholds of interest.

3. Results

Current rates of wind turbine fatalities are sufficiently high to substantially change the probability of population stability and risk of extinction across a range of plausible demographic scenarios for hoary bats (Figs. 1 and 2). Mortality from wind turbines increased the isoline of stable population growth after 50 years indicating that annual population growth rate (λ) would have to be substantially higher, particularly at lower population sizes, to compensate for wind-associated mortality (Fig. 1). The annual population growth rate would need to be at least 6% per year (λ = 1.06) to maintain a stable population if initial population size was 2.5 million bats and as great as 14% per year if there are only 1 million hoary bats (Fig. 1). Similarly, mortality from wind turbines increased the isoline for population persistence, indicating that mortality from wind turbines could also increase the risk of extinction over the next 100 years (Fig. 2).

Mortality from wind turbines could result in a 50% reduction in population size in just 50 years even in an optimistic scenario of a hoary bat population as large as 10 million bats and a mean annual growth rate of 1% per year, which would otherwise support stable population growth (Fig. 3). At the ‘most likely’ demographic scenario from the expert elicitation (N_i = 2.5 million bats and pre-wind λ = 1.015), the median projected population size after 50 years was reduced by 90% (Fig. 3) and the probability of extinction increased to 22% (Fig. 4). Growth rate

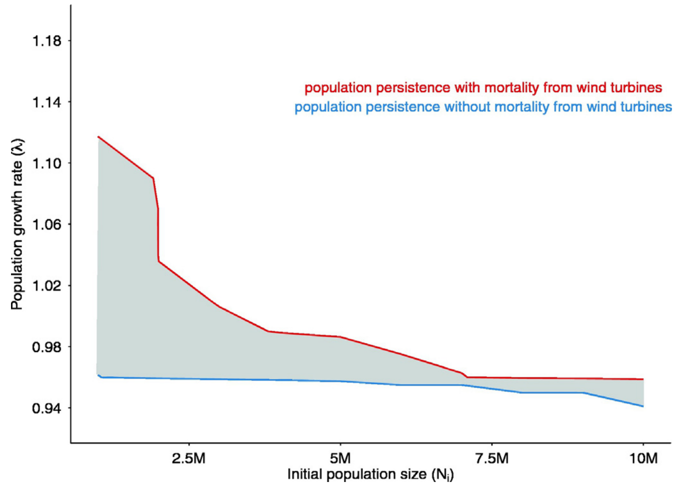

Fig. 2. Comparison of the isolines showing population persistence (e.g. <1% of probability of extinction) after 100 years of population growth with (red) and without (blue) mortality from wind energy turbines for hoary bats. Population persistence is positive above isolines and negative below the isolines. Gray shaded area indicates where proportional mortality from wind turbines changes population trajectories by shifting the isoline upward, indicating that annual population growth rates must be higher, especially at low population sizes, to compensate for mortality associated with wind energy turbines for populations to persist. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

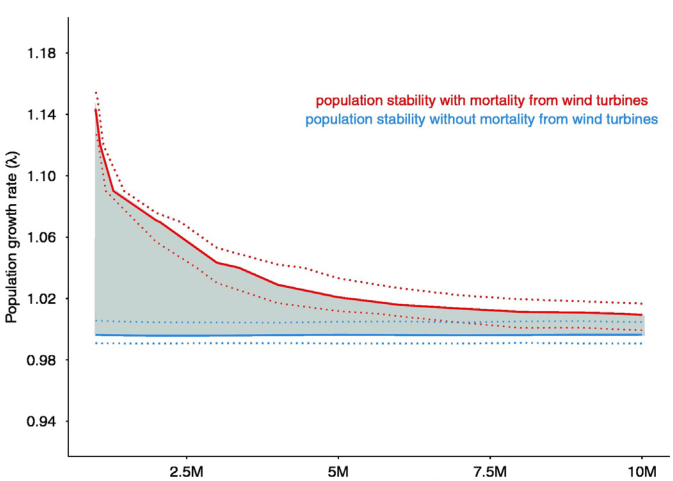

Fig. 1. Comparison of the isolines of stable population growth after 50 years of population growth with (red) and without (blue) mortality from wind energy turbines for hoary bats. Solid lines are the median values from 10,000 simulations and dotted lines show the 25th and 75th quartiles. Population stability is positive above isolines and negative below the isolines. Gray shaded area indicates where proportional mortality from wind turbines changes population trajectories by shifting the isoline of population stability upward, indicating that annual population growth rates must be higher, especially at low population sizes, to compensate for mortality associated with wind energy turbines for populations to remain stable. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

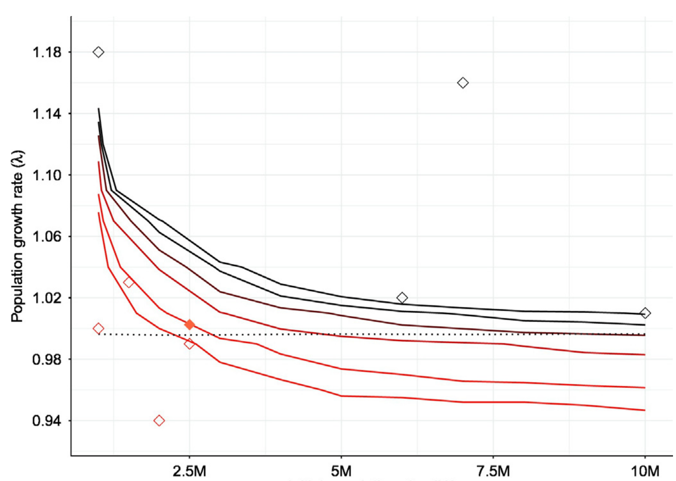

Fig. 3. Isoline contours of projected population declines after 50 years of simulated growth with proportional mortality of hoary bats from wind energy turbines across combinations of possible initial population sizes (N_i) and population growth rates (λ). Isolines display the combinations of N_i and λ where the median population of 10,000 simulations after 50 years of simulated growth was stable (black line) or decreased by 25%, 50%, 75%, 90% and 95%. The dotted line shows the isoline of population stability without wind mortality for comparison as shown in Fig. 1. Open diamonds show the ‘most likely’ values of N_i and λ from each of 8 experts from the expert elicitation. The orange filled diamond indicates the median ‘most likely’ value for N_i and λ from expert elicitation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

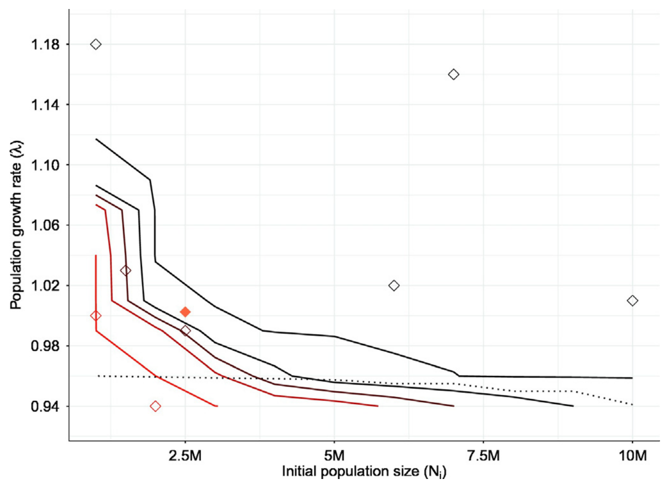

Fig. 4. Isoline contours of probability of extinction after 100 years of simulated population growth with proportional mortality from wind energy turbines across combinations of possible initial population sizes (N_i) and population growth rates (λ) for hoary bats. Isolines display the combinations of N_i and λ where the proportion of populations (<1%, 25%, 50%, 75%, 99%) of 10,000 simulations went extinct during 100 years of simulated population growth. The dotted line shows the isoline of persistence (<1% chance of extinction) without wind mortality for comparison as shown in Fig. 2. Open diamonds show the 'most likely' values of N_i and λ from each of 8 experts from the expert elicitation. The orange filled diamond indicates the median 'most likely' value for N_i and λ from expert elicitation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and population size combinations from four experts fell above the isolines for population stability and persistence, but values from the other four experts fell well below the isolines of stability and persistence (Figs. 3 and 4).

The median population growth rate ($\lambda = 1.015$) from the expert elicitation was similar but slightly higher than the median of 14 published estimates of population growth rate calculated from vital rate matrices for other bats species ($\lambda = 1.0025$) (Fig. 5).

4. Discussion

Reports of large numbers of bats killed at wind energy facilities have attracted conservation attention for the past decade (Kunz et al., 2007).

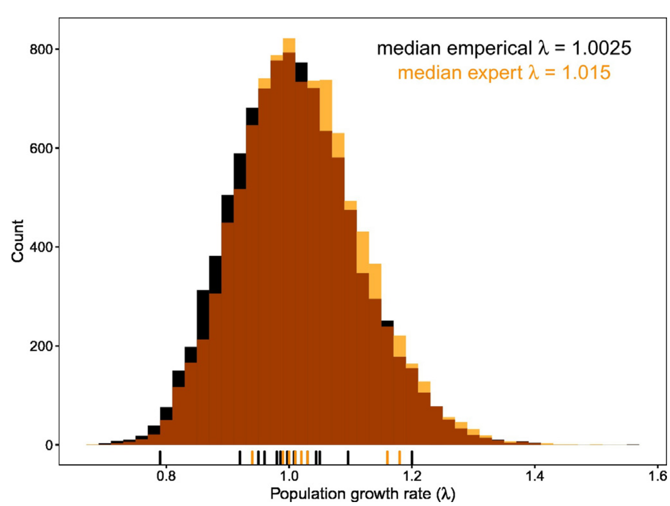

Fig. 5. Histograms of 10,000 simulated λ values drawn from a log normal distribution. The black histogram centers on the median of 14 reported values of λ from empirical studies on bat species. The orange histogram centers on the median λ from expert elicitation. All simulations used a variance at 0.10 to account for environmental variation and uncertainty in population growth. Rug values show reported λ's from published studies (black) and expert elicitation (orange). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

However, the lack of basic demographic information about bats in general and migratory bats specifically, has hindered our ability to empirically address whether bat fatalities from wind energy developments presents a serious threat to the viability of these species (Diffendorfer et al., 2015). Likewise, few studies have directly estimated population-level impacts from mortality from wind turbines on bird populations (Carrete et al., 2009; Schaub, 2012; Stewart et al., 2007), although numerous studies have documented collision rates for both birds and bats (see Arnett et al., 2016; Erickson et al., 2014 for recent reviews). We parameterized population models using a range of values from expert elicitation and informed from empirical estimates from other bat species and show that, across a range of plausible demographic scenarios, current mortality from wind turbines could result in rapid and severe declines of bat populations within 50 years and increased risk of extinction in 100 years.

For hoary bat populations to sustain stable, persisting populations with levels of mortality from wind turbines current through 2014 in North America, the mean annual population growth rate must be substantially higher than what appears most likely from both the expert elicitation exercise and empirical estimates from other bat species. While two experts provided demographic estimates that produced robust population growth rates ($\lambda = 1.16$ and $\lambda = 1.18$; i.e., growth rates of 16–18% more bats per year) and a few empirical estimates were similarly high (Fig. 5), the median values of λ from published studies and expert opinion ($\lambda = 1.0025$ and $\lambda = 1.015$, respectively) suggest much more modest population growth rates that were sufficient for stable populations in the absence of wind energy associated mortality but that are too low to sustain the level of observed mortality currently caused by wind turbines. As expected, the impact of wind energy related mortality is most dramatic and concerning at lower population sizes, although we note that even at the optimistic scenario of at least 10 million bats, the isolines for both population stability and persistence were shifted upwards, indicating that increased population growth is necessary to compensate for wind-associated mortality even at large population sizes. In contrast to the availability of empirical estimates for population growth from other bat species, there is scant information available about the total population sizes of bats. Six of the eight experts put their most likely estimate at or below 2.5 million bats. If the hoary bat population is around 2.5 million bats, our results suggest that growth rates that we expect as reasonable for bat populations ($\lambda = 1.01$) would result in a 90% decline of the population in 50 years.

Although our modeling focused on hoary bats, the qualitative conclusions are likely broadly informative about the relative risk to other migratory species that share similar life histories and high fatality rates at wind turbines, such as eastern red bats (*Lasiurus borealis*) and silver-haired bats (*Lasionycteris noctivagans*) in North America (Arnett and Baerwald, 2013) and noctule bats (*Nyctalus noctula*) in Europe (Lehnert et al., 2014). Future work combining expert elicitation and modeling could examine vulnerability to other species with high fatality rates to identify species most at risk. In North America, species that migrate latitudinally and do not hibernate for extended periods in caves and mines do not appear at high risk from white-nose syndrome, a disease that causes high mortality for hibernating bats (Frick et al., 2010, 2015; Langwig et al., 2015). Fortunately, fatality rates from wind turbines are typically lower for many of the species susceptible to white-nose syndrome (Arnett and Baerwald, 2013; Langwig et al., 2012), yet the combined effects of mortality from disease and wind turbines may threaten some species (Erickson et al., 2016).

The range of scenarios we modeled was based on current available information and conservative estimates of bat fatalities. We used the lowest published estimate of bat fatality rate although higher estimates of annual fatality rates have also been published (Hayes, 2013; Smallwood, 2013). Furthermore, we held megawatt capacity constant at installed capacity in 2014 and did not account for future growth of the wind energy industry to reduce other forms of uncertainty in the models. Wind energy currently represents approximately 5% of electricity generation in Canada and U.S.A., with a target of increasing to 20% by 2025 in Canada and by 2030 in U.S.A (American Wind Energy Association, 2016; Canadian Wind Energy Association, 2016). Installed capacity increased by over 5100 MW (a 7% increase from 2014 installed capacity) in 2015 alone (American Wind Energy Association, 2016; Canadian Wind Energy Association, 2016). With more turbines and no reductions in fatality rates at wind energy facilities, we expect fatalities and species-level impacts to migratory bats to increase (i.e., greater declines in N). Future modeling efforts should explore the impact of increased turbine development and assessment of how mitigation efforts can be applied to reduce population-level impacts.

The only method documented to reduce fatalities at wind turbines is limiting operation during high risk periods, such as nocturnal periods of low wind speeds during autumn migration (Arnett et al., 2011; Baerwald et al., 2009). Such operational curtailment can reduce bat fatalities by 44–93% with minimal impact on power generation (Arnett et al., 2011). The American Wind Energy Association recently adopted policies to limit blade movement in low wind speeds as a voluntary operating protocol to reduce fatalities (American Wind Energy Association, 2015). Industry-wide implementation of operational mitigation or emerging technologies (e.g. acoustic deterrents; Arnett et al., 2013) may be necessary to successfully manage migratory bat populations and ensure stable and viable populations in North America. Siting wind energy facilities in places perceived as lower risk for causing bat fatalities could also help reduce impacts, although further research is needed to determine the efficacy of predicting risk from pre-siting assessments (Baerwald and Barclay, 2009; Hein et al., 2013; Lintott et al., 2016).

Conservation decisions must often be made with imperfect knowledge and data gaps. We lack empirical data on population sizes and trends for hoary bats and other migratory bat species, and given the ecology of these species and technologies available, we are unlikely to collect empirical population data in the near future. Our analyses suggest there is a range of realistic possibilities for the impact of fatalities from wind turbines that includes substantial population declines and increased risk of extinction. The magnitude of these predicted impacts may warrant re-evaluation of the status of hoary bats from least concern to a threatened category on the IUCN Red List (IUCN, 2012). Given the possibility for near or total extinction from wind-energy-related fatalities, our results suggest that conservation planning to manage migratory bat populations should include actions to reduce bat fatalities at wind energy facilities in North America.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.biocon.2017.02.023.

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