CFE
fn. 2 - Assessing fatality minimization...bats...
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Friedenberg, N. A., and W. F. Frick. 2021

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Declaration of Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Abstract

Wind energy is an important sector of the renewable energy market. Observations of bat fatalities at wind farms raise concern about impacts to biodiversity, particularly amid projections of wind energy build-out. We investigated how continued wind energy development in the United States and Canada, as well as adoption of measures to reduce bat fatality rates, influence the population viability of the hoary bat (*Lasiurus cinereus*). Our model included uncertainty about population size and dynamics as well as future wind energy development. Results indicate that current levels of wind energy build-out may have already caused substantial population declines. Under our lowest-risk scenario of high maximum growth rate and low wind energy build-out, the median simulated population of 2.25 million hoary bats experienced a 50% decline by 2028. We show that risks of decline and extinction may still be mediated with rapid adoption of measures to reduce bat fatalities. We find that levels of fatality reduction shown to be achievable in empirical studies of fatality minimization, by turbine curtailment, may be sufficient to manage risks. Simulations of population trends suggest that declines exceeding 5% per year support fatality reduction to manage extinction risk. Importantly, both the risks and the level of fatality reduction necessary to manage them were highly uncertain. Population size remains the most critical data gap to determining population viability of hoary bats. Studies to empirically determine baseline estimates of population size and trends over time remain urgently needed to inform conservation action.

Keywords

renewable energy, migratory bats, density-dependence, population viability, management

Introduction

Rapid growth of installed wind energy generation capacity around the world has been driven by domestic and international approaches to emissions reductions (Gu and Zhou 2020; IRENA 2019) and is a key component of the global energy transition strategy to limit the impacts of climate change (Gielen et al. 2019). In the United States and Canada, sustained wind energy development has been encouraged by a combination of public policy and market forces (NEB 2018; USEIA 2020). Despite its benefits, however, wind energy development must contend with immediate and local environmental impacts, including habitat loss and direct mortality of wildlife (Allison et al. 2019; Arnett et al. 2007). Wind turbines are known to kill a variety of wildlife species, including birds and bats (Katzner et al. 2016; Thaxter et al. 2017). High rates of observed bat fatalities at wind turbines have raised conservation concern (Arnett et al. 2007; Kunz et al. 2007; Rydell et al. 2010) and motivated research efforts to identify contributing factors (Cryan 2008; Cryan et al. 2014) as well as strategies to minimize fatalities (Arnett et al. 2013a; Arnett et al. 2011; Hayes et al. 2019). Continued global expansion of wind energy requires research to guide evidence-based conservation targets to manage risks to sensitive taxa.

In North America, three bat species that perform long-distance seasonal migrations (hoary bats, *Lasiurus cinereus*; eastern red bats, *Lasiurus borealis*; and silver-haired bats, *Lasionycteris* *noctivagans*) comprise an estimated 72-79% of bat carcasses reported in post-construction surveys at wind energy facilities (estimate depends on dataset AWWI 2020; Thompson et al. 2017), and make up the majority of bat fatalities at wind farms except in the southwestern United States (AWWI 2020). The hoary bat is the most widespread species among carcasses recorded during post-construction monitoring at wind farms in the United States and Canada (present in 95% of monitoring studies in the U.S., AWWI 2020) as well as the most prevalent (31-38% of all carcasses, depending on dataset, Arnett and Baerwald 2013; AWWI 2020; Thompson et al. 2017). Despite the accumulation of fatality monitoring data and advances in fatality estimation methods (Dalthorp et al. 2018), a lack of empirical data on population size and underlying demographic rates for hoary bats and other affected species has limited the determination of population-level risks (Frick et al. 2017).

Fatality rates of bats, most often measured as fatality per megawatt (MW) of generation capacity, can be reduced by increasing the minimum wind speed at which turbines become operational given a strong association of higher fatalities on nights with low wind speeds (< 6 m/s) (Arnett et al. 2008; Arnett et al. 2011; Arnett et al. 2013b; Berthinussen et al. 2021). The effect of turbine curtailment varies among bat species. While the fatality reduction generally increases with the cut-in wind speed, the achieved reduction of a given curtailment regime has differed among experiments. For instance, cut-in speeds of 4.5-5.5 m/s were associated with a 60% reduction in hoary bat carcass detections compared with controls at the Fowler Ridge wind farm in Indiana in 2010 (Good et al. 2011) and an 85% reduction in 2011 (Good et al. 2012). Meta-analysis of curtailment studies suggests an exponential decrease in fatality rate with increases in the cut-in speed above 3 m/s, a typical minimum wind speed for energy generation. A 5 m/s cut-in was associated with a mean fatality reduction for hoary bats of 48% (95% CI = 24-64% Whitby et al. 2021). Adoption of operational curtailment in North America has been limited by its potential impact on energy generation and research continues on optimization (e.g., Hayes et al. 2019) as well as the development of alternative technologies such as ultrasonic acoustic deterrents (Arnett et al. 2013a). Converting fatality minimization research into widespread practice is greatly impeded by the lack of information on what level of fatality reduction is deemed necessary or sufficient. However, mounting concern about the potential for population-level impacts to hoary bats (Davy et al. 2020; Frick et al. 2017; Rodhouse et al. 2019) and the consequences of regulatory protection for a species with a transcontinental range and broad habitat associations have elevated a sense of urgency to quantify risk and identify strategies to mitigate impacts.

In response to the need to assess the potential impact of turbine-related fatalities on the hoary bat population, the United States Fish and Wildlife Service initiated an expert elicitation to establish a range of plausible population sizes and demographic parameters. This provided estimated ranges of key parameters to project hoary bat population dynamics with turbine-related fatality to provide the first estimates of potential population-level impact of observed fatalities at wind turbines for the hoary bat population in North America (Frick et al. 2017). That modeling effort found mortality from wind turbines was sufficient to cause rapid and steep decline of hoary bat populations under certain conditions. However, installed wind energy capacity has nearly doubled since 2014, highlighting the need to address how continued growth of wind energy development may influence risk to populations. Furthermore, there is a need to identify fatality reduction targets to manage risk.

We extend the modeling approach used by Frick et al. (2017) to determine risk to hoary bat populations from anticipated growth of the wind energy sector in the United States and Canada through 2050. We address four questions, (1) How will continued build-out of land-based wind energy capacity in the United States and Canada affect the risk of population decline or extinction of hoary bats? (2) How much fatality reduction at wind energy facilities is necessary to manage population-level impacts? (3) How would the approximately 50% reduction in fatality rate associated with operational curtailment below wind speeds of 5 m/s (Whitby et al. 2021) change risk to hoary bat populations? and (4) Are population trends over time useful for informing fatality minimization targets for risk management? We parameterized stochastic models to predict the trajectory of hoary bat populations through 2050 that incorporated uncertainty about mean fatality rates and variability in population growth rates using an integrated model of mortality and a density-dependent model of population growth rate. We generate probabilistic outcomes to assess the risk of population decline or extinction associated with estimated levels of mortality from two projected build-out scenarios of continued development of wind energy facilities in the United States and Canada. Our study characterizes the range of possible targets for minimizing fatality rates that lower risk to the population given broad uncertainty about population size and dynamics as well as future wind energy capacity build-out. We use the risk analysis framework to assess the potential benefit of adopting an intervention such as curtailing turbines below 5 m/s, which is expected to reduce hoary bat fatalities by nearly half. Lastly, we explore how efforts to estimate trends in hoary bat populations, in the absence of estimates of total population size, can help inform risk management.

Methods

Population model

We used a model of population growth for the hoary bat that included demographic sensitivity to sources of additional mortality similar to models of fisheries under harvest pressure (Pascual et al. 1997). The model's form corresponds to Beverton-Holt density-dependence (Beverton and Holt 1957) with an additional mortality term,

$$\lambda_t = \lambda_{max}\left[1 + \frac{N_t}{K}(\lambda_{max} - 1)\right]^{-1}(1 - m_t), \qquad \textit{Eq. 1}$$

where λ_t is realized population growth rate at time t, λ_{max} is the maximum population growth rate, N_t is abundance at time t, K is the carrying capacity in the absence of additional mortality, and m_t is additional mortality at time t. In the absence of additional mortality, a stable equilibrium abundance, $N^* = K$, exists if the population can grow ($\lambda_{max} > 1$) and K is positive. If $\lambda_{max} = 1$, Eq. 1 collapses to the density-independent model described by Frick et al. (2017). We explored a range of maximum population growth rate, from a low of $\lambda_{max} = 1$ to a high of $\lambda_{max} = 1.18$, the highest value of population growth rate from the Frick et al. (2017) elicitation. We used the expert elicitation estimates of abundance as indicative of carrying capacity. Equilibrium abundance, N^*, declines linearly as m increases, such that

$$N^* = K\left(1 - m\frac{\lambda_{max}}{\lambda_{max} - 1}\right) \qquad \textit{Eq. 2}$$

for $\lambda_{max} > 1$. Thus, hoary bat equilibrium abundance, when one exists, declines with the introduction of turbine-related mortality. Conversely, reducing mortality from collisions with wind turbines causes the model equilibrium to recover toward K. With $\lambda_{max} = 1$, no equilibrium exists. In this case, trajectories were limited by a ceiling an order of magnitude above initial abundance.

We projected abundance using lognormal temporal variability in expected growth rate and turbine-related mortality,

$$\lambda_t = \lambda_{max}\left[1 + \frac{N_t}{K}(\lambda_{max} - 1)\right]^{-1}(1 - m_t\varepsilon_{1t})\varepsilon_{2t}, \qquad \text{Eq. 3}$$

where ε_{1t} and ε_{2t} are uncorrelated lognormal random deviates for wind farm mortality and maximum population growth rate, respectively, each with mean = 1 and a 10% coefficient of variation. To minimize any truncation error, variation was applied to the smaller of m or $1 - m$.

Mortality from wind turbines

Our model of mortality from wind turbines assumed that fatalities of hoary bats are proportional to the megawatts (MW) of installed capacity, as in earlier studies (Arnett and Baerwald 2013; Frick et al. 2017), but applied this proportionality at a time scale much shorter than a year, resulting in an instantaneous per capita rate effect on population growth of $-aC_t$, where C_t is installed capacity in year t and a is an interaction term and is much smaller than the annual mortality rate. Annual mortality was then found by integrating over one year, leading to an expression familiar from the Nicholson-Bailey predator-prey model (Murdoch et al. 1985):

$$m_t = 1 - e^{-aC_t}, \qquad \text{Eq. 4}$$

where e is the base of the natural logarithm. In our context, m equates to the probability of a hoary bat encountering and being killed by a turbine over the course of a year, assuming encounters occur at random.

Mortality was scaled to installed capacity by solving Eq. 4 for a under 2012 conditions. If N_{2012} and F_{2012} are abundance and the number of fatalities in 2012, respectively, then the per capita probability of surviving wind farms in 2012, s_{2012}, is $1 - F_{2012} / N_{2012}$. Taking installed capacity in that year to be C_{2012},

$$a = \frac{1}{C_{2012}}\ln(s_{2012}), \qquad \text{Eq. 5}$$

where ln is the natural logarithm. Substituting Eq. 5 into Eq. 4, mortality becomes

$$m_t = 1 - (s_{2012})^{C_t/C_{2012}}. \qquad \text{Eq. 6}$$

We used Eq. 6 to adjust mortality over the course of scenarios in which installed capacity, C_t, increased over time. Our model did not explicitly track geographic variation in hoary bat fatality rates, which are known to vary regionally (Arnett and Baerwald 2013; AWWI 2020). The assumption that turbine-related mortality rates scale with total installed capacity therefore implicitly also assumes that the geography of future build-out will follow historical patterns. It also implies that the population is well-mixed among regions, an assumption supported by large-scale genetic homogeneity in the continental hoary bat population (Russell et al. 2015).

Uncertainty in the base fatality rate used to compute s_{2012} was captured by drawing estimates from a normal distribution corresponding to the 95% confidence interval for all 2012 bat fatalities (summed over all installed capacity) given in Arnett and Baerwald (2013), scaled by the frequency of hoary bats among fatalities scored in that study (38%) and 2012 installed capacity in the United States and Canada (66,268 MW, AWEA and CANWEA). The base 2012 fatality rate had a mean (standard deviation) of 1.7 (0.3) hoary bats per MW, respectively. Each model projection used a single random draw from the fatality distribution to compute 2012 survival given the scenario's population size.

Wind energy build-out scenarios

Market forecast models indicate varying levels and tempos of build-out of the wind energy sector over the next 30 years. We developed two build-out scenarios, termed high and low. The high scenario projected 318.3 GW of installed land-based wind energy capacity by 2050 in the United States based on the 2015 Wind Vision report (USDOE 2015) and 24 GW by 2040 in Canada (NEB 2018). We assumed Canadian installed capacity additions would continue at their 2040 rate, reaching 26.5 GW by 2050 and resulting in total capacity projection of 345 GW by 2050. The low build-out scenario used a market forecast of 80% less additional land-based development in the United States after 2020 than called for in the Wind Vision report, assuming tax policy and competing energy prices would make wind energy uncompetitive (USEIA 2020). The Canadian projection was unchanged in the low-buildout scenario, leading to a forecasted total installed capacity of 165 GW in 2050. By the end of 2020, the United States had already reached 118 GW (www.eia.gov), leaving only 20 GW of further development before the low build-out end-point is reached.

Quantifying the effect of continued build-out of land-based wind energy capacity on population decline and extinction risk to hoary bats

We projected dynamics from 2012 through 2050 under the high and low build-out scenarios. Initial population size and baseline population growth rate were based on the ranges developed by expert elicitation (Frick et al. 2017). We treated this uncertainty as non-probabilistic. Initial population sizes included the minimum (1 million), median (2.25 million) and maximum (10 million) of expert opinions on "most likely" abundance and for an initial abundance of 4 million, as a midpoint between the median and maximum values from expert opinions. Mean population growth rate was set either at replacement ($\lambda = 1$) or the highest expert opinion, ($\lambda = 1.18$). The monotonicity of risk as a function of population growth rate implies that results for all possible intermediate values would fall between these extremes.

We defined two metrics to summarize risk at each time step. The first, population decline risk, measured the proportion of model simulations falling by at least 50% of their initial abundance. The second metric, extinction risk, scored the proportion of simulations falling below a quasi-extinction threshold of 2,500 individuals. Simulations were run in R (R Core Team 2020) using base libraries. Probabilities were summarized from 10,000 replicates of each combination of population size and population growth rate. Code is available from the authors upon request.

Estimating fatality reduction targets to manage decline and extinction risk to hoary bats

For each build-out scenario, we systematically explored the effect of fatality reduction on decline and extinction risk over initial population sizes ranging from 1 to 10 million hoary bats, in increments of 0.25 million, at low and high growth rates. Fatality reductions were modeled as a reduced baseline rate of fatalities per MW. The model was agnostic about the mechanism by which fatality rate was reduced. All new MW capacity additions were assumed to adopt fatality reduction strategies beginning in 2021. Adoption by existing capacity was assumed to increase linearly to 100% over a 10-year period beginning in 2021.

For a target of reducing fatalities by a proportion, γ, and a level of adoption, p_t in year t, baseline mortality was calculated by modifying Eq. 5,

$$a_t = \frac{1}{C_{2012}} \ln[1 - m_{2012}(1 - \gamma p_t)], \qquad \text{Eq. 7}$$

where m_{2012} is turbine-related mortality in 2012. We recorded the minimum fatality reduction, to whole-percentage precision, necessary for less than a 50% chance of a 50% decline and, separately, less than a 1% chance of quasi-extinction.

Estimating the change in risk to hoary bat populations of a simulated industry adoption of curtailing turbines below wind speeds of 5 m/s

The fatality minimization achieved by operational curtailment of wind turbines has been tested for a variety of cut-in wind speeds. Meta-analysis of these studies suggests that blanket adoption of a 5 m/s cut-in speed would achieve an expected 48% reduction in hoary bat fatalities per MW, with a 95% confidence interval of (24%, 64%) (Whitby et al. 2021). This estimate is useful for illustrating how a given conservation action might affect population-level risk for hoary bats, particularly for its quantification of uncertainty. Coincidentally, the anticipated 48% reduction in fatality aligns closely with the 47.8% reduction in final installed generation capacity of the low build-out scenario, providing a case of comparable ultimate mortality reduction through curtailment or reduced wind energy development. We used the estimated distribution of fatality reduction at 5 m/s cut-in to explore the potential impact on risk over time under high and low build-out scenarios. For fatality reduction γ, the empirical distribution of $\ln(1 - \gamma)$ was approximately symmetric. We modified each population projection's fatality rate with a single random draw of $1 - \gamma$ from a lognormal distribution with mean -0.67 and standard deviation 0.19, yielding a mean and 95% confidence interval of $\gamma = 0.48$ (0.26, 0.65). Hence, the distribution of risk produced by the model included uncertainty about the actual level of fatality reduction achieved.

Relating simulated population trends to inform targets for fatality reduction

Population size estimates have been difficult to obtain for hoary bats (Korstian et al. 2014). However, trend information has been obtained in regional studies using acoustic detections (Rodhouse et al. 2019) or wind farm fatality data (Davy et al. 2020). The NABat program aims to assess trends at broader spatial scales (Reichert et al. 2021). We explored using the risk assessment modeling framework to facilitate decision-making with population trends rather than population size. Trends were measured as the geometric mean annual percentage decline in hoary bat abundance projected by our population model from the beginning of 2012 to the end of 2020 (log-linear regressions produced similar results). We generated 10,000 replicate trends at high and low population growth rates across all initial population sizes and estimated the fatality reduction necessary to manage extinction risk associated with these trends by simulating population growth under the high build-out scenario at varying fatality reduction levels from 2021 through 2050. For each initial abundance in 2012, the population model produced a range of trends through 2020. We used the 2.5% and 97.5% quantiles of projected abundance in 2020 to assess minimization targets to manage the risk of extinction by 2050. For the lowest initial abundance in 2012 (1 million hoary bats), we assessed minimization targets at 10 additional quantiles.

Results

Projected mortality in 2050

Our model projected mean annual turbine-related mortality in 2050 under the high build-out scenario at 46%, 23%, and 6% for initial population sizes of 1, 2.25, and 10 million, respectively. Under the low build-out scenario, mean 2050 mortality at those initial abundance levels was reduced by roughly half to 26%, 12%, and 3%, respectively. Simulated 5 m/s curtailment had an effect similar to build-out reduction, yielding 2050 mortality levels of 27%, 13%, and 3% under high build-out at the three benchmark initial population sizes, respectively.

The effect of wind energy build-out on population decline and extinction risk to hoary bats

Simulations of risk over time indicated that fatality at wind energy facilities can significantly impact the hoary bat population but that risk is highly uncertain. With a high initial abundance of 10 million hoary bats, mean declines by 2050 were 32-70% under high build-out and 17-50% under low build-out, depending on population growth rate. Across initial abundance levels, the probability of a 50% decline ranged from 0.01 to 1.0 with a median year ranging from 2016 to beyond 2050 (Table 1). At low initial abundance, mortality rates were sufficiently high to drive a 50% reduction in the hoary bat population before 2019 regardless of the strength of the density-dependent demographic response or build-out scenario (Fig. 1a,b), suggesting realized population declines of more than 9% annually. Demography influenced decline risk at high initial abundances. For instance, with an initial abundance of 10 million hoary bats, population growth rate made the difference between a median year of decline prior to or beyond 2050. Differences in build-out had generally smaller qualitative effects on risk (Fig. 1a,b), only affecting whether decline was expected within the 30 year time horizon at intermediate population sizes and high population growth rate (Table 1).

The probability of extinction by 2050 ranged from 0.0 to 1.0 and was highly sensitive to initial abundance. Extinction risk existed only for initial population sizes less than about 3.25 million. If there were 1 million hoary bats in 2012, then the population was expected to fall below the quasi-extinction threshold within the next 20-30 years under the high build-out scenario (Fig. 1c). Lower build-out delayed extinction risk and increased the influence of demography, yielding a larger range of uncertainty at the lowest initial population size (Fig. 1d), but still produced up to a 97% chance of extinction by 2050. The slower population decline under low build-out translated to a reduced maximum initial population size for extinction risk, 2.25 million, a level at which the high build-out scenario produced up to a 40% chance of extinction by 2050.

Fatality reduction targets necessary to manage population decline and extinction risk to hoary bats

The target reduction of fatality rates to manage risk was sensitive to initial abundance, demography, and build-out, spanning the full range from 0 to 100% for decline risk (Fig. 2a) and 0 to 90% for extinction risk (Fig. 2b). Management of decline risk was particularly sensitive to the strength of compensatory population growth. If the initial population size of hoary bats was less than about 4 million bats, declines of 50% or more occurred prior to the adoption of fatality reduction measures and could not be mitigated if the population did not exhibit compensatory dynamics (Table 2). Even at the largest population size considered (10 million bats), the model indicated a fatality reduction target over 60% in the absence of compensation (Table 2). With high population growth (λ_{max} =1.18), fatality reduction was only required to manage decline risk at initial population sizes below 4-6 million, depending on build-out (Fig. 2a). With high growth rate and low build-out, conditions with the lowest average risk of decline, minimization targets still ranged as high as 75%.

Management of extinction risk required fatality reductions ranging from 0 to 90% (Table 2, Fig. 2b). The initial size of the hoary bat population was the primary determinant of whether minimization was required (Fig. 2b). Within the narrow range of initial population sizes exhibiting extinction risk, fatality minimization targets were highly sensitive to abundance. Conversely, the minimum population size that would be protected from extinction risk was relatively insensitive to the choice of fatality minimization target. For instance, a 20% reduction in fatality rate per MW installed capacity would address extinction risk in a population of at least 2.5 million hoary bats, while an 80% reduction would manage risk for a population of 1.25 million. Uncertainty about demography and build-out produced a large range of fatality minimization targets for management of extinction risk at the lowest initial abundance tested (Table 2).

Change in risk to hoary bat populations of a simulated industry adoption of curtailing turbines below wind speeds of 5 m/s

With mean long-term fatality reductions drawn from a distribution (mean = 48%, 95% CI = 26-65%), the range of probabilities of 50% declines included or exceeded 0.5 in all high build-out scenarios (Fig. 3a) but fell below 0.5 under low build-out with high initial population size (Fig.3b). Low build-out simulations with high population growth rate illustrated the potential for recovery after fatality minimization, evidenced by temporary decreases in decline risk after adoption (Fig. 3b). Extinction risk was absent in simulations with initial populations of at least 2.25 million, regardless of build-out (Fig. 3c,d). Under the most conservative scenario, initial abundance of 1 million hoary bats and no compensatory dynamics, a simulated 5 m/s cut-in shifted the median year of extinction from 2033 to 2040 under high build-out and from 2038 to just beyond 2050 in the low build-out scenario (Fig. 3c,d). Uncertainty in the simulated effect of curtailment below wind speeds of 5 m/s did not alter its expected effect on risk.

Utility of population trends to inform targets for fatality reduction

Simulated population trends between 2012 and 2020 varied substantially, even within population types defined by initial abundance and maximum population growth rate. For instance, replicates of populations starting with 1 million hoary bats in 2012 displayed over 30% variation around their mean annual decline rates of 16 and 10 percent for the low and high population growth rates, respectively (density plots, Fig. 4a). In contrast, the fatality reduction target for managing extinction risk showed little variation within population types (e.g., lines, Fig. 4a), suggesting that trend information is an imprecise indicator of management needs. However, patterns in the simulation data suggested coarse relationships between population trend information and minimization targets. Fatality reduction targets ranged from 0 to 25% for populations showing no decline (Fig. 4b). When expected (mean) rates of decline were greater than 5% per year (heavy curves, Fig. 4b), some level of fatality reduction was required to manage extinction risk regardless of maximum population growth rate (Fig. 4b). When projected annual rates of decline exceeded 12%, the minimum fatality reduction target increased rapidly and the uncertainty in fatality reduction target decreased.

The width of the shaded areas in Figure 4b were a function of our choice of confidence limits, the uncertainty of estimated 2012 total fatality, and assumptions including environmental variability and the rate of and extent to which fatality reduction measures were adopted. The upper bounds of the shaded areas were imposed artificially by restricting simulations to a minimum initial abundance of 1 million hoary bats; lower initial abundance would produce greater mean rates of decline and higher minimization targets.

Discussion

This study examined the risk of hoary bat decline or extinction posed by fatalities at wind farms in the United States and Canada. We extended previous modeling (Frick et al. 2017) by assessing risk on a shorter timeline, incorporating projections of continued wind energy development, considering compensatory population dynamics, and exploring the range of fatality minimization targets necessary to manage risk. Our findings, taken at a gross level, indicate clearly that the current fatality rate of hoary bats at wind energy facilities in the United States and Canada poses a risk to the population. Of particular concern, turbine-related mortality may plausibly be high enough to have already caused a substantial decline. However, management of the risk of decline or extinction over the next 30 years remains possible through timely adoption of measures that reduce fatality. Our results incorporate and reflect broad uncertainties about the status and population dynamics of hoary bats as well as future wind energy development in North America. The extent of missing information and the sensitivity of risk to this information prevents a succinct recommendation for fatality minimization level. As has been noted for over a decade (BWEC 2018; Frick et al. 2017; Kunz et al. 2007), reducing uncertainty about population size is key to understanding how fatality at wind farms influences population viability for this species. However, our modeling suggests retrospective population trend information could help determine whether extinction risk is moderate or severe.

Consideration of future wind energy development increased the assessment of risk to hoary bats but highlighted that timely adoption of minimization practices at wind energy facilities could delay or prevent declines that could trigger the need for regulatory protection. Holding installed wind energy at 2014 levels, Frick et al. (2017) found populations capable of 18% annual growth would not be at risk of decline in 50 years or extinction in 100 years. In contrast, we found that continued additions of wind energy generation capacity meant a population capable of 18% annual growth is at risk of decline and extinction in under 40 years. Importantly, risks could be addressed by technically achievable fatality minimization measures over most of the parameter space explored. Simulation of operational curtailment below wind speeds of 5 m/s, a measure expected to reduce fatality by 48% (Whitby et al. 2021), indicated slower future declines and reduction of extinction risk at all but the smallest initial population sizes.

Our approach of focusing on the impact of a known stressor is consistent with IUCN Red List status assessment guidelines, which allow a minimum status classification to be achieved even under large uncertainty (IUCN 2012). Under our lowest-risk scenario of high maximum growth rate and low wind energy build-out, the median simulated population of 2.25 million hoary bats experienced a 50% decline by 2028. IUCN Red List criterion A4d, focusing on past and future decline, would classify such a population as Endangered if its generation time was 5-6 years, a range that is plausible for hoary bats. The full range of purported hoary bat abundance produces all levels of classification from Critically Endangered to Least Concern under the lowest-risk scenario. A focus on the median level of 2.25 million level is supported by IUCN guidance not to use extreme or "worst case" values, though variation in evidentiary attitudes leaves classification open to interpretation (IUCN 2019). Importantly, wind energy is likely not the only stressor on hoary bat populations. Threats such as a decline in abundance of insect prey (Sánchez-Bayo and Wyckhuys 2019) and habitat loss and degradation from land-cover change across North America may also pose population-level risk (Frick et al. 2020; Weller 2008). Incorporating other stressors in our assessment would decrease projected population viability over a larger range of possible hoary bat abundance and increase minimization targets, but also reduce the dependence between viability and wind energy development.

Hoary bat population size remains the most important knowledge gap obscuring guidance on overall risk and how much fatality reduction is necessary. We used a range of likely abundance developed by expert elicitation from Frick et al. (2017), but empirical basis for estimating a plausible minimum population size for hoary bats is a top research priority. Progress toward an estimate has been challenging. The most concrete efforts, estimation of genetic effective population size, have so far either been inconclusive (Korstian et al. 2014) or offered dramatically varying assessments (Pylant et al. 2016; Sovic et al. 2016). The continental-scale North American Bat Monitoring Program (NABat) has made recent progress in compiling data from multiple sources to estimate population size for bats in North America from acoustic detections (Reichert et al. 2021).

In the absence of a population estimate, trend information may be useful in guiding hoary bat conservation. Indirect evidence for regional declines in hoary bat abundance has been found in studies of occupancy in the northwestern United States (Rodhouse et al. 2019) and fatality rates at wind farms in the Great Lakes region of Canada (Davy et al. 2020), both of which showed strong downward trends since 2010. However, analysis of mist-netting data in Saskatchewan, Canada, found only weak support for a decline (Green et al. 2021). It may be possible to estimate a population trend from fatality monitoring data from wind farms across the U.S.A. and Canada, though statistical rigor is difficult to achieve due to the nature of the dataset (Huso and Dalthorp 2014); wind farms are non-randomly distributed in the landscape, use different turbine designs, and are typically only monitored for 1-3 years after construction. NABat's probabilistic sample design provides an opportunity to overcome some of these limitations with robust estimation of population trends over large spatial extents (Loeb et al. 2015; Reichert et al. 2021).

Simulated short-term population trends from our model suggested several rough benchmarks that may be useful in supporting management decision-making without an estimate of population size. If no annual trend of decline can be statistically determined, a fatality reduction target of 25% is precautionary. Decline rates between 0 and 5% per year could be viewed as only supporting a precautionary attitude toward extinction risk management. This zone lies to the left of the mean trends exhibited by populations with appreciable extinction risk in Figure 4b. For annual declines between 5 and 10%, a more reactionary attitude to risk appears warranted given that this range is typical for populations at risk, even in simulations with high growth rate. However, the uncertainty in appropriate minimization target in this middle range remains high. Rates of decline in excess of roughly 10% per year unambiguously indicate the need for some level of fatality reduction, corresponding to the zone of Figure 4b where the minimum reduction target becomes greater than zero. Finally, any trend greater than 15% per year would indicate a fatality minimization target of at least 50%.

In addition to population size, uncertainty about population dynamics and wind energy development limited our characterization of risk to hoary bat populations. The capacity for compensatory population growth in bats is not well-understood. However, the stabilizing effect of compensatory population growth up to 18% per year was not a panacea for reducing risk in our model and therefore did not qualitatively alter the assessment that risk exists and may require management actions. Likewise, the pace of wind energy development, which derives its uncertainty from variable market forces influenced by policy (USEIA 2020), had nuanced rather than qualitative effects on risk. Assuming that the per-MW impact of wind energy development on hoary bat survival would otherwise remain unchanged in the future, our results indicate population-level risks even under our more conservative scenario of build-out through 2050.

It is striking that operational curtailment below wind speeds of 5 m/s had the same effect as reducing future build-out by eighty percent. Relying on lower build-out to avoid wildlife impacts contradicts current goals for renewable energy adoption and ignores current trends in annual increases in installed capacity. For example, the largest increase on record in the United States for installed capacity occurred in 2020 with 14 GW (www.eia.gov). Wind energy is an important and growing source of renewable energy around the world and part of efforts to lower carbon emissions from energy production (Gielen et al. 2019). Biodiversity conservation is also a global priority (Secretariat of the Convention on Biological Diversity 2020). Solutions that allow continued growth of renewable energy development without risking loss of biodiversity are available but require rapid implementation.

Strategies for minimizing bat fatalities at wind turbines include both operation curtailment and ultrasonic deterrents (Berthinussen et al. 2021). Ultrasonic acoustic deterrents are still largely in a phase of technological research and development. Field tests have demonstrated total bat fatality reductions ranging from as low as 20% (Arnett et al. 2013a) to over 70% (Weaver 2019), but have shown possible benefits for hoary bats (Romano et al. 2019). Unlike acoustic deterrents, operational curtailment affects energy generation (Hayes et al. 2019; Martin et al. 2017), but has been shown to be broadly effective at reducing bat fatalities (Berthinussen et al.

2021; Whitby et al. 2021). The rate of fatality reduction achieved by curtailment generally increases with the cut-in wind speed (Arnett et al. 2013b). A test of curtailment at a site with high bat fatality found an average 85% reduction in hoary bat fatality with cut in speeds of 5 m/s or more (Table 9 in Hein et al. 2014). While results for given cut-in speeds are variable, this level of efficacy suggest the potential to address extinction and decline risk over much of the range of hoary bat population sizes we assessed. The cost of lost energy production hinders adoption of curtailment by wind energy companies and motivates research into optimized, or "smart", curtailment. Current research into smart curtailment includes systems that can detect and respond to the presence of bats locally (Hayes et al. 2019) or trigger curtailment using statistical models that relate fatality risk to conditions either at the wind farm (Martin et al. 2017; Weller and Baldwin 2012) or in the region (Good et al. 2020). Curtailment practices at wind energy facilities in the United States are regionally variable and currently implemented primarily via Habitat Conservation Plans and Technical Assistance Letters by the United States Fish and Wildlife Service in regions where bat species that are federally protected by the Endangered Species Act occur (e.g. Indiana bats, *Myotis sodalis*). Determining policy and market incentives for industry-wide adoption of turbine-level fatality minimization measures remains a major challenge.

Finally, a reduction in the mean rate of fatalities per MW of installed wind energy generation capacity could be achieved with strategies focused at scales beyond individual turbines. The distribution of bat fatality rates among wind facilities is highly skewed, with 75% of facilities reporting fewer than five bat carcasses per MW per year. Sites with higher fatality rates are over-represented in the Midwest and Northeast regions of the United States (AWWI 2020), implying that the geographic distribution of future wind energy build-out will affect population-level risk. A meaningful next step in our risk assessment modeling would be to consider predicted regional patterns of wind energy development. Meanwhile, a greater understanding of site-level determinants of fatality rate within regions is needed (Allison et al. 2019). While convenience samples of fatality monitoring data suggest site effects on bat fatality (e.g., Davy et al. 2020; Thompson et al. 2017), a clearer picture could be gained through further standardization of monitoring methods (Conkling et al. 2020) and systematic monitoring at existing facilities (Huso and Dalthorp 2014). Recent research also suggests that the fundamental unit of fatality rate, fatalities per power manufacturer-rated generation capacity (nameplate capacity) ignores variation in actual power generation and fatality rate among turbines (Huso et al. 2021), which is likely to have both site-level and regional effects. Ultimately, a multi-scale approach to cumulative impact management for hoary bats at wind facilities is likely to strike the best balance between the competing goals of sustainable energy production and biodiversity conservation.

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Tables

Table 1. Projected probability and median year of a 50% decline in hoary bat abundance in the U.S.A. and Canada over a range of initial population sizes at two levels of future wind energy development. Ranges reflect uncertainty in population growth rate (range = 1 to 1.18).

Measure	Initial Abundance (Millions)	Decline Risk Low Build-out	 High Build-out
Probability	1	1.00	1.00
	2.25	0.90 – 1.00	1.00
	4	0.30 – 0.98	0.93 – 1.00
	10	0.01 – 0.62	0.12 – 0.87
Median Year	1	2016 - 2018	2016 - 2018
	2.25	2021 - 2028	2021 - 2025
	4	2026 - >2050	2025 - 2035
	10	2043 - >2050	2036 - >2050

Table 2. Target reduction of bat fatalities occurring at wind turbines to manage risk of hoary bat decline or extinction in the U.S.A. and Canada for a range of population sizes. Targets to manage risk equate to reduction levels that result in < 50% chance of the population declining by 50% by 2050 (decline risk) and reduction levels that result in < 1% chance of extinction by 2050 (extinction risk). Range of target reductions depends on the underlying assumption of the maximum annual population growth rate (range = 1 to 1.18) used in the population model projections. Note that fatality reductions sufficient to manage extinction risk will still allow decline.

Risk Type	Abundance (Millions)	Target Reduction of Bat Fatalities (%) Low Build-out λ = 1.18 to 1.0	 High Build-out λ = 1.18 to 1.0
Decline	1	75 - 100*	88 - 100*
	2.25	35 - 100*	66 - 100*
	4	0 - 93	38 - 98
	10	0 - 30	0 - 63
Extinction	1	24 - 79	59 - 90
	2.25	0	0 - 39
	4	0	0
	10	0	0

*For low initial population sizes and low population growth, decline risk could not be managed even with 100% future fatality reduction.

Figures

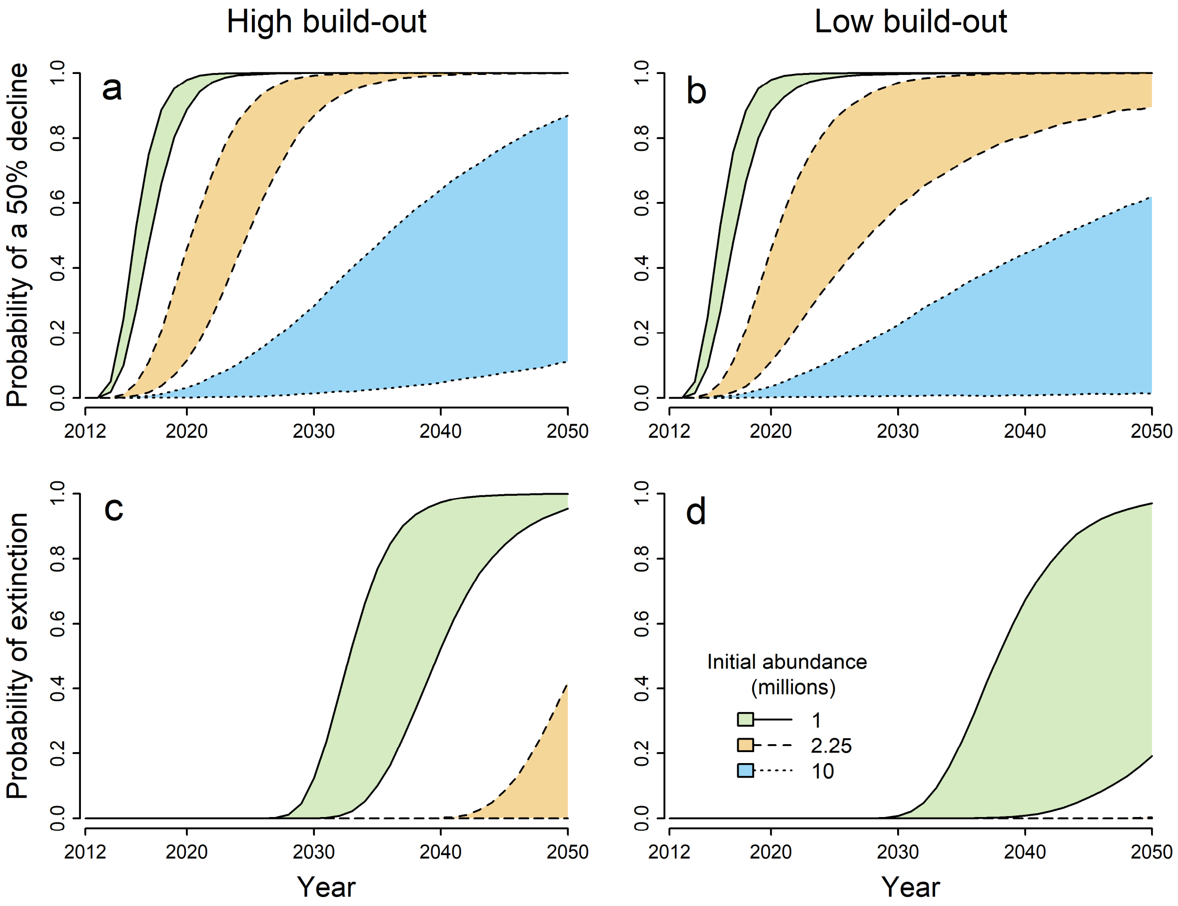

Figure 1. The probability of population decline or extinction over time for hoary bat populations exposed to projected mortality without fatality reduction at wind farms in the U.S. and Canada under high and low build-out scenarios. Shaded regions denote intervals of risk at three initial abundances. Each interval is commensurate with a range of expert opinions on likely population growth rate, with λ_{max} set to 1 and 1.18 at the left and right boundaries of the shaded region, respectively. **(a)** Decline risk under high build-out. **(b)** Decline risk under low build-out. **(c)** Extinction risk under high build-out. (Populations initiated with 10 million individuals exhibited no risk of extinction by 2050.) **(d)** Extinction risk under low build-out. (Populations initiated with either 2.25 or 10 million individuals exhibited no extinction risk by 2050.)

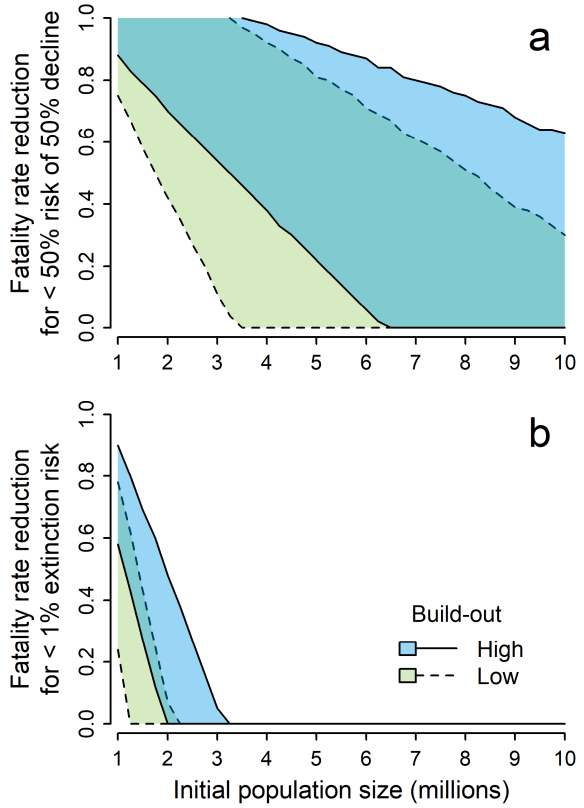

Figure 2. Proportional reduction in fatality rate needed to manage **(a)** the risk of population decline or **(b)** extinction across a range of initial population sizes. Shaded regions represent the interval of risk commensurate with a range of expert opinions on likely population growth rate, with λ_{max} set to 1 and 1.18 at its right and left boundaries, respectively, and a scenario of future wind energy build-out. Darker region indicates overlap of build-out scenario outcomes.

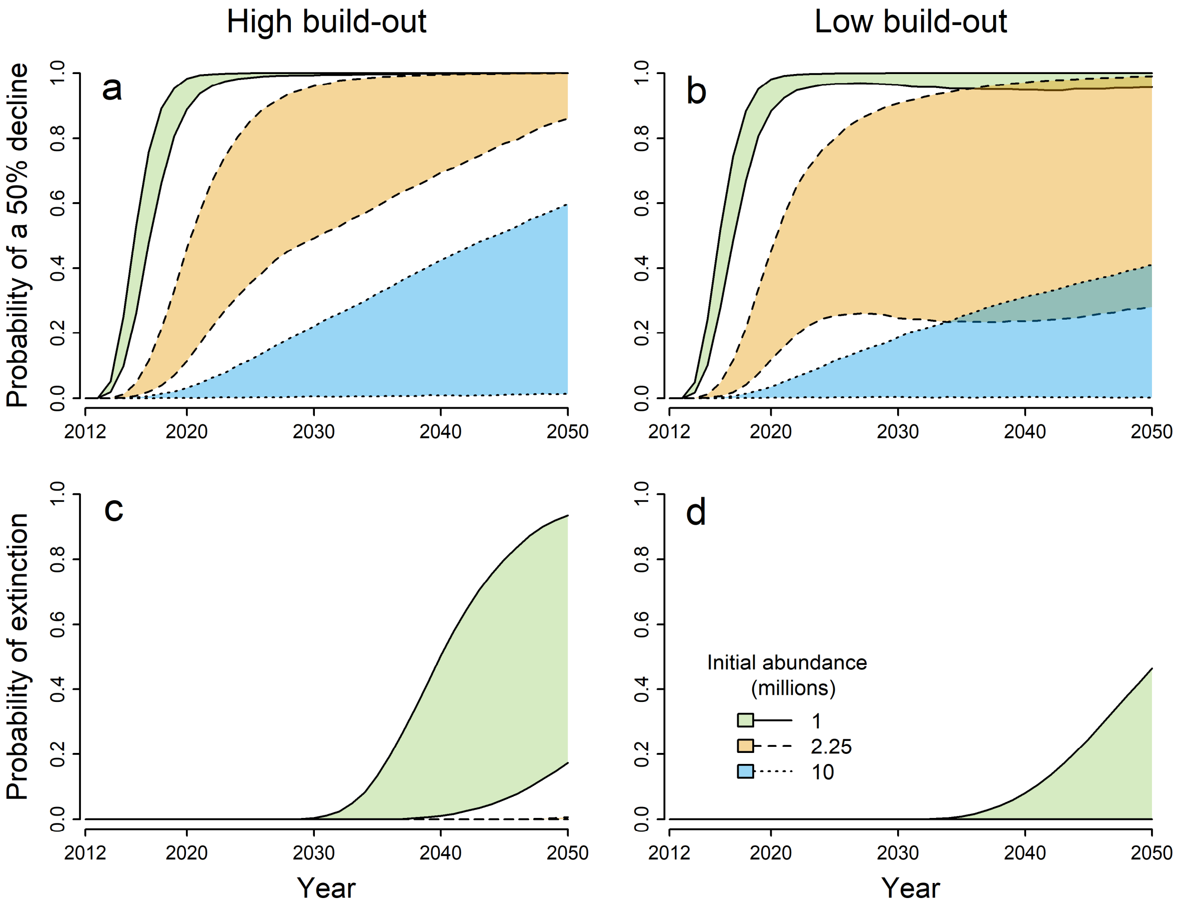

Figure 3. The probability of population decline or extinction over time for hoary bat populations with a 48% mean reduction in mortality based on assuming a universal adoption of curtailment to 5 m/s cut-in speed at wind farms in the U.S.A. and Canada by 2030. Shaded regions denote intervals of risk at three initial abundances. Each interval is commensurate with a range of expert opinions on likely population growth rate, with $\lambda_{\max}$ set to 1 and 1.18 at its left and right boundaries, respectively. **(a)** Decline risk under high build-out. **(b)** Decline risk under low build-out. **(c)** Extinction risk under high build-out. **(d)** Extinction risk under low build-out. Of the three initial abundances in the figure, only the lowest exhibited a risk of extinction by 2050 under simulated universal adoption of 5 m/s curtailment.

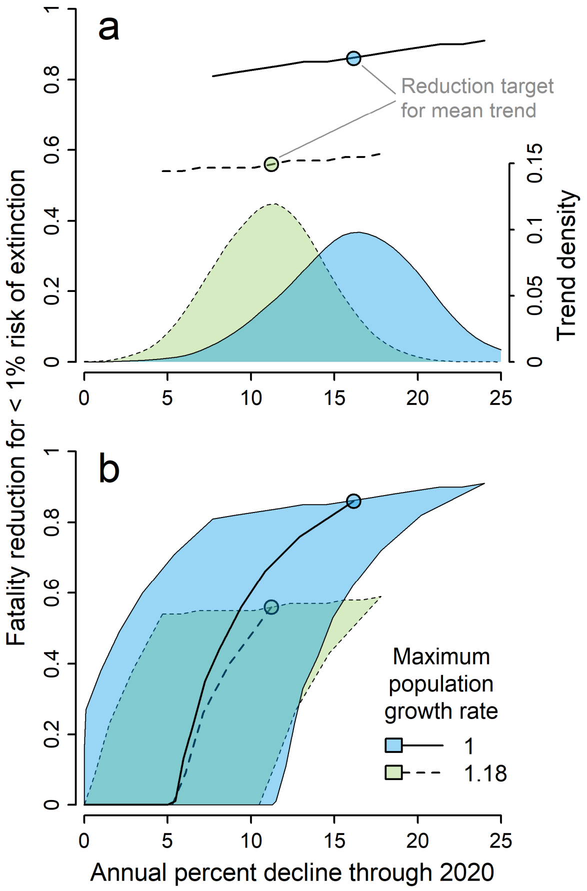

Figure 4. Fatality reductions necessary to manage hoary bat extinction risk over a range of simulated rates of population decline at two maximum population growth rates. **(a)** For simulations initialized with 1 million hoary bats in 2012, projected trends and attendant reduction targets. Shaded areas illustrate the distribution of trends (right axis) at each growth rate. Lines are fatality reduction targets (left axis) for the central 95% of trends at each growth rate. **(b)** Fatality reduction targets for trends simulated over a range of 2012 abundance levels from 1 to 10 million hoary bats. Shaded regions cover the central 95% of trends at each initial abundance level, while heavier central curves indicate mean trends per abundance level. In both panels, the shaded circles mark the fatality reduction target for the mean annual rate of decline of populations starting with 1 million hoary bats. Only stable or decreasing trends are pictured.