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A decade of curtailment studies demonstrates a consistent and effective strategy to reduce bat fatalities at wind turbines in North America

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Abstract

1. There is a rapid, global push for wind energy installation. However, large numbers of bats are killed by turbines each year, raising concerns about the impacts of wind energy expansion on bat populations. Preventing turbine blades from spinning at low wind speeds, referred to as curtailment, is a method to reduce bat fatalities, but drawing consistent inference across studies has been challenging.
2. We compiled publicly available studies that evaluated curtailment at six wind energy facilities in North America across 10 years. We used meta-regression of 29 implemented treatments to determine fatality reduction efficacy as well as sources of variation influencing efficacy. We also estimated species-specific fatality reduction for three species that comprise most fatalities in North America: hoary bat (*Lasiurus cinereus*), eastern red bat (*Lasiurus borealis*) and silver-haired bat (*Lasionycteris noctivagans*).
3. We found that curtailment reduced total bat fatalities by 33% with every 1.0 ms^{-1} increase in curtailment wind speed. Estimates of the efficacy for the three target species were similar (hoary bats: 28% per ms^{-1}, 95% CI: 0.4%–48%, eastern red bats: 32% per ms^{-1}, 95% CI: 13%–47% and silver-haired bats: 32% per ms^{-1}, 95% CI: 3%–53%).
4. Across multiple facilities and years, a 5.0 ms^{-1} cut-in speed was estimated to reduce total bat fatalities by an average of 62% (95% CI: 54%–69%). Mortality reductions at individual facilities in any given year were estimated to fall between 33%–79% (95% prediction interval). Inter-annual differences rather than inter-site or turbine characteristics accounted for most of the variation in efficacy rates. Species-specific average mortality reduction at 5.0 ms^{-1} curtailment wind speed

was 48% (95% CI: 24%–64%) for hoary bats, 61% (95% CI: 42%–74%) for eastern red bats and 52% (95% CI: 30%–66%) for silver-haired bats.

5. *Practical implication*. curtailment reduced bat mortality at wind turbines in this North American study. Efficacy increased proportionally as curtailment speed is raised, and patterns and rates of efficacy were similar across species. This indicates that curtailment is an effective strategy to reduce bat fatalities at wind energy facilities, but exploration of further refinements could both minimize bat mortality and maximize energy production.

KEYWORDS

bats, climate change, curtailment, decarbonization, meta-analysis, mitigation, wind energy

1 | INTRODUCTION

There is a rapid push to decarbonize energy production, and the 2050 net zero carbon emission goals have made wind energy generation one of the fastest-growing energy sectors. In the United States, the installed capacity of land-based wind energy more than doubled between 2010 and 2019 (AWEA, 2019) and is expected to grow from supplying roughly 10% of the U.S. energy supply in 2023 to supplying over 35% by 2050 (Energy, 2023; Gielen et al., 2019; Wiser et al., 2015). However, the increasing number of wind energy facilities in the United States and around the world poses significant risk to some species, and the documented collisions with aerial wildlife, as well as secondary effects such as avoidance, have raised concerns about cumulative impacts to biodiversity (Kunz et al., 2007; Smallwood, 2007; Voigt, 2021). This has been framed as a 'green-on-green' dilemma (Straka et al., 2020) as both decarbonizing energy production and preserving biodiversity are essential to maintaining global ecological stability. Determining ways to produce wind energy while limiting adverse effects on biodiversity is essential and has been a long-standing goal of collaborative efforts between the wind industry and wildlife conservation groups.

Certain species of bats are particularly vulnerable to strikes from wind turbines (Arnett et al., 2008; Kunz et al., 2007) and in the United States and Canada alone, hundreds of thousands of bats die each year in collisions with wind turbines (Arnett et al., 2015; Hayes, 2013; Smallwood & Bell, 2020). High rates of bat mortality at wind farms have also been noted in Europe (Barré et al., 2023; Roemer et al., 2019; Voigt et al., 2022), South America (Agudelo et al., 2021; do Amaral et al., 2020), Africa (Aronson, 2022), Asia (Chou et al., 2017) and Oceana (Bennett et al., 2022; Hull & Cawthen, 2013). However, it is challenging to estimate the impact of wind energy facilities on bat populations due to a lack of empirical data on population sizes and demographic data of bats (Frick et al., 2017, 2020; Friedenberg & Frick, 2021). The best estimates for population-level impacts of wind energy are for hoary bats (*Lasiurus cinereus*) in North America. These migratory insectivores comprised 38% of documented bat fatalities at wind farms in the United States and Canada in the early 2000s (Arnett & Baerwald, 2013). Models projecting population viability based on estimated population size, reproductive rates and mortality rates based on current and future wind energy facility expansion suggest rapid population declines or even possibly extinction of hoary bats (Frick et al., 2017; Friedenberg & Frick, 2021). However, data on population sizes of migratory insectivores remains a critical knowledge gap. The effect of fatalities associated with wind energy buildout on hoary bats would be greater if populations are already declining due to other threats like climate change and habitat destruction (Friedenberg & Frick, 2021). No efforts have yet been made to assess risk of population declines or extinction for eastern red bats (*L. borealis*) or silver-haired bats (*Lasionycteris noctivagans*), which comprised 22% and 19% of documented fatalities at wind energy facilities (Arnett & Baerwald, 2013). Finding solutions that reduce the risk of impacts to biodiversity (e.g. extinction) helps ensure that the wind industry sector can meet the world's aggressive decarbonization targets while minimized impacts on biodiversity.

Curtailment has been suggested to significantly reduce bat fatalities at wind energy facilities (Arnett et al., 2011; Martin et al., 2017). Very simply, curtailment requires that rotor rotation be slowed or stopped when winds are below some designated speed. To implement curtailment, blades are rotated parallel to the wind in a process called feathering. This slows the blades, often to less than one rotation per minute, thus reducing risk of collision with bats. All turbines have a minimum wind speed that is needed to generate electricity (the manufacturer's cut-in speed or cut-in speed) and feathering above the cut-in speed limits rotor rotations during times they would normally produce electricity. Feathering below the cut-in speed prevents rotors from spinning at speeds dangerous to wildlife even when turbines are not yet generating power. Feathering below cut-in speed results in minimal loss in power generation. Wind energy operators in the United States made a progressive action in 2015 and issued a best management practice to feather turbine blades below the cut-in speed during the autumn migration period when temperatures are above 50°F, when financially feasible (American Clean Power, 2015), but is not yet adopted as required standard practice.

The first curtailment studies were conducted in 2006 and 2007 in Alberta, Canada (Baerwald et al., 2009) and 2008 and 2009 in Pennsylvania, USA (Arnett et al., 2011). Both studies found a decrease in bat fatalities when turbines were feathered below certain wind speeds. Multiple studies were conducted in the following years, and a subsequent narrative synthesis of peer-reviewed and grey literature reports concluded that curtailing turbine rotation when winds were below the turbine cut-in speed yielded substantial reduction in mortality of bats (Arnett et al., 2013). Since that synthesis, the efficacy of curtailment across facilities and different curtailment wind speeds has been questioned (BWEC (Bats and Wind Energy Cooperative), 2018; Hein & Straw, 2021). Of particular concern was if the unique conditions of each study make it difficult to extrapolate and compare results of studies among different facilities. The most common way to compare results has been to correlate reported percent reduction in bat fatalities with a curtailment treatment speed. However, simply correlating reductions in bat fatalities across studies ignores important variation across studies. Variation may be due to differences in turbine model characteristics (e.g. cut-in speeds, size of the rotor-swept area, etc.), the sample size of turbines assigned as treatment and controls, variation in the control cut-in speed to which the treatment is compared, and the variation in wind-speed regimes, that is how often winds were below cut-in or curtailment speeds. Ignoring these factors as individual contributions, even within a meta-analysis framework (Adams et al., 2021), limits our ability to quantify the expected effect of curtailment to reduce bat fatalities under specific conditions and inform wind energy installations that are safer for bats.

We used quantitative meta-analysis (Nakagawa et al., 2023) to estimate trends in the efficacy of curtailment of wind turbines to reduce bat fatalities while accounting for the variation documented within and among a range of individual studies. Specifically, we ask whether curtailing turbine operation results in lower bat mortality relative to normal operations. We explored factors that moderate variation in efficacy of curtailment, including turbine characteristics, geography and study design and examine species-specific mortality reduction.

2 | MATERIALS AND METHODS

2.1 | Data collection and curation

We gathered publicly available literature from the BWEC Bats and Wind Energy Bibliography (https://tethys.pnnl.gov/organization/bats-wind-energy-cooperative-bwec) and from the results of a Google Scholar search of 'bats wind curtailment' on 7 August 2019. To be included in our meta-analysis, documents had to report the fatality rate and associated measure of uncertainty (standard deviation, variation, standard error or confidence interval) for a control and treatment conducted in the same year (or provide data that could be used to calculate these values). We extracted these values from each study using all information available for each study, including posters, presentations, reports and/or published literature, when available. Nineteen treatments at eight study sites reported appropriate data to be included in the meta-analysis, including peer-reviewed studies at four facilities (Table 1). For studies that did not report fatality rates, we used their raw data to calculate the estimated fatality rate for each treatment (Table 1). Methods for the calculation of fatality rates using raw data are provided in Supplemental Material. Studies varied in their control cut-in speed, the size and type of turbines used and the years in which they were conducted, in addition to the treatment curtailment speed.

We removed two studies from the meta-analysis and meta-regression because they each had curtailment strategies that were not used in other studies and, therefore, were not comparable with meta-analysis. At the Sheffield Wind Facility, curtailment was only implemented when temperatures were above 10°C (Martin et al., 2017). The curtailment treatment at BlueSky–Green Field was only implemented when bats were detected in the area with acoustic sensors (Hayes et al., 2019). Nonetheless, we include the effect size of these two sites in graphs to allow qualitative comparison of their results to other curtailment strategies. We also excluded the wind-speed and direction treatments at the Wolf Ridge Wind facility (Hale & Bennett, 2014) since this treatment was not repeated at another facility.

All analyses were conducted in R version 4.0 (R Core Team, 2020). We calculated the log ratio of the mean (ROM) for each study. The ROM was calculated using the mean and uncertainty (standard error, confidence interval, etc.) and sample size for both the treatment (i.e. the curtailment strategy) and control (i.e. normal operation). We log transformed fatality rates and limits of the confidence intervals prior to calculating effect size. Log transformation is necessary since fatality rates cannot fall below zero. We calculated effect size by taking the difference of the log transformed values of treatment and control turbines. We calculated the variance of each effect size on the log scale using Equation (2) (Table S1). To estimate the variation among effect sizes beyond sampling error, we calculated heterogeneity (I^2) for the mixed effects model (Nakagawa et al., 2023). I^2 ranges from 0 to 1, and we tested for the presence or absence of heterogeneity using Chochrane's Q test (Borenstein et al., 2021).

Variance of the mean effect size for a treatment was calculated with Equation (2) (Table S1), implemented by the *metafor*::*escalc* function (version 2.4; Viechtbauer, 2010), using the effect size calculation for mean difference (measure = 'M.D.'). Data and supporting analysis code are publicly available (Whitby, 2024).

2.2 | Representation of installed turbines

Facilities used in the meta-analysis were primarily located in the eastern Midwest (Indiana, Ohio) and Mid-Atlantic regions (West Virginia, Pennsylvania), as well as one facility in Texas and one in Alberta, CA. The greatest number of installed turbines in the United States were in the western Midwest (e.g. Iowa) and Southern Great Plains (e.g. Texas; Figure S1). Therefore, facilities in the southwestern and northwestern United States were not well represented by available studies. Geographic distribution of facilities built in 2007–2012 were similar to the current fleet (Figure S1), suggesting that lack of geographic representation in western regions is not due to

TABLE 1 Publicly available studies on curtailment of wind turbines that include bat fatality rates at control and treatment turbines for the same year.

Facility	Year	Location	Source(s)	Data source	Treatments	Species
Blue Creek	2017	Ohio, USA	Schirmacher (2020)	Calculated from raw data[a]	5.0 ms^{-1}	*L. cinereus* *L. borealis* *L. noctivagans*
Blue Sky—Green Field	2015	Wisconsin, USA	Hayes et al. (2019)* Sutter and Schumacher (2017)	Hayes et al. (2019)[b]	7.9 ms^{-1} (if bats present)	*L. cinereus* *L. borealis* *L. noctivagans*
Casselman	2008	Pennsylvania, USA	Arnett et al. (2011)*[c] Arnett et al. (2009)	Arnett et al. (2009)	5.0 ms^{-1} 6.5 ms^{-1}	
	2009		Arnett et al. (2010)	Arnett et al. (2010)	5.0 ms^{-1} 6.5 ms^{-1}	
Fowler Ridge[d]	2010	Indiana, USA	Good et al. (2011)	Calculated from raw data in report[a]	5.0 ms^{-1}[e] 6.5 ms^{-1}	*L. cinereus* *L. borealis* *L. noctivagans*
	2011		Good et al. (2012)	Calculated from raw data in report[a]	3.5 ms^{-1}[f] 4.5 ms^{-1} 5.5 ms^{-1}	*L. cinereus* *L. borealis* *L. noctivagans*
Pinnacle	2012	West Virginia, USA	Hein et al. (2013)	Combined species from Schirmacher et al. (2016)[c] Species-specific from BCI raw data[a]	6.0 ms^{-1}	*L. cinereus* *L. borealis* *L. noctivagans*
	2013		Hein et al. (2014)	Hein et al. (2014)	6.0 ms^{-1}	*L. cinereus* *L. borealis* *L. noctivagans*
Sheffield	2012 2013	Vermont, USA	Martin et al. (2017)*[c] Martin (2015)	Martin (2015)[b]	6.0 ms^{-1}	
Summer View	2007	Alberta, CA	Baerwald et al. (2009)*	Baerwald et al. (2009)*	5.5 ms^{-1} Low wind speed idle	*L. cinereus* *L. noctivagans*
Wolf Ridge	2011 2012 2013 2014	Texas, USA	Hale and Bennett (2014)	Provided by authors	5.0 ms^{-1}	*L. cinereus*[g] *L. borealis*[g]

Note: Sources include all reports and peer-reviewed publications (*). The data source indicates the document that provided fatality rates used in the meta-analysis.

[a]See Supporting Information for methods used to calculate fatality rates from raw data.

[b]Data presented for comparison purposes only. Data are not used in the meta-analysis due to unique study design that involves acoustic detections (Blue Sky—Green Field) and temperature (Sheffield).

[c]This later report included standardized results from multiple years.

[d]Data from Fowler Ridge was split into to an effect size for each of three turbine models (G.E., Vestas and Clipper) that were used in the study to allow for meta-regression using turbine-specific characteristics.

[e]Treatments at Fowler Ridge in 2010 did not feather below the curtailment speed.

[f]3.5 ms^{-1} at Fowler Ridge 2011 was simply feathering of blades below the curtailment speed.

[g]Species fatality rates from Wolf Ridge were only available for 2013 and 2014.

recent trends in buildout. Turbines used in curtailment studies were generally smaller in term of rotor-swept areas to turbines operating in the U.S. fleet. Turbines with 100-m hub height tended to be over-represented, while turbines of 80m tended to be under-represented (Figure S1C).

2.3 | Meta-analysis and meta-regression

We conducted the meta-analysis and meta-regression for all bat fatalities combined and for three species that had enough data on species-specific fatalities: hoary bats, eastern red bats and silver-haired bats. The analysis for all species combined was conducted with 29 control-treatment comparisons at six facilities, some conducted over successive years. When species were analysed individually, six facilities with 21 control-treatment comparisons reported data usable for analysis of curtailment efficacy for eastern red bats. Data from 21 control-treatment comparisons at seven facilities were used for hoary bats, and data from 19 control-treatment comparisons from six facilities were used when evaluating silver-haired bats.

We fit a multilevel null model with intercept using *metafor* (Viechtbauer, 2010) for each bat species, including for all bat species combined. We specified a nested random effect of year within facility to examine variation between years at the same facility and among facilities. We used the default process in *metafor* to assign weights to each comparison based on the inverse of the variability (sampling and random effects, accounting for covariance) of each comparison (Viechtbauer, 2010).

Models without moderators (i.e. fixed-effects) indicated heterogeneity in results for all species combined and each species individually (*Q* test *p*-value <0.05). Therefore, we performed meta-regression to evaluate the influence of study-specific moderators on the variability in effect size using a set of candidate models. Moderators added to the null multilevel model represented four hypotheses to explain variation: study design differences, geographic variation, turbine characteristic variation and treatment differences (Table 2). Treatment differences were split into multiple models to explore which treatment measure best accounted for variation.

All candidate models were fit using maximum likelihood with t-test for significance of fixed effect moderators. We compared support for candidate models using an information-theoretic model selection criteria approach (AICc; Burnham & Anderson, 2004). The top model based on lowest AICc value was refit using restricted maximum likelihood estimation (REML) to produce unbiased estimates of variance and covariance parameters. This top model was used to describe the relationship of the relevant moderators to the effect of curtailment. To better contextualize the impact of curtailment across our studies, the mean effect size (log Ratio of Means) is presented as the result transformed to percent reduction in fatalities within a given treatment.

Studies with a stronger statistical result tend to be published more frequently than studies without statistically significant results, which can bias the results of meta-analysis by overestimating the effect size (Møller & Jennions, 2001; Song et al., 2000). Our use of grey literature, in addition to peer-reviewed studies, may help protect against publication bias. To better contextualize potential publication bias we used funnel plots and rank correlation tests (Begg & Mazumdar, 1994).

TABLE 2 Candidate model set ($n=8$) to account for variation in effect size of curtailment studies.

Model name	Moderators	Prediction
Study design	Plot Size + Treatment Allocation[a]	The study design will determine the strength of the results
Geographic	Latitude × Longitude	Curtailment effect will vary based on location of the wind facility
Turbine characteristics	Rotor-Swept Area + Hub Height	Curtailment effect will vary based on the size of the turbine
Treatment difference models		
Cut-in Speed and Feathering	Control Cut-In Speed + Control Feathering + Treatment Curtailment Speed + Treatment Feathering	Higher cut-in speeds and feathering reduce mortality levels
Cut-in Speed	Control Cut-In Speed + Treatment Curtailment Speed	Higher cut-in speeds reduce mortality levels
Non-linear Treatment Curtailment	Natural Spline of Treatment Curtailment Speed with 3 degrees of Freedom	Increasing Curtailment speed has a diminishing effect on mortality reduction
Treatment Curtailment	Treatment Curtailment Speed	Increasing Curtailment speed has a linear effect on mortality reduction

Note: Moderators are the numerical and factor variables used to model the described prediction. All models included the same random effect of year nested within facility and a covariance matrix to account for multiple treatments being compared to a single control. In addition to the seven hypothesis driven models shown a Null model was tested.

[a]Randomized Block Design—treatments were rotated so every turbine received all treatment or Completely Randomized Design—each turbine had a fixed treatment.

3 | RESULTS

3.1 | Total bat fatalities

The best-fit model predicting mortality reductions for all bats combined, as well as for individual species, was a treatment only model (Table 3). The estimated reduction in mortality was greater than 35.3% in all but one contrast (Figure 1). Six of the 32 contrasts included in the meta-analysis have lower confidence intervals that overlapped zero, implying the potential for the treatment to potentially increase mortality.

As expected, there was significant heterogeneity in estimated reductions in mortality of all bat species combined due to treatments when no moderators were used ($Q_{28}=68.12$, p-value <0.001). The top model using moderators to explain the variation included the linear effect of curtailment wind speed and accounted for 72% of the weight in the model set (Table 3). No publication bias existed in the top model ($p=0.54$, Kendall's tau$=0.08$; Figure S2). There was not statistically significant residual heterogeneity (variability was less than what would be expected given sampling variability) when treatment speed was used as a moderator ($Q_{27}=39.38$, p-value$=0.06$). However, a more liberal interpretation of the p-value would indicate that additional covariates could explain more heterogeneity. True heterogeneity accounted for 39.6% (I^2) of the observed variation, meaning 60.4% was attributable to sampling variation across years (Table S2). The linear effect of curtailment speed was significant ($t=4.908$, df$=27$, p-value <0.0001, $\beta \pm SE=0.40 \pm 0.08$). This indicates that curtailment reduced fatalities, on average, by 33% (95% CI: 21%–43%) for each 1 ms^{-1} increment of curtailment (Figure 2; Table S1, Equation 3; Table S3). The expected reduction at a given cut-in speed includes the effect of feathering below the control cut-in speed.

3.2 | Species-specific effects

When tested separately, there was significant mortality reduction each 1 ms^{-1} increase in curtailment wind speed for hoary bats (28%, 95% CI: 0.4%–48%, Figure S3), eastern red bats (32%, 95% CI: 13%–47%, Figure S3) and silver-haired bats (32%, 95% CI: 3%–53%, Figure S3). The curtailment wind-speed model was the best predictor of mortality reduction for two of the three target species, that is, Eastern red bats and silver-haired bats. For Hoary bats, none of our candidate models was clearly better than the null random effects model. Individual species summaries are provided in Supporting Information.

4 | DISCUSSION

We found that reduction in bat mortality was positively associated with increased curtailment wind speeds at wind energy facilities in our study. The efficacy of operational minimization is measurable

TABLE 3 Model ranks and ΔAICc values (from top model) for candidate model set ($n=8$) tested for each species and total bat fatalities. Models <2 ΔAICc from top model are shaded grey.

		Total bats			*Hoary Bat*[a]			*Eastern red bat*			*Silver-haired bat*		
Model name	df	Rank	ΔAICc	Weight	Rank	ΔAICc	Weight	Rank	ΔAICc	Weight	Rank	ΔAICc	Weight
Treatment curtailment speed	4	1	0	0.72	1	0	0.41	1	0	0.76	1	0	0.44
Cut-in speed (control & treatment)	5	2	2.25	0.23	4	2.34	0.13	2	3.12	0.16	2	0.51	0.34
Non-linear treatment curtailment	6	3	6.05	0.04	5	6.24	0.02	4	6.86	0.02	4	1.81	0.18
Cut-in speed & feathering	7	4	8.33	0.01	8	11.21	<0.01	3	6.82	0.03	5	5.53	0.03
Null model (Random effects only)	3	5	21.16	<0.01	3	2.06	0.15	5	6.91	0.02	3	7.5	0.01
Turbine characteristics	5	6	24.92	<0.01	2	0.72	0.29	6	8.97	0.01	6	8.15	<0.01
Study design	5	7	26.53	<0.01	6	8.35	<0.01	7	10.75	<0.01	7	8.29	<0.01
Geographic	6	8	29.68	<0.01	7	8.77	<0.01	8	12.86	<0.01	8	11.38	<0.01

Note: All models included the same random effect of year nested within facility and a covariance matrix to account for multiple treatments being compared to a single control. Table 2 has model descriptions.

[a]Because the turbine characteristics and treatment curtailment speed models were <2 ΔAICc units apart, we conducted a second model selection process that included the Rotor-Swept Area and Treatment Cut-in Speed. This new model was the top model and had a weight of 0.48.

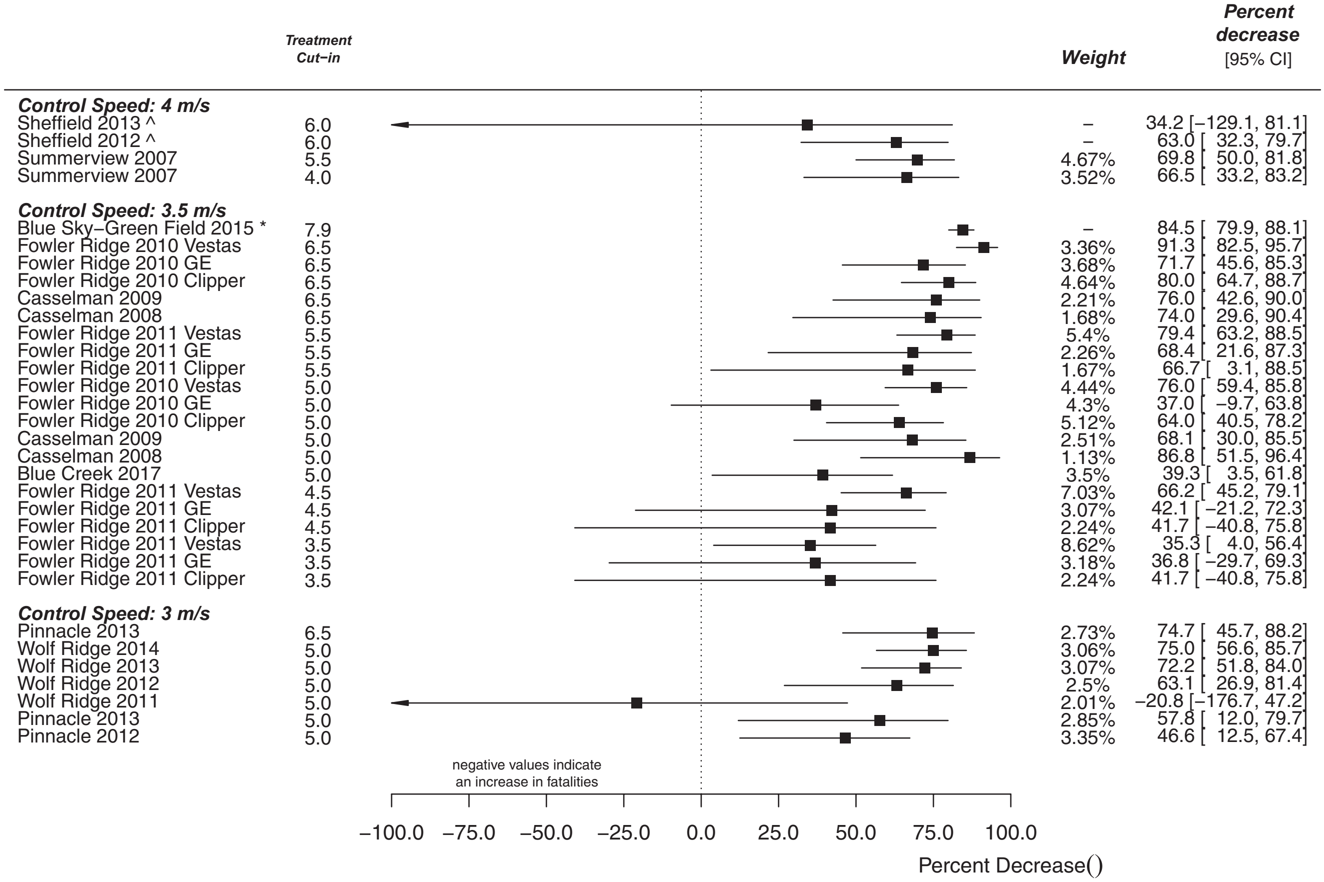

FIGURE 1 Effect size (log ratio of means transformed to percent decrease) of reduction in total bat fatalities from tested curtailment strategies. Ratios are converted to percentages for interpretation. A higher percent decrease indicates a greater reduction in mortality due to curtailment. A negative percentage indicates an increase in fatalities and likely arises from the highly variable nature of bat fatality estimates, factors not accounted for the model, or both. Squares represent mean percent difference for individual studies; lines represent the 95% confidence interval. Results from the ^Sheffield and *Blue Sky-Green Field facilities are included for reference only and were not used in the meta-analysis or meta-regression.

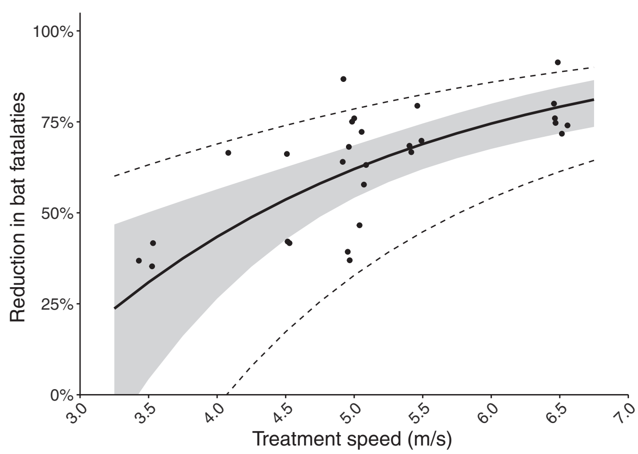

FIGURE 2 Reduction in bat fatalities across all treatment curtailment speeds based on predicted model fit from treatment curtailment speed model. Dotted lines are a 95% confidence interval and shaded area is the 95% CI of the mean. Points represent study observations.

across the circumstances of individual sites and studies, and on average reduced total mortality by 33% with every 1.0 ms^{-1} increase in curtailment speed (Figure 2). Average total bat mortality across facilities and time periods in our study was reduced by 62% (95% CI: 54%–69%) when turbine operation was curtailed below wind speeds of 5.0 ms^{-1}. Similar declines in mortality for a 5.0 ms^{-1} curtailment speed were estimated for hoary bats (48%; 95% CI: 24%–64%), eastern red bats (61%; 95% CI: 42%–74%) and silver-haired bats (52%; 95% CI: 30%–66%). Declines in fatality rates of this magnitude could be essential to prevent population declines of vulnerable species, such as hoary bats (Friedenberg & Frick, 2021). The only published curtailment study to use fatality surveys outside North America found that total bat fatalities decreased by 54% when the cut-in speed was raised from 3.0 to 4.5 ms^{-1} at a wind energy facility in Australia (Bennett et al., 2022), well within our expected range.

Since the first mass mortality events of bats were detected, there has been a call for some level of curtailment to reduce bat fatalities (Arnett et al., 2011, 2015; Baerwald et al., 2009; Frick et al., 2017). However, a common theme in discussion of the broad application of curtailment is the transferability of individual studies onto the unique circumstances of each wind energy facility (Hein & Straw, 2021). Individual studies of curtailment often lack the statistical power to detect decreases in mortality among species, or between multiple curtailment speeds given the natural variability in wind regimes, fatality rates and experimental design constraints (e.g. number of observed fatalities and low sample sizes, including the number of turbines). Our meta-regression results demonstrate that curtailment to reduce bat fatalities is consistently effective and that raising the curtailment wind speed is associated with increased reduction of mortality across facilities and turbine characteristics. The exception to this was for hoary bats, where the model that included turbine characteristics was equally ranked with the curtailment-only model and the null model carried 15% of the model weight indicating poor explanatory power. Similarly, at facilities across the US and Canada total fatalities of hoary bats were primarily associated with turbine ground clearance but varied greatly across the studies (Garvin et al., 2024). Our results suggest an increased effectiveness for hoary bat fatality reduction of curtailment at taller turbines with larger rotor-swept areas. As turbines increase in size and decrease their ground clearance, the bats with low foraging flights may be put that at increased mortality risk. There is some evidence that bats around wind turbines fly at lower altitudes than previously expected (Aghababian, 2023), and this may increase fatality risk for hoary bats (Garvin et al., 2024). More detailed studies that focus on hoary bat mortality in the context of curtailment could help increase understanding of risk, particularly with increasing turbine size, decreasing ground clearance and lower cut-in speeds. Our meta-analysis leveraged the combined efforts of individual studies to determine the overall efficacy of curtailment and found that the largest sources of variability among studies were the treatment curtailment speeds used, the reference cut-in speed, and potentially the size of the rotor-swept area of the individual turbines. Identifying the most salient contributors to fatality reduction is useful to determine the general applicability of curtailment to reduce bat fatalities.

When not accounted for, plot size can influence fatality estimates, which may confound interpreting curtailment effects across studies (Dalthorp et al., 2024; Huso & Dalthorp, 2014). Plot size of the searched area was not informative in our models (Table 3), but there was little variability in the plot sizes included in our study, which limited our ability to detect a weak effect. If carcasses land farther from the turbine as wind speed increases, including more carcasses landing beyond the search plot perimeter, then mortality reduction will be overestimated at higher wind speeds. Huso (Huso, 2018) found that the proportion of carcasses that land >60 m from the turbine base increased consistently with increasing wind speed. Most curtailment studies limit search area to within 60 m, which likely results in estimating a stronger curtailment effect on reducing fatalities than what actually occurs. Schirmacher et al. (2016) monitored fatalities in 90-m radius plots to compare control turbines (3.5 $\mathrm{ms^{-1}}$) and curtailed turbines (5.0 $\mathrm{ms^{-1}}$) and found a non-significant effect of 0%–38% reduction in bat fatalities. However, this study only had enough statistical power to detect a potential 50% reduction for turbines curtailed to 5.0 $\mathrm{ms^{-1}}$. Future studies to quantify the effect of curtailment on reducing bat fatality can account for the bias induced by wind speed (Huso, 2018) by having plots sizes larger than 60 m.

Compared to a mean reduction of 53% at a curtailments speed of 5.5 $\mathrm{ms^{-1}}$ reported by an unpublished study using quantitative meta-analysis of curtailment efforts at 12 facilities across Ontario, Canada (Zimmerling & Francis, 2016), our results suggest an overall stronger average effect of fatality reduction of 69% (95% CI: 62–75). Likewise, our results suggest stronger effects of curtailment than the 40%–63% in a recent published meta-analysis of the difference between control and treatment curtailment (Adams et al., 2021). We restricted our meta-analysis to comparisons of control and treatments made in the same year at the same location. Accounting for inter-annual variation in fatality rates and number of turbines in each study improved the estimate of efficacy of curtailment.

It has been proposed that a range of turbine characteristics in addition to the rotor diameter (or rotor-swept area) may influence bat mortality, including manufacturer and nacelle height (BWEC (Bats and Wind Energy Cooperative), 2018, Hein & Straw, 2021, Garvin et al., 2024). While turbine height, rotor diameter and manufacturer did not contribute significantly to the best fatality reduction models for all bat species combined, the individual species models show that the hoary bats, which are potentially the most vulnerable of the species in this study, may be more susceptible to variation in turbine structure. The efficacy of curtailment at reducing hoary bat mortality increased slightly with rotor-swept area size. If the influence of ground clearance is predictive of hoary bat mortality (Garvin et al., 2024), and ground clearance reduced with increased turbine size, then future curtailment studies can be more effective by incorporating a more diverse range of turbine sizes than are currently available. More work can help evaluate this relationship as sampling is minimal at low rotor-swept areas, and there were few studies that provided hoary bat-specific data. Despite the lack of influence on the best multi-species candidate models in our meta-analysis, it is still important to evaluate turbine-specific moderators when comparing studies, particularly when incorporating work that spans large time periods. Increases in turbine height, rotor-swept area, and low wind-speed efficiency will continue to challenge evaluating the efficacy of curtailment protocols.

There is a current push to decarbonize energy production around the world to meet global climate mitigation goals and improve equitable access to clean, inexpensive electricity. Renewable energy infrastructures installed to achieve global decarbonization goals should also meet the global no net loss of biodiversity standards (IFC, 2012). Beyond siting appropriate locations for development, strategies to minimize environmental impacts of wind development are needed (Arlidge et al., 2018; Barré et al., 2023). Our meta-analysis approach can be applied to incorporate results from future studies for comparing regional differences in efficacy of curtailment or comparing the efficacy of new minimization strategies (e.g. efficacy of acoustic emitters as deterrents).

Various efforts are currently focused on improving methods to predict finer-scale mortality risk (e.g. smart curtailment), and our results may help refine studies and technology aimed to preserve power generation while minimizing bat mortality. Algorithm-based smart curtailment uses additional data streams (e.g. time of year, temperature, wind speed and direction and bat acoustic activity) to make automated decisions that curtail wind operation during periods identified with the highest bat mortality risk. Some of these methods show promise of being effective at reducing bat mortality, including the Sheffield and Blue Sky–Greenfield projects (Figure 2). Curtailment up to 6.0 ms^{-1} at Sheffield was based on wind speed and temperature and demonstrated a 62% reduction in fatality (95% CI: 34–78); although, temperature affected curtailment decisions only 5% of the time, it reduced power loss by 18% (Martin et al., 2017). The Blue Sky–Greenfield study used the proprietary Turbine Integrated Mortality Reduction system (TIMR) to activate curtailment for a restricted period when bat echolocation calls were detected at wind speeds up to 8.0 ms^{-1} and was 1.5 times more effective than simple curtailment at 4.5 ms^{-1} (Hayes et al., 2019; Rabie et al., 2022). However, activation of TIMR reduced the overall operation time of the wind turbines, and this reduction was estimated at 2.8 times the cost of simple curtailment. Incorporating the results from our meta-analysis can inform study design and help identify curtailment strategies of smart curtailment systems to both minimize bat mortality and maximize energy production.

AUTHOR CONTRIBUTIONS

Cris D. Hein and Winifred F. Frick conceived the study. Michael D. Whitby acquired, analysed, interpreted and drafted the initial manuscript. Manuela Huso assisted with analysis and interpretation. Cris D. Hein, Winifred F. Frick and M. Teague O'Mara assisted with interpretation of data as well as drafting the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest to declare.

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DATA AVAILABILITY STATEMENT

Data used in the analysis are publicly accessible and have been archived along with analysis code at OSF https://doi.org/10.17605/OSF.IO/3Z8YN (Whitby, 2024).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Table S1: Equations used to calculate variance from studies where this information was not directly provided, as well as transformation of proportional reduction of fatality.

Table S2: Summary of important statistics from top model explaining the heterogeneity curtailment for total bat fatalities and fatalities of individual bat species.

Table S3: Predicted total bat fatality reduction for curtailment cut-in speeds.

Table S4: Predicted fatality reduction of hoary bats (*L. cinereus*) across various curtailment cut-in speeds.

Table S5: Predicted fatality reduction of eastern red bats (*L. borealis*) across curtailment cut-in speeds.

Table S6: Predicted fatality reduction of silvered-haired bats (*Lasionycteris noctivagans*) across curtailment cut-in speeds.

Figure S1: Wind turbine distribution and kernel densities of size metrics for the 2019 fleet of wind turbine facilities (A–C) and the facilities online between 2007 and 2017 (D–F) for all utility-scale wind turbines (>1.5 MW) in the United States Wind Turbine Data Base.

Figure S2: Funnel plots of contrast used in meta-analysis and meta-regression of reduction in bat fatalities at curtailment studies for total bat, hoary bat, eastern red bat, and silver-haired bat fatalities.

Figure S3: Percent reduction of bat fatalities for curtailment strategies with different treatment cut-in speeds (*x*-axis) for total bat, hoary bat, eastern red bat, and silver-haired bat fatalities.

Figure S4: Predicted log ratio of control to treatment total bat fatalities for curtailment strategies with different treatment cut-in speeds (*x*-axis).

Figure S5: Effect size (log ratio of means transformed to percent decrease) of reduction in hoary bat fatalities from tested curtailment strategies.

Figure S6: Relationship between rotor swept area and predicted percent reduction of hoary bats when turbines were curtailed at $5.0\,ms^{-1}$.

Figure S7: Effect size (log ratio of means transformed to percent decrease) of reduction in eastern red bat fatalities from tested curtailment strategies.

Figure S8: Effect size (log ratio of means) of reduction in silver-haired bat fatalities from tested curtailment strategies.

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