

Article

# USA Wind Energy-Caused Bat Fatalities Increase with Shorter Fatality Search Intervals

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**Abstract:** Wind turbine collision fatalities of bats have likely increased with the rapid expansion of installed wind energy capacity in the USA since the last national-level fatality estimates were generated in 2012. An assumed linear increase of fatalities with installed capacity would expand my estimate of bat fatalities across the USA from 0.89 million in 2012 to 1.11 million in 2014 and to 1.72 million in 2019. However, this assumed linear relationship could have been invalidated by shifts in turbine size, tower height, fatality search interval during monitoring, and regional variation in bat fatalities. I tested for effects of these factors in fatality monitoring reports through 2014. I found no significant relationship between bat fatality rates and wind turbine size. Bat fatality rates increased with increasing tower height, but this increase mirrored the increase in fatality rates with shortened fatality search intervals that accompanied the increase in tower heights. Regional weighting of mean project-level bat fatalities increased the national-level estimate 17% to 1.3 (95% CI: 0.15–3.0) million. After I restricted the estimate's basis to project-level fatality rates that were estimated from fatality search intervals <10 days, my estimate increased by another 71% to 2.22 (95% CI: 1.77–2.72) million bat fatalities in the USA's lower 48 states in 2014. Project-level fatality estimates based on search intervals <10 days were, on average, eight times higher than estimates based on longer search intervals. Shorter search intervals detected more small-bodied species, which contributed to a larger all-bat fatality estimate.

**Keywords:** bats; fatality estimation; search interval; tower height; wind energy; wind turbine

## 1. Introduction

As wind energy expands worldwide, bats are increasingly at risk of deadly encounters with wind turbines. The most recent effort to assess large-scale wind energy impacts on bats was in 2013, when several papers synthesized reports of fatality monitoring across North America. One predicted 196,190 to 395,886 bat fatalities at US and Canadian wind projects in 2012 [1]. Two later studies, both based on a larger accumulation of fatality monitoring reports, estimated the numbers of bats killed by US wind turbines in 2012 to have been 683,910 [2] and 888,036 (90% CI: 384,643–1,391,428) [3]. The installed capacity of USA wind energy was 51,630 megawatts (MW) in 2012, but capacity increased every year to 64,485.5 MW in 2014 and to 100,125 MW by September 2019 [4]. Annual fatality numbers most likely increased with installed wind energy capacity. However, an increasing proportion of fatality monitoring reports have not been made publicly available since 2010. There has been no follow-up to the 2012 USA-wide and USA-Canada estimates.

The utility of national estimates of wind turbine-caused bat fatalities was recently questioned: “Species-specific levels of fatality at wind energy facilities are more useful for regulatory decisions and conservation planning related to wind energy than the cumulative national estimates that garner more attention” [5]. However, species-specific estimates of fatalities at individual projects are largely interpreted relative to other estimates, including those at regional or national levels. Due to the fact that project-level estimates are used to generate the national estimate, problems with accuracy at the

project level can be magnified at the national level. Estimating the regional or national levels of wind energy-caused mortality serves as an opportunity to focus attention on inter-project variation in fatality monitoring methods, estimation methods, and assumptions [3,6]. For example, national-level estimates have been criticized for potential regional bias [5]. In lieu of a national sampling program, national-level estimates are founded on available fatality monitoring reports that might over- or under-represent particular regions over others, relative to the distribution of wind energy. This potential bias was in fact revealed in efforts to make national estimates [3,7]. So long as bat fatality estimation remains of questionable accuracy at the national level, project-specific fatality estimates remain of questionable comparability. Yet, comparability of bat fatality estimates has often been assumed among wind projects [8–13]) and between wind energy and other anthropogenic sources of bat mortality [5,8,9].

Prior to synthesizing project-level fatality estimates for making national estimates [3], multiple sources of uncertainty and bias had been overlooked. Wind turbine size and tower height vary among projects. Fatality search interval, maximum search radius, and monitoring duration vary. Searcher detection trials and carcass persistence trials vary in methodology and in their accuracy in estimating the proportion of carcasses not found during fatality monitoring. Even the fatality metric has varied. Research on the effects of these sources of uncertainty continued since 2012, while the installed wind energy capacity continued to increase across the USA.

The goal of this study was to compare fatality rates from available reports of post-construction fatality monitoring of bats in USA and Canada through 2014. By improving the comparability of project-level fatality rates, one objective was to test whether the trend toward installing larger wind turbines on taller towers might increase fatality rates [11]. Another objective was to test whether the shorter fatality search intervals implemented at projects with turbines on taller towers might increase fatality rates. A third objective was to weight fatality estimates regionally to minimize regional bias in national-level fatality estimation. To improve comparability, I independently estimated fatality rates from the reported data, using consistent adjustment factors, and I expanded them to the 65,874 MW of installed capacity of wind energy in the USA's lower 48 states in 2014.

## 2. Materials and Methods

I collected and reviewed all publicly available reports of bat fatality monitoring at North American wind-energy projects through 2014, and which met my reporting standards [14–108]. My reporting standards for fatality estimates included the reporting of fatality data, along with descriptions of specific wind project and fatality monitoring attributes I needed for independent estimation of fatalities (Table 1).

**Table 1.** Fatality monitoring study attributes that I recorded from available reports through 2014, where attributes in italics were not required for fatality estimation, but useful for hypothesis-testing.

Attribute	Explanation
Project size	MW of rated capacity or number of turbines identified to model
Extent of study	Number of MW or turbines monitored for fatalities
<i>Tower height</i>	Height (m) from ground to rotor hub
<i>Project start date</i>	Date of initial commercial operations
Monitoring period	Start and end dates of fatality monitoring per search interval (below)
Search interval	Average or scheduled number of days between searches
Searchers	Humans or dogs
Max search radius	Maximum distance (m) searchers searched from turbine, often measurable from search plot dimensions
<i>Transect width</i>	Distance (m) separating fatality search transects within plot
Omissions	Whether fatalities were omitted as incidental or clearing-search finds
Fatalities	Species, dates and wind turbine attributes of detected fatalities
<i>Distance from turbine</i>	Distance (m) between fatality and the nearest wind turbine

I independently estimated fatality rates from data in monitoring reports, using a common estimator for the purpose of removing variation due to differing assumptions among the available estimators. I relied on a simple fatality estimator [3,109]:

$$\hat{F} = \frac{F}{S \times R_C \times d}, \quad (1)$$

where  $\hat{F}$  was the fatality estimate from the number of found fatalities,  $F$ , divided by the product of terms that represented fatalities not found during monitoring. Values for  $S$  and  $R_C$  were typically calculated from results of independent trials performed, in conjunction with fatality monitoring [3], where  $S$  was the average proportion of carcasses that were detected in searcher detection trials, and  $R_C$  was mean daily proportion of trial carcasses that persisted for the number of days into the trial corresponding with the number of days in the average fatality search interval. A trial administrator typically would confirm that trial carcasses had been available to be found by searchers in searcher detection trials, i.e., that carcasses had not been removed by scavengers. A trial administrator typically would also periodically visit carcasses to assess their status during the carcass persistence trial. I averaged estimates of carcass persistence and searcher detection rates from trials reported from US and Canadian wind projects [3]. Values for  $d$ , the adjustment for maximum search radius bias, were estimated for each combination of turbine tower height and maximum search radius (Table 1). I fit a logistic model to the cumulative increase in fatalities, with increasing distance from the turbine. I then projected each model to 99% of its asymptote, to estimate the number of fatalities that would have been found had searches extended to the asymptotic distance predicted by the model. I used the difference between the predicted number of fatalities and the recorded number of fatalities to calculate the proportion of fatalities found within the maximum search radius, otherwise termed ‘search radius bias’ in fatality rate estimates [3]. I used averages to represent  $S$ ,  $R_C$ , and  $d$  to dampen the influence of anomalous values from a few studies. I calculated SE of fatality estimates using the delta method.

After reviewing written characterizations and both reported and aerial imagery of each fatality monitoring site, I broadly classified detection trials by ground visibility. I classified ground visibility as ‘low’ on areas covered by dense forest, wetlands, or tall, dense crops such as corn; ‘moderate’ on areas covered by shrublands, tall grassland, or crops such as wheat, barley and hay; and ‘high’ on areas covered by annual grassland, short-grass prairie, sage brush, short annual grasslands, reclaimed land, snow, or barren. Based on fatality monitoring reports from both the USA and Canada,  $S$  averaged 0.113 (SE = 0.013; 271 trial carcass placements in 2 studies) on low ground with low visibility, 0.449 (SE = 0.104; 346 placements in 4 studies) on ground with moderate visibility, and 0.595 (SE = 0.057; 552 placements in 9 studies) on ground with high visibility [3]. I drew values for  $R_C$  and  $d$  (and SE) from look-up tables derived from both USA and Canadian fatality monitoring reports [3], where  $R_C$  corresponded with average search interval of each fatality monitoring study, and  $d$  corresponded with the combination of tower height (hub height) and maximum fatality search radius that best matched each study.

Based on reports of fatality monitoring through 2014, I averaged project-level fatality estimates within regions of installed wind energy projects within the USA. I defined regions with the help of the US Geological Survey’s U.S. Wind Turbine Database (<https://eerscmap.usgs.gov/uswtodb/viewer/#3/37.25/-96.25>). I defined the regions as Southwest (California, Nevada, Arizona) Pacific Northwest (Oregon and Washington), Rocky Mountains (Idaho, western Montana, Wyoming, Utah, western Colorado), High Plains (eastern Montana, eastern Colorado, Nebraska, Kansas, Iowa, North Dakota, South Dakota, western and southern Minnesota, Illinois, Indiana), Great Lakes (eastern Minnesota, Wisconsin, Michigan, northern Pennsylvania, eastern New York), Appalachia/Northeast (Maine to West Virginia), Texas Gulf, and Texas High Plains. I estimated mean (and 95% CI) bat fatalities/MW/year at the MW of wind turbines that had been monitored at each wind project. I added zero values where no fatalities had been reported for bats or for particular species of bats whose geographic ranges overlapped the project site. I expanded my region-specific average fatality rates to the installed MW of

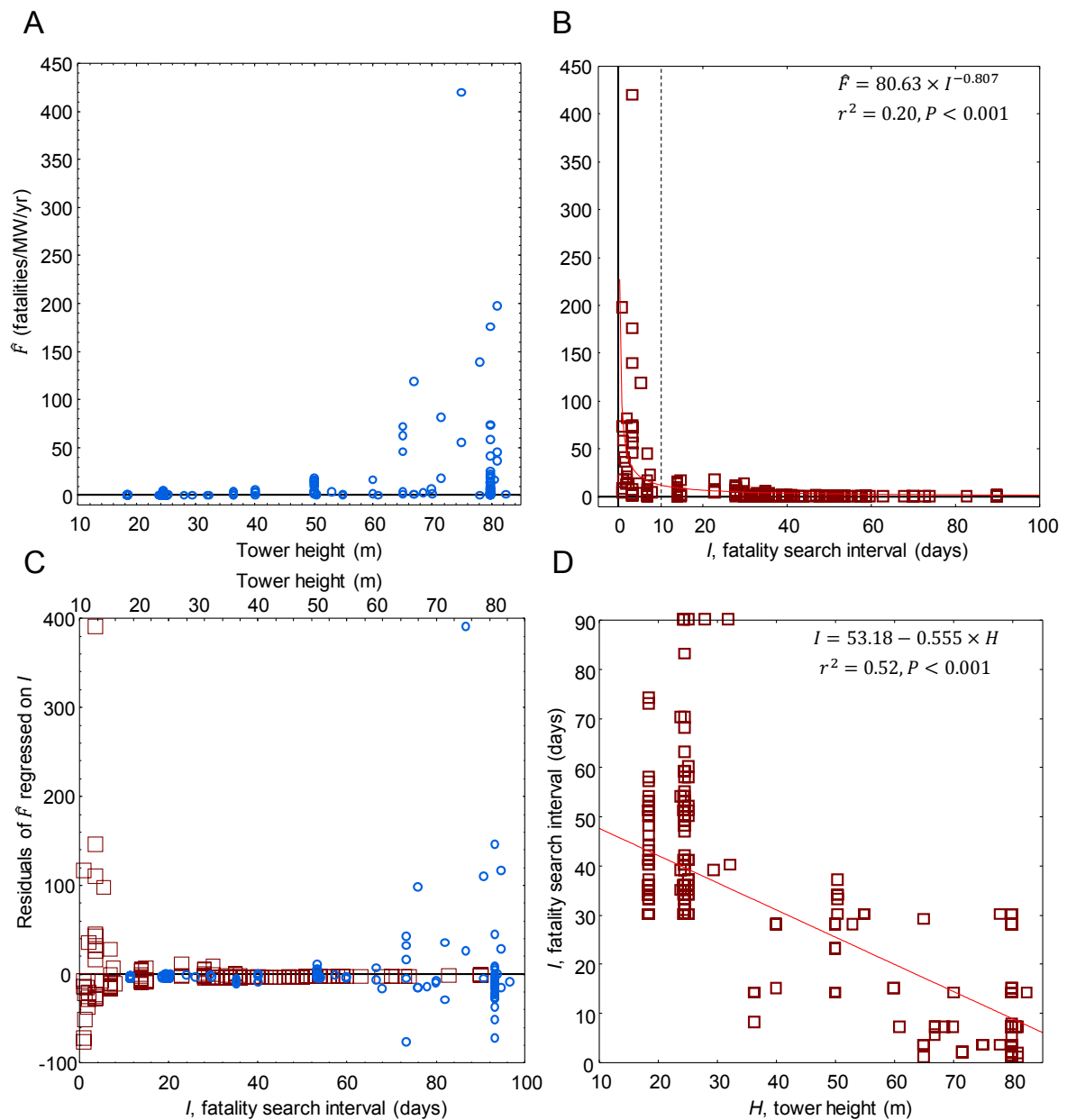
wind turbines in each region. I summed regional estimates for the national-level estimate of USA bat fatalities in 2014. The basis of the national-level estimate was 64,485.5 MW of wind-energy capacity that had been installed across the USA's lower 48 states by 2014 [4]. I also estimated species-specific fatality estimates adjusted for the proportion of the lower 48 states composed of each species' geographic range: USA-wide  $\hat{F} = \hat{F} \times 64,485.5 \text{ MW} \times P_i$ , where  $P$  was proportion of the area of the USA's lower 48 states covered by the approximated geographic range of the  $i$ th species ( $P = 1$  in the case of all bats). Finally, I estimated fatalities/MW/year, based on search intervals of  $I < 10$  days ( $\hat{F}_{<10d}$ ) and  $I \geq 10$  days ( $\hat{F}_{\geq 10d}$ ) among wind turbines  $\geq 0.66$  MW in rated capacity (modern wind turbines), that were monitored for at least 6 months. All fitted models used in hypothesis-testing were based on least-squares regression analysis.

### 3. Results

#### 3.1. Tower Heights and Search Intervals

Estimates of fatality rates of all bats did not correlate significantly with wind turbine size (MW), but they did increase with increasing tower height (Figure 1A). However, estimated fatality rates of all bats related to fatality search interval as an inverse power function (Figure 1B). The residuals from the model-fit were symmetric with both search interval and tower height, but they increased in magnitude with increasingly shorter search intervals and taller towers (Figure 1C). Average search interval decreased significantly with increasing tower height (Figure 1D).

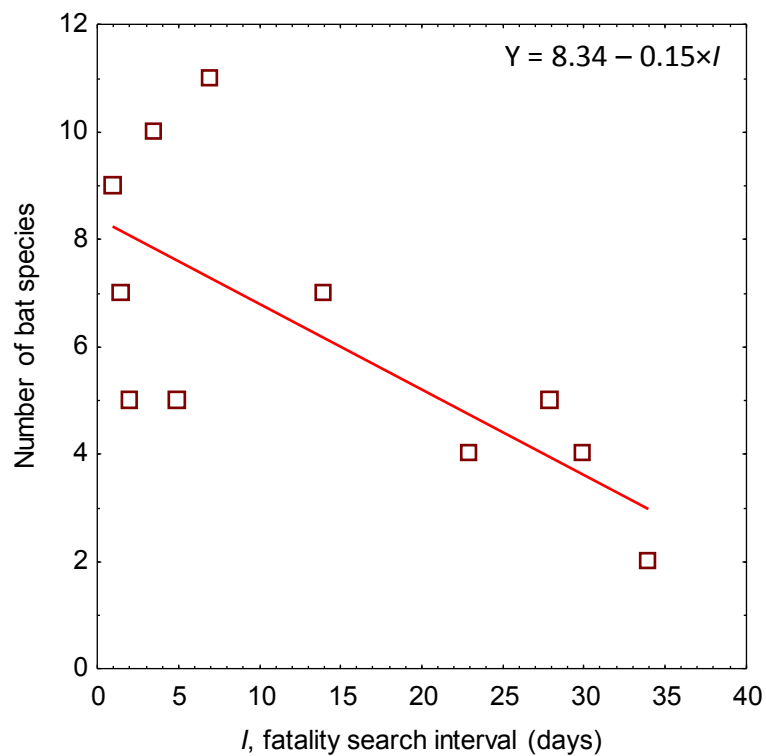
Species-specific  $\hat{F}_{<10d}$  did not correlate with  $\hat{F}_{\geq 10d}$ . For all bats,  $\hat{F}_{<10d}$  averaged nearly five times higher than  $\hat{F}_{\geq 10d}$  did (Table 2).  $\hat{F}_{<10d}$  was higher than  $\hat{F}_{\geq 10d}$  for each and every species, ranging up to 22.3 times higher for little brown bat (Table 2). Eleven bat species were represented in fatality estimates based on  $I < 10$  days, whereas only eight species were represented in fatality estimates based on  $I \geq 10$  days (Table 2). The number of bat species represented in fatality monitoring increased with the decreasing search interval (Figure 2). The number of ha searched per species of bat detected as wind turbine fatalities increased significantly with increasing search interval (Figure 3A), and even more so for species of bat typically weighing  $< 10$  g (Figure 3B). The rate of increase in the number of ha needed to be searched per represented bat species was nearly five times higher for small bat species (slope coefficient = 17.95), as compared to all bats (slope coefficient = 3.68). Bat fatalities unidentified to species ("Bat spp.") composed 5% of  $\hat{F}_{<10d}$ , whereas they composed 24.5% of  $\hat{F}_{\geq 10d}$  (Table 2).



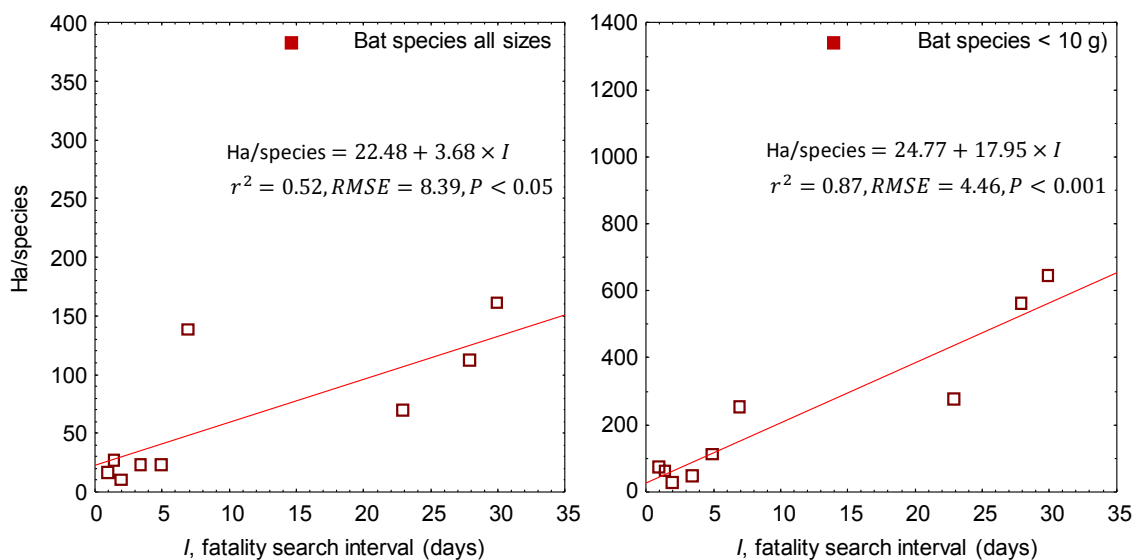
**Figure 1.** Through 2014, project-level bat fatality rates among North American wind projects increased with increasing tower height (A) and decreasing fatality search interval (B), the regression residuals of which were symmetric for both tower height (blue circles) and search interval (maroon squares) (C). Fatality search interval decreased with increasing tower height (D).

**Table 2.** Weighted mean (95% CI) annual bat fatalities/MW among US wind turbines of  $\geq 0.66$  MW in rated capacity, monitored  $\geq 0.5$  years, and searched at intervals  $< 10$  days or  $\geq 10$  days, where N was the number of combinations of monitored wind projects, wind turbine size, and search interval.

Species/Group	Mass (g)	Fatalities/MW/Year among Turbines $\geq 0.66$ MW						$\hat{F}_{<10d}$ $\hat{F}_{\geq 10d}$
		I < 10 days			I $\geq 10$ days			
		$\bar{x}$	95% CI	N	$\bar{x}$	95% CI	N	
Mexican free-tailed bat, <i>Tadarida brasiliensis</i>	10.0	2.709	0.332–5.120	5	0.288	0.063–0.606	14	9.4
Big brown bat, <i>Eptesicus fuscus</i>	20.5	0.981	0.774–1.274	23	0.052	0.000–0.163	24	18.9
Silver-haired bat, <i>Lasionycteris noctivagans</i>	11.0	6.217	5.148–7.413	33	0.617	0.107–1.210	41	10.1
Hoary bat, <i>Lasiurus cinereus</i>	26.0	5.307	4.034–6.795	30	2.824	0.274–5.669	41	1.9
Western red bat, <i>Lasiurus blossevillii</i>	13	0.073	0.000–0.199	5	0.000		14	
Eastern red bat, <i>Lasiurus borealis</i>	12.5	3.635	1.759–5.968	18	1.374	0.000–3.264	4	2.6
Northern yellow bat, <i>Lasiurus intermedius</i>	23.0	0.456		1			0	
Tricolored bat, <i>Perimyotis subflavus</i>	6.3	1.588	0.924–2.317	17	0.168	0.000–0.451	4	9.5
Northern long-eared bat, <i>Myotis septentrionalis</i>	7.4	0.241	0.171–0.310	9			0	
Little brown bat, <i>Myotis lucifugus</i>	9.0	1.937	1.397–2.498	28	0.087	0.000–0.250	38	22.3
California myotis, <i>Myotis californicus</i>	4.3			5	0.004	0.000–0.012	14	
Western small-footed bat, <i>Myotis ciliolabrum</i>	4.9	0.060		5	0.000		3	
Bat spp.		0.993	0.849–1.186	35	1.002	0.158–1.941	42	1.0
All bats		19.690	11.486–28.989	35	4.083	0.407–8.342	42	4.8



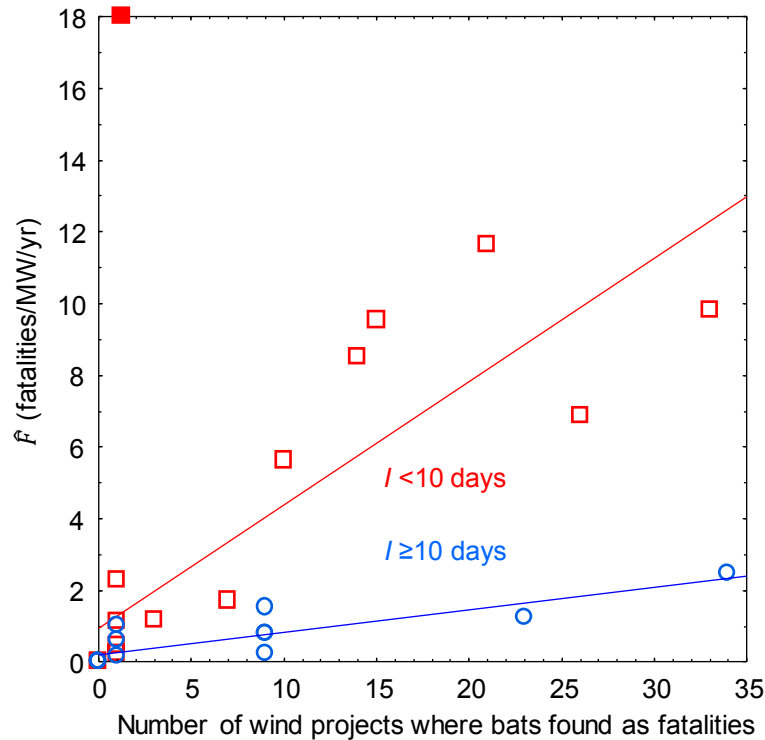
**Figure 2.** The number of bat species found as wind turbine fatalities declined, with mean fatality search interval used among wind turbines of  $\geq 0.66$ -MW of rated capacity in North American wind projects through 2014.



**Figure 3.** Mean number of ha/species needed to be searched per species of bat represented as wind turbine fatalities increased with increasing fatality search interval (**left**), and increased 5-fold for bat species typically weighing <10 g (**right**), among North American wind projects through 2014. The filled square represents an outlier.

Species-specific  $\hat{F}_{<10d}$  and  $\hat{F}_{\geq 10d}$  increased with the number of monitored wind projects where bats of each species were found as fatalities, but more rapidly for  $\hat{F}_{<10d}$  (Figure 4). After omitting the evening bat (*Nycticeius humeralis*) fatality estimate as an outlier due to its single project sampled within the species’ small geographic range within the USA,  $\hat{F}_{<10d} = 0.95 + 0.34 \times I$  ( $r^2 = 0.75$ ,  $RMSE = 5.4$ ,  $p < 0.001$ ), and  $\hat{F}_{\geq 10d} = 0.19 + 0.06 \times I$  ( $r^2 = 0.72$ ,  $RMSE = 5.3$ ,  $p < 0.001$ ). Without the lone evening

bat estimate, species-specific  $\hat{F}_{<10d}$  correlated with species' geographic range ( $r = 0.90$ ,  $p < 0.001$ ). Species-specific  $\hat{F}_{\geq 10d}$  also increased with geographic range, but the correlation was weaker ( $r = 0.60$ ,  $p < 0.05$ ). The number of studies where bats were found as fatalities increased with increasing species' geographic range ( $r = 0.91$ ,  $p < 0.001$ ).



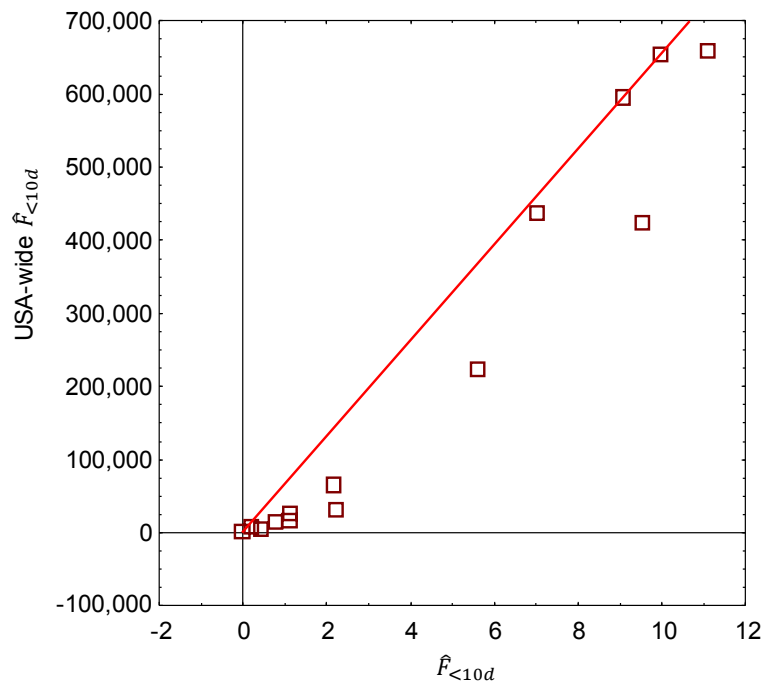
**Figure 4.** Species-specific bat fatalities/MW/year increased with the number of wind projects, where bats were found as fatalities across North America through 2014, and did so at an increased rate where search intervals averaged  $<10$  days. The filled square represents an outlier of one bat species detected at a single study.

### 3.2. Estimates of Bat Fatalities in the USA

Projecting estimates of mean fatalities/MW/year to the estimated installed capacity of wind energy in the United States in 2014, I estimated annual fatalities of 2,223,270 (95% CI: 1,766,173–2,722,457) bats based on search intervals  $<10$  days, 274,030 (95% CI: 9360–600,986) bats based on search intervals  $\geq 10$  days, and 1,300,569 (95% CI: 154,214–3,032,370) bats based on all search intervals. I estimated an eight-fold difference between fatality monitoring efforts, based on search intervals shorter and longer than 10 days.

A simple expansion of  $\hat{F}$  to the USA's installed capacity of wind energy in 2014 would have overestimated fatalities of most bat species, because their geographic ranges do not cover the entire USA. Expansions of mean project-level fatality rates to species' geographic ranges resulted in national under-estimates. Under-estimates were indicated by USA-wide  $\hat{F}_{<10d}$ , located under the line connecting the all-bats estimate to the axes' origin (Figure 5). For only those species with geographic ranges spanning  $\geq 90\%$  of the area of the USA, and for which installed wind energy capacity would have increased collision vulnerability almost wherever the capacity was installed in the USA, and for which size and conspicuousness would have seldom resulted in carcasses going unidentified, I estimated USA-wide  $\hat{F}_{<10d}$  as 840,843 (95% CI: 780,496–904,738) silver-haired bats, 827,929 (95% CI: 749,479–918,921) hoary bats, and 40,042 (95% CI: 37,076–44,556) big brown bats.



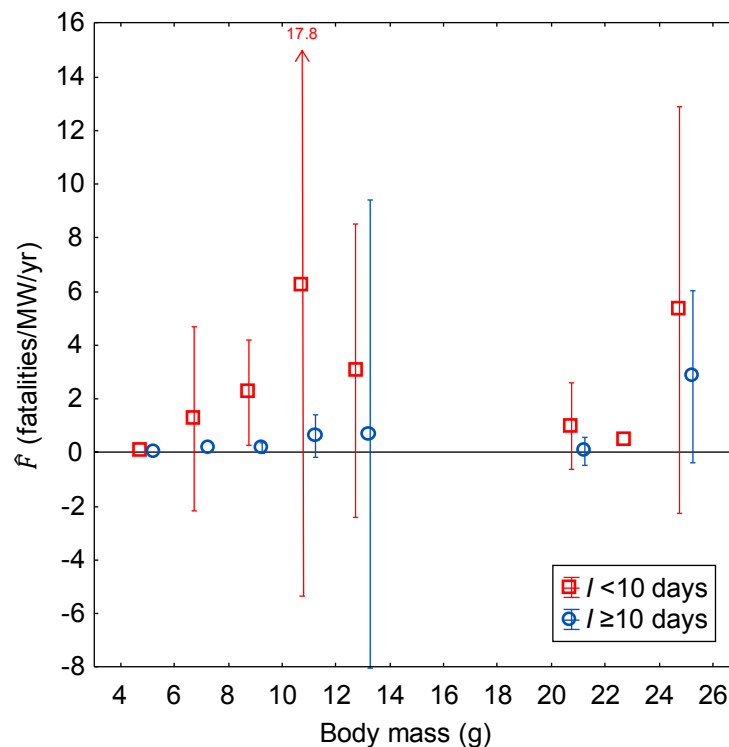


**Figure 5.** For most species, species-specific estimates of USA-wide bat fatalities/MW/year increased less than proportionally (red line connecting the axes’ origin to the all-bats estimates), with mean project-specific fatalities/MW/year. USA-wide estimates were adjusted to installed wind energy capacity: USA-wide  $\hat{F} = \hat{F} \times 64,485.5 \text{ MW} \times P_i$ , where  $P$  was proportion of the area of the USA’s lower 48 states covered by the approximated geographic range of the  $i$ th species ( $P = 1$  in the case of all bats). Those species whose estimates fell along the line that was proportional to the all-bats estimates either occurred within a small geographic range or across nearly all of the USA.

$\hat{F}_{<10d}$  for all bats averaged lower than  $\hat{F}_{<10d}$  in the Pacific Northwest and Rocky Mountains regions, but it was higher in other regions where both short and long search intervals had been used (Table 3). Averaged among regions,  $\hat{F}_{<10d}$  was higher than  $\hat{F}_{\geq 10d}$  for most bat species, and the difference appeared larger for medium to small-sized bats (Figure 6).

**Table 3.** Mean estimates of bat fatalities/MW/year at wind turbines  $\geq 0.66$  MW in rated capacity, monitored for  $\geq 0.5$  years, and whether based on fatality search intervals  $< 10$  days,  $\hat{F}_{<10d}$ , or  $\geq 10$  days  $\hat{F}_{\geq 10d}$ , through 2014, within regions of the USA.

Region	$\hat{F}_{<10d}$		$\hat{F}_{\geq 10d}$		$\frac{\hat{F}_{<10d}}{\hat{F}_{\geq 10d}}$
	$\bar{x}$	95% CI	$\bar{x}$	95% CI	
Southwest	1.89	0.12–3.95	1.21	0.51–1.97	1.6
Pacific Northwest	1.02	0.00–2.28	3.23	0.49–6.33	0.3
Rocky Mountains	2.44	1.51–3.46	8.16	1.02–15.64	0.3
High Plains	62.83	58.22–67.53	7.64	0.00–17.26	8.2
Great Lakes	16.74	10.20–24.04			
Appalachia/Northeast	57.84	14.12–108.85			
Texas Gulf	7.71				
Texas High Plains	7.05		0.16		44.1
Southwest, Pacific Northwest, Rocky Mountains, High Plains, Texas High Plains	15.04	11.97–18.26	4.08	0.41–8.34	3.7
Total	19.69	12.39–36.79	3.69	2.12–5.26	5.3



**Figure 6.** Averaged among regions of the USA's lower 48 states,  $\hat{F}_{<10d}$  (95% CI) was higher than  $\hat{F}_{\geq 10d}$  (95% CI) for most species of bat through 2014.

#### 4. Discussion

Even though tower height appeared to be confounded with fatality search interval in its prediction of bat fatality rates, tower height remains a potential collision risk factor. Relative to concurrently monitored old-generation turbines mounted on towers of mostly 18.5 m to 24 m height that were searched at 41-day intervals in the Altamont Pass Wind Resource Area (WRA), bat fatalities/MW/year were nine times higher at 0.66-MW turbines mounted on 50-m and 55-m towers that were searched at 33-day intervals over two years [87], and 13 times higher at 2.3-MW turbines mounted on 80-m towers that were searched at 28-day intervals over three years [20] in the same WRA. Such large differences in fatality rates could not have resulted from variation in what were already long search intervals. In another comparison between largely concurrent monitoring over three years at neighboring wind projects, searchers found two bats among 11.67 MW of turbines mounted on 18.5-m and 24-m towers that were searched at five-day intervals [110], whereas they found 31 bats among 39.1 MW of turbines on 80-m towers searched at seven-day intervals [20]. In this comparison, bat fatalities found per MW numbered 4.6 times more at turbines on the taller towers. A mere two-day difference in search interval was unlikely to be the reason for this difference. Although shorter search intervals increase the detection rates of bat fatalities, increased tower height likely increases collision risk and deposits more bats to be found in monitoring.

I estimated 2.22 million bat fatalities at 64,485 MW of installed wind-energy capacity in the United States in 2014. This estimate could be inaccurate if reported fatality rates remain biased by region or if they changed between the earliest to the latest reports due to changes in wind turbine design and operations (e.g., lower cut-in speeds) or in mitigation (e.g., implementation of operational curtailment) [3,7]. More important than whether my estimate was accurate, however, was its change in magnitude when relying on project-level fatality estimates based on shorter search intervals.

My latest estimate was 2.5 times higher than my estimate for 2012 [3]. Part of this increase can be explained by the 25% increase in installed wind energy capacity in the two years between 2012 and 2014. Part of it can be explained by my expansions of mean project-level fatality rates

to regions. However, most of the increase was due to my restriction of the source data to fatality monitoring efforts with search intervals <10 days. I found an eight-fold difference in estimates of mean project-level fatality rates between search intervals shorter or longer than 10 days. More frequent searches for fatalities greatly improves the likelihood of detecting bat fatalities, by more competently competing against vertebrate scavengers at being the first to find carcasses. More frequent searches also allows searchers more opportunities to find bat carcasses before they deteriorate to obscurity. In integrated carcass detection trials involving small birds, which are also difficult for human searchers to find, searchers averaged 4.3 searches per first detection with an average search interval of five days (Smallwood et al., 2018). Through 2014, variation in the fatality search interval among monitoring efforts was one of the largest sources of variation in bat fatality estimates at wind projects.

The fatality search interval can also contribute to bias in bat fatality estimation, depending on how adjustments are made for the proportion of undetected fatalities. At one project monitored at seven-day intervals, separate trials for carcass persistence and searcher detection rates resulted in a bat fatality estimate that was three times higher than the estimate, based on integrated carcass detection trials [20]. This difference was largely due to the integrated trials' presentation of multiple opportunities for searchers to find trial carcasses, each of which the trial administrator left indefinitely to simulate fatalities remaining where deposited by wind turbines until removed either by scavengers or the elements [110]. Results of integrated detection trials [20,110] confirmed an inflation bias predicted for the results of conventional carcass detection trials applied to fatalities found at short search intervals [111]. Additionally, consistent with predictions [111], bat fatalities estimated from a 28-day search interval did not differ between conventional and integrated detection trials [20]. If the implementation of integrated trials at additional wind projects bears out the inflation bias of conventional detection trials applied to shorter search intervals [20], then my USA-wide fatality estimates would need to be adjusted down accordingly (however, see my later discussion on potential biases that underestimate USA-wide fatalities). Our understanding of the magnitude of wind turbine collision fatalities hinges on whether future fatality monitoring adopts more rigorous fatality search protocols.

That more rigorous fatality monitoring influences bat fatality estimates was also evident in the number of species represented in fatality estimates. More species of bats were found in monitoring with shorter search intervals (Figure 2, Table 2). Of seven bat species typically weighing <7 g and found as fatalities at wind turbines  $\geq 0.66$  MW, all seven were represented where  $I \leq 7$  days, whereas only two were found where  $I > 7$  days. At one project monitored for three years with seven-day search intervals at half the turbines and 28-day search intervals at the other half, fatalities of four bat species were detected at  $I = 7$ , but fatalities of only two of these bat species were detected at  $I = 28$ , having missed a species that typically weighs 4.3 g and another that weighs 11 g [20]. Conversely, the area needed to be searched per additional bat species increased with longer search intervals, and the rate of this increase in search area was five times greater for small-bodied bat species than for all bat species (Figure 3). Whereas the results of conventional detection trials applied to short search intervals can inflate bat fatality estimates, increasingly, longer search intervals in fatality monitoring under-represents bat species in fatality estimates. My USA-wide fatality estimates were most likely biased against small-bodied bat species, which affected my all bat fatality estimate to an unknown degree.

Shorter search intervals also generated fatality estimates that were composed of fewer bat fatalities unidentified to species. The proportion of estimated mean project-specific fatalities/MW/year that was composed of unidentified bat species was five times higher, when based on search intervals longer than 10 days. Fatality monitoring based on shorter search intervals increases the frequency of finding recently-killed bats, and therefore facilitates species identifications. As more of the bat fatalities are identified to species, the accuracy of the species-specific fatality estimation will increase.

Despite my averaging of project-specific fatality estimates within regions as a first step toward estimating USA-wide fatalities, my national-level estimate could still be biased high or low, depending on the degree to which wind projects that were selected for monitoring and reporting also represented vulnerability of bats to wind turbine collisions across the USA [3,7]. Disproportionate absence of

reporting from regions within the USA, such as from Texas, could have biased my estimates. Any such bias could be lessened by publicly reporting all fatality monitoring efforts. It could also be lessened by designing a sampling program among existing wind projects, regardless of the time since project operations initiated, rather than by performing a year of monitoring each time a new project is constructed and becomes operational.

A potential source of error in my approach was assuming zero values for bat species that were unreported as fatalities at specific wind projects, but for which it remains uncertain whether these species occurred at those projects. Species undetected as fatalities go unreported. I assigned these species zero fatalities if they had been reported as fatalities at other wind projects within the same region. My assumption would have introduced error wherever I added zero values for bats that truly did not occur at those projects. Local species of bat that were not found as fatalities could have been missed by searchers due to insufficient search effort, or they could have been found and unidentified to species, or even misidentified [110]. Future monitoring efforts could be more informative by implementing surveys for live bats, to characterize the suite of bat species using wind projects.

I likely under-estimated bat fatalities due to deficiencies in the maximum search radius among wind projects. I developed an adjustment for this deficiency [3]. However, I have more recently discovered that my adjustment was insufficient, because it changes with increasing maximum search radius [112]. Future fatality monitoring would contribute to more accurate fatality estimation by searching farther from a subset of turbines than is typically practiced.

In 2013, I introduced a more efficient estimator,  $\hat{F} = \frac{F}{D}$ , where  $D$  is the overall detection rate of carcasses integrated into routine fatality monitoring [3]. The advantages of the new estimator include (1) the elimination of biases from previously neglected interaction effects among  $S$  and  $R_C$  and  $d$ , (2) a predictive relationship between body mass and  $D$ , and (3) the opportunity to treat trial carcasses as training data, which are useful for assessing estimation accuracy. However, many of the older fatality monitoring efforts did not perform detection trials suited for estimating  $D$ , so I estimated  $S$ ,  $R_C$ , and  $d$  from those reports that provided suitable data for those adjustment terms, and I applied them to fatality data from all of the reports.

Fatality estimation can also be more accurate by using scent-detection dogs in place of human searchers. Where dogs were used at the same turbines concurrently searched by humans, and monitoring methods were otherwise the same, 71 bat fatalities were found [112], where humans found one [113]. At another project previously monitored for three years by humans, fatality finds using dogs resulted in a bat fatality estimate that was 11 times higher than the estimate based on human searchers, despite the search interval and maximum search radius being equal [114]. Dogs can find trace evidence of bats that human searchers would unlikely find, and likewise they can find bats hidden in tall vegetation. The recent use of scent-detection dogs suggests that searcher detection rates likely biased fatality estimates to be low through 2014.

Whereas fatality estimators are often compared for their accuracy [111,115,116], accuracy in fatality estimation is most substantially affected by the field methods used to inform the terms of the estimators. Accuracy in fatality estimation depends on detecting as many of the fatalities as possible and accurately adjusting the fatality count for the proportion undetected. Finding more of the fatalities diminishes the necessary adjustments along with the adjustments' error and biases. Accuracy in 'all bat' fatality estimation depends on detecting all of the species represented by fatalities. Unless the monitor is aware of which species could have been found but were not found, there is no suitable adjustment for increasing the accuracy of negative findings of a species. At a wind project where fatality searches overlapped the same wind turbines, with one team of human searchers averaging 39 days per search and the other team averaging five days, the searchers averaging 39 days found only 10% of the bats and small birds in the 10–40 g size range that were found by the other team, and they found fatalities representing only 37.5% of all of the bird and bat species that the searchers averaging five days detected [117]. No adjustments for carcass persistence can alone remove such large effects of search interval.

Finding more of the available carcasses and representing more of the species truly affected is most facilitated by using scent-detection dogs instead of human searchers [112,118–122], shorter search intervals [110,117,123], and appropriate search areas [3,110,124]. More accurately adjusting for the proportion of undetected fatalities is most facilitated by integrating detection trial carcasses of appropriate species, carcass condition, and range of body masses into routine fatality monitoring to obtain a single adjustment factor instead of several factors, and a training data set against which fatality counts can be compared [3,110,117,125]. The integrated approach further avoids the biases of carcass persistence rates caused by scavenger swamping in windfall trial carcass placements [125], persistence trial duration [110], and unrealistic application of trial carcass size classes to fatalities that vary continuously in body size [110] and single-search searcher detection rates from trial carcasses placed just prior to the search [20].

In summary, I estimated 2.22 million bat fatalities across the USA in 2014, but with a 95% CI of 1.77 million to 2.72 million bat fatalities. My estimate was made in the face of very substantial biases, potentially shifting the mean lower by a factor of three and higher by up to a factor of 11. The proportion of mortally injured bats leaving the search areas under their own volition, otherwise known as crippling bias [109], could also shift my USA-wide estimate higher [114]. Furthermore, since 2014, the installed capacity of wind energy has increased 52% to 100,025 MW, and bat fatalities likely increased proportionally with this increase in capacity, so long as the pool of vulnerable bats has not diminished. The decline of hoary bats in the Pacific Northwest [126] suggests that the pool of vulnerable bats might be diminishing. It is imperative, therefore, that methods of fatality monitoring improve to more accurately estimate bat fatalities. Future fatality monitoring could vastly improve the accuracy of fatality estimation, by replacing human searchers with scent-detection dogs. It is also imperative that the benefits of wind energy be weighed against the ecological costs [127,128]. Improved methods are also imperative for measuring the efficacy of mitigation measures [129], such as operational curtailment strategies [130–133] and deterrents [134].

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