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Wind Energy and Wildlife Conservation

Comparing Bird and Bat Fatality-Rate Estimates Among North American Wind-Energy Projects

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ABSTRACT Estimates of bird and bat fatalities are often made at wind-energy projects to assess impacts by comparing them with other fatality estimates. Many fatality estimates have been made across North America, but they have varied greatly in field and analytical methods, monitoring duration, and in the size and height of the wind turbines monitored for fatalities, and few benefited from scientific peer review. To improve comparability among estimates, I reviewed available reports of fatality monitoring at wind-energy projects throughout North America, and I applied a common estimator and 3 adjustment factors to data collected from these reports. To adjust fatality estimates for proportions of carcasses not found during routine monitoring, I used national averages from hundreds of carcass placement trials intended to characterize scavenger removal and searcher detection rates, and I relied on patterns of carcass distance from wind turbines to develop an adjustment for variation in maximum search radius around wind turbines mounted on various tower heights. Adjusted fatality rates correlated inversely with wind-turbine size for all raptors as a group across the United States, and for all birds as a group within the Altamont Pass Wind Resource Area, California. I estimated 888,000 bat and 573,000 bird fatalities/year (including 83,000 raptor fatalities) at 51,630 megawatt (MW) of installed wind-energy capacity in the United States in 2012. As wind energy continues to expand, there is urgent need to improve fatality monitoring methods, especially in the implementation of detection trials, which should be more realistically incorporated into routine monitoring.

KEY WORDS fatality monitoring, fatality rate estimates, scavenger removal, search radius, searcher detection, wind energy, wind turbines.

Estimates of bird and bat fatality rates are often made at wind-energy projects. Fatality rate estimates are made to assess project impacts, and a principal means of assessing impacts is to compare new estimates with those made at other places or times. In most reports of fatality rate estimates, the reported estimates were compared with estimates made elsewhere, including most reports listed in Appendix 1, online (e.g., Smallwood and Thelander 2005). Fatality rates have also been compared in published papers (Barclay et al. 2007, Ferrer et al. 2012), industry reports (Erickson et al. 2001), and in government reports (Erickson et al. 2005, GAO 2005). These comparisons, however, were of fatality rates made from various mathematical estimators and associated assumptions, from highly variable methodology in carcass removal and searcher detection trials used to adjust fatality rates for undetected fatalities (Smallwood 2007), and from fatality searches that varied widely in search interval and maximum search radii around wind turbines mounted on various tower heights. Because wind energy is rapidly expanding worldwide, the comparability of fatality rate estimates needs to be evaluated, and changes made, if needed.

My goal was to compare fatality rates from available reports of post-construction fatality monitoring of birds and bats throughout North America. Comparable fatality rates could then be used to test whether the trend toward installing larger wind turbines might reduce fatality rates, or whether variation in fatality rates could be explained by other methodological, environmental, or turbine design factors. Comparable rates could also be averaged and projected to the installed capacity of wind energy to crudely estimate fatality rates of all bats, all raptors, and all birds across the United States. To improve comparability, I estimated fatality rates from the reported data, using the most uniform set of assumptions and the most consistent methods possible. I also introduced a new fatality-rate adjustment factor to account for variations in maximum search radius and wind-turbine tower height.

Fatality monitors at wind projects have had to decide on the maximum search radius around wind turbines selected for monitoring. Occasionally, the maximum search radius has been dictated by dense vegetation cover, water bodies, or property boundaries. Hull and Muir (2010) developed a

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Additional supporting information may be found in the online version of this article.

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method for deciding on maximum search radii by predicting carcass distances from turbines based on tower height, blade length, and ballistics. Hull and Muir's method could serve as a basis for deciding on the maximum search radius, but I have yet to see evidence that their method has been used in North America. Of the fatality reports I reviewed, 62% provided no explanation for the maximum search radius chosen, one cited a wind company protocol, and 33% cited other fatality monitoring reports as empirical support for a claim that nearly all carcasses can be found within a distance equal to the wind-turbine tower height. One of these cited reports was Johnson et al. (2002), who used a maximum search radius of 63 m, but found all bird carcasses within 33 m of the turbines. I have yet to see this pattern of fatality distribution repeated. In other cases, it should be expected that nearly all fatalities found would have been found within the maximum search radius, because the searchers were not searching beyond the maximum search radius. Given such weak empirical support for the conclusion that the maximum search radius should equal tower height, I decided to use carcass distributions around wind turbines to develop an adjustment factor for search radius bias.

METHODS

I collected and reviewed all available reports that I could find of bird and bat fatality monitoring at North American wind-energy projects, and I recorded attributes of each study needed for estimating comparable fatality rates. For example, expanding upon the review of Smallwood (2007) I synthesized estimates of scavenger removal and searcher detection rates, which were derived from volitionally placed birds and bats in separate trials performed parallel to the routine fatality monitoring. I recorded wind-turbine tower heights and maximum search radius, from which I developed an adjustment to account for what I termed 'search radius bias' in fatality rate estimates. I recorded the size of each project, including the number and rated capacities of wind turbines, and I recorded the sample size of wind turbines monitored for post-construction impacts. Additionally, I recorded start and end dates of fatality searches, average search interval, inter-transect separation distance, type of search plot (circular, square, rectangular), whether clearing searches were used, whether incidentally found fatalities were included, and wind-turbine model, along with the turbine's cut-in and cut-out speeds, revolutions per minute, and blade length.

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 formula derived from Horvitz and Thompson (1952) and expanded upon by Smallwood (2007) and in this study:

$$F_A = \frac{F_U}{S \times R_C \times d}$$

where F_A and F_U were adjusted and unadjusted fatality-rate estimates, respectively, S (p in many reports) was the search detection rate expressed as the average proportion of available carcasses that were actually found among all searches within the time span defining the rate, R_C was the scavenger removal rate expressed as the average proportion of carcasses remaining at the time of the next periodic search, and d was the average proportion of carcasses not found due to an insufficient maximum search distance from the turbines (each of these adjustment terms are described further below). I used averages to represent S, R_C, and d to lessen the chance of deriving anomalous adjustment values from one study.

After an earlier review of searcher detection and scavenger removal trials, I concluded that many of the trials yielded biased results for various reasons (Smallwood 2007). Some search detection trials utilized house mice (*Mus musculus*), rubber toys for bats, or paper machete models for birds; and some used conspicuous birds to represent the more cryptically colored birds typically killed by wind turbines. Some removal trials utilized birds that had been dead for unknown lengths of time, or used species known to be removed quickly (e.g., gallinaceous birds and chicks) or more slowly for the body size (e.g., rock pigeons [*Columba livia*]). Removal trials varied in duration, which can affect mean days to removal used in other estimators (Smallwood 2007), and they varied in numbers of carcasses placed and frequency of status checks. The magnitude of adjustments to fatality rate estimates could be caused more by variation in methodology than in local environmental conditions. To minimize the effects of the various biases due to variation in methodology, I used the methods in Smallwood (2007) to integrate the results of searcher detection and scavenger removal trials across North America and to arrive at means and standard errors for groups of species defined by body size (small <32 cm body length, medium = 32–45 cm, large >45 cm, with exceptions around boundaries for body mass) and whether species were raptors, nonraptor birds, or bats.

Search Detection Adjustment

A searcher detection rate is estimated in field trials. Bird or bat carcasses are placed prior to a search, and the proportion of available carcasses found is used as the estimate of searcher detection rate. However, fatality searches in monitoring usually occur at bimonthly or monthly intervals, so carcasses available to be found vary in time on the ground. Carcasses available to be found can consist of the evidence remaining after a scavenger removed the rest of the carcass, and carcasses can vary in visibility due to vegetation growth, exposure to the sun, and the transect walked by searchers. Furthermore, the search interval can affect searcher detection rates, because carcasses missed after the first search can be found in subsequent searches and the probability of being found probably increases with shorter search intervals.

Howe and Atwater (1999) tested searchers on carcasses left in the field across multiple searches (Fig. 1), but did not estimate an average detection rate of accumulated carcasses, S_c. Ideally, the average proportion of available carcasses

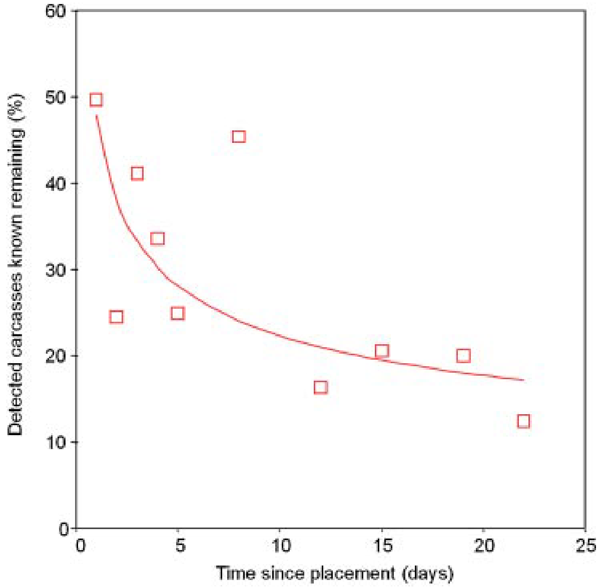

Figure 1. Searcher detection rates calculated from repeat visits to ovenbird (*Seiurus aurocapilla*) carcasses yet to be removed by scavengers declined as an inverse power function of days since placement at a wind project in Wisconsin, USA: $S = 47.959\ (\text{days})^{-0.332}$ ($r^2 = 0.55$, RMSE $= 0.33$, $P < 0.05$), where S was searcher detection rate, "days" were days into trial, RMSE was root mean square error, and data were from Howe and Atwater (1999).

detected in trials would be calculated as

$$S_c = \frac{\sum_{i=1}^{I} S_i}{I}$$

where S_i is the predicted proportion of carcasses detected each day into a long-term trial after fitting a model to the original data to smooth the curve, and I is average search interval. Lacking estimates of S_c, I was left with using reported values of S_1—the typical trial result of testing searchers on carcasses placed just before the first and only search. Using values of S_1 precludes adjusting fatality rates for declines in searcher detection rates as the carcasses age. This bias will lead to under-estimates of fatality rates, more so for searches over longer intervals. Using values of S_1 also precludes adjusting fatality rates for repeat opportunities to find carcasses that persist across multiple searches (Korner-Nievergelt et al. 2011). These 2 biases likely cancel each other out to some degree yet to be measured, but for now I can rely only on S_1.

I also tested whether searcher detection rates were related to an index of ground visibility, season and year of trial, sample size of placed carcasses, number of carcasses placed per MW of rated capacity subject to fatality searches, and whether searchers were aware of the trial. Each test was performed on small birds, medium birds, large birds, and bats, and where ground visibility was low, medium, high, and very high. Relying on imagery of each site and on reported site descriptions, I classified carcass search 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; "high" on areas covered by annual grassland, short-grass prairie, or sage brush; and, "very high" on areas covered by short annual grasslands, reclaimed land, snow, or barren areas.

Scavenger Removal Adjustment

I calculated the average proportion of carcasses remaining in scavenger removal trials as

$$R_C = \frac{\sum_{i=1}^{I} R_i}{I}$$

where R_i was the predicted proportion of carcasses remaining each day into a trial after fitting a nonlinear regression model to the original data to smooth the curve, and I was average search interval (Smallwood 2007). Using data in available reports, I estimated R_C values for bats, small birds, large birds, and rock pigeons.

Some removal trials utilized carcasses that had aged since death, usually consisting of birds or bats found along roadways or during fatality monitoring at the particular wind-energy project or from another wind project site. These found carcasses were described as "fresh," but carcasses appearing to be fresh could easily have been dead 1–4 days or longer, depending on environmental conditions and investigator experience with dead birds and bats. Therefore, I considered carcasses obtained from fatality monitoring programs with 15–30-day search intervals to have been 3 days since death, carcasses from weekly searches to have been 2 days since death, and carcasses from daily searches to have been 1 day since death by the time the carcasses were deployed in field trials. Because these carcasses had already begun decomposing, and thus growing less attractive to multiple species of terrestrial scavengers, I adjusted the removal curves from these trials by adding back into the sample the proportion of carcasses that would have been removed by 1, 2, or 3 days had all the carcasses been fresh.

I selected trials based on carcasses of known origins and known to have died within a day of freezing (or deployment). I fit inverse power functions to the persistence rates of these carcasses, and I predicted the proportions of carcasses remaining after 1, 2, and 3 days, represented as R_1, R_2, and R_3, respectively. I then divided the number of placed older carcasses by $1 - R_i$ to account for the proportion of carcasses that likely would have been removed by scavengers in the ith day since death. These likely removed carcasses were added back into the sample, and day 0 of the trial was adjusted accordingly, to adjust persistence rates for the use of older carcasses (Fig. 2).

Search Radius Adjustment

To obtain d in Equation (1), I reviewed tables and appendices in available reports to obtain distances of fatalities from wind turbines. In a few cases, I used a ruler to measure distances from turbines in maps of fatalities around monitored wind turbines. I rounded all distances to the nearest meter. I omitted wounded animals that remained mobile when discovered. I recorded the species of each fatality, and later

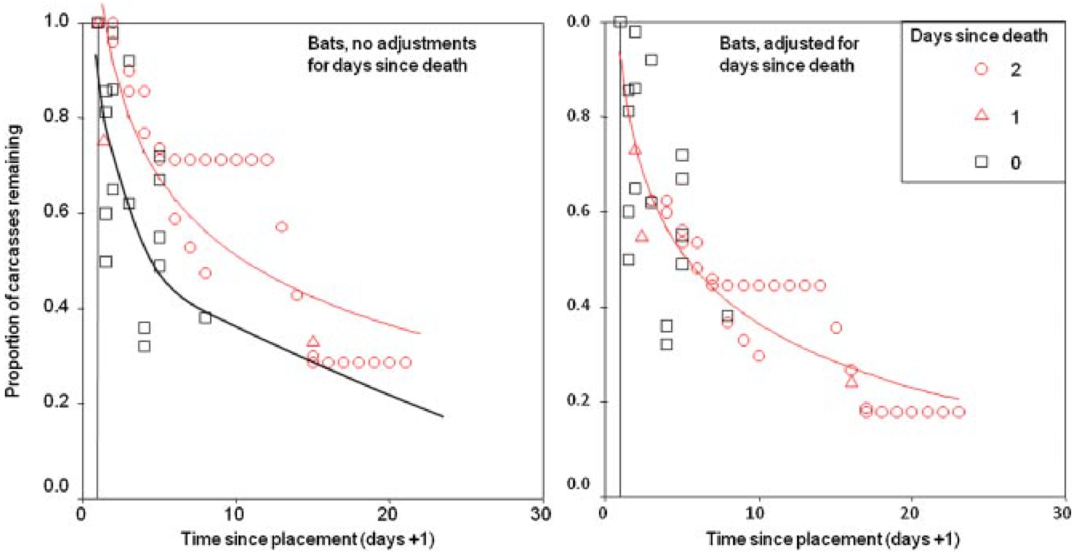

Figure 2. Example adjustment for use of found bat carcasses in removal trials performed in wind projects across North America, where the originally reported removal rates (left graph) were adjusted for the proportions of carcasses likely to have been removed by scavengers 0, 1, and 2 days following death (right graph). Carcasses differing in time since death appeared to express different removal rates (left), but after adjustment they appeared to exhibit the same removal rate (right).

I separated analyses by taxonomic groups and body size class. Finally, I recorded wind-turbine tower height and maximum search radius, though for analyses I lumped tower heights and maximum search radii into groups based on breaks in the distributions.

I summed fatalities at 1-m intervals for each group of tower heights and each group of maximum search radii, and I used least-squares regression analysis to fit curves to the relationships between cumulative sum fatalities and distance from the turbine. The regressions were restricted to the distance of the maximum search radius plus 5 m to account for the area likely searched as the searcher reached the search boundary. In all cases, I used a logistic function to fit the data, iteratively changing the upper bound value of the dependent variable in the model until the minimum root mean square error (RMSE) was obtained:

$$Y = \frac{1}{\left(\frac{1}{u} + a \times b^{X}\right)}$$

where *u* was the upper bound value of the dependent variable, *Y*, *X* was meters from wind turbine where nearest fatality remains were located, and *a* and *b* were fitted coefficients.

I used the regression models to predict cumulative sum fatalities as functions of distance from the turbine, and I extended the predictions to distances beyond the maximum search radii that were reported at wind-energy projects. I extended predictions to greater distances to identify asymptotic values, which I then divided into predicted values at each 1-m interval to represent the predicted value as a proportion of the asymptotic value. The result was a predicted cumulative proportion of fatalities relative to the predicted maximum (1.0) that would have been found had the searches extended well beyond the search boundary. For each tower height class of 50 m, 60 m, 67.5 m, and 80 m, I averaged predicted cumulative proportions of fatalities at each 1-m interval across the 2–3 largest maximum search radii. In other words, for towers of about 80-m height, I averaged the proportions of fatalities at each meter that were predicted by logistic functions applied to fatalities found when the maximum search radii were 90 m, 105 m, and 120 m.

I arranged the predicted cumulative proportions of fatalities under combinations of tower height class and maximum search radius (or means of 2–3 max. search radii, when possible), and by meter from the turbine. This arrangement served as a look-up table to identify the proportion of carcasses predicted to have been found among monitoring studies, based on reported tower heights and maximum search radii. When reported tower heights did not match the tower heights in the look-up table, I used the nearest tower height class in the table. I used the RMSE of each regression model to carry the error through the calculations leading to fatality rate estimates. Thus, RMSE served as a factor in deciding which of multiple candidate regression models to use, because smaller RMSE values indicated better model fits.

Carrying the Error Terms

I calculated the standard error of the adjusted fatality rate, SE[F_A], using the Delta Method (Goodman 1960):

$$\mathrm{SE}[F_A] = \sqrt{\left(\frac{1}{p \times R_C \times d} \times \mathrm{SE}[F_U]\right)^2 \times \left(\frac{F_U}{p \times d} \times \frac{-1}{{R_C}^2} \times \mathrm{SE}[R_C]\right)^2 \times \left(\frac{F_U}{R_C \times d} \times \frac{-1}{p^2} \times \mathrm{SE}[p]\right)^2 \times \left(\frac{F_U}{R_C \times p} \times \frac{-1}{d^2} \times \mathrm{SE}[d]\right)^2}$$

Fatality Estimates

I expanded my estimates of mean annual fatality rates of all raptors, all birds, and all bats to the 51,630 MW of wind-energy capacity that was installed across the United States by September 2012, according to the American Wind Energy Association (http://www.awea.org/learnabout/industry stats/index.cfm, accessed 4 December 2012).

RESULTS

Through 2010, I found reports of fatality rate estimates for 71 wind-energy projects in North America, including 19 in the Altamont Pass Wind Resource Area (Appendices 1 and 2, online). These estimates were made at wind turbines of 27 rated capacities, ranging from 0.04 MW to 3.0 MW each, and on 28 tower heights, ranging from 18.5 m to 90 m at the rotor hub. They were based on 40 average fatality search intervals, ranging from daily to 90 days, and 20 maximum search radii from turbines, ranging 30–126 m. They were also based on 425 search detection trials, which varied in species used, number of carcasses placed, season, ground cover conditions, and whether personnel knew they were being tested. They were based on 413 scavenger removal trials spanning 21 years, which varied in species used, time since death, carcass origin, whether carcasses were stored in freezers, carcass placement relative to turbines, ground cover conditions, and season.

Search Detection Trials

Searcher detection rates in the low-visibility cover class averaged 80% lower than in high-visibility cover for bats, 30% lower for small birds, and 67% lower for medium-sized birds, but only 13% lower for large birds (Table 1; Fig. 3). For small and medium-sized birds in high and very high visibility classes, searcher detection rates did not vary seasonally (ANOVA $F = 0.20$, df $= 3.54$, $P > 0.10$). No other groups of birds or bats showed any seasonal trend in searcher detection rates, possibly because sample sizes were often small. Searcher detection rates showed no inter-annual trends for birds or bats. They did not relate to sample size of placed bird and bat carcasses, nor to the number of placed carcasses per MW of the wind turbines included in fatality searches. Searcher detection rates did not differ based on searcher awareness of the trial.

Scavenger Removal Trials

Compared with Smallwood (2007), the additional removal trials included in this study reduced the mean accumulated carcass persistence rate at 30 days into the trial from 82% to 62% for rock pigeons, from 35% to 30% for small birds, from 56% to 51% for medium and large birds, and there was no change for game hens and chicks at 10% (Table 2; Fig. 4). Smallwood (2007) had included a carcass persistence curve representing large raptors placed in a single trial in 1989; whereas, this time I averaged the persistence rates from the 1989 trial with those of a trial in 2007 (Smallwood et al.

Table 1. Mean and standard error searcher detection rates of carcasses (proportion found) among trials performed at wind-energy projects throughout North American through the year 2010 (from data in references in Appendix 1 [online]: 1–11, 13, 14, 16.1, 17, 20, 23–34, 36–41, 43–45, 47, 48, 52, 53).

Species group	Visibility	No. trials	No. placed	$\bar{x}$	SE
Bats	Low	2	271	0.113	0.013
Bats	Moderate	4	346	0.449	0.104
Bats	High	9	552	0.595	0.057
Bats	Total	15	1,169	0.492	0.060
Small birds	Low	7	401	0.491	0.088
Small birds	Moderate	24	1,407	0.458	0.034
Small birds	Low and moderate	31	1,808	0.466	0.032
Small birds	High	26	850	0.569	0.039
Small birds and raptors	High	32	892	0.603	0.037
Small birds	Very high	6	72	0.661	0.054
Small birds	Total	63	2,830	0.527	0.024
Medium birds	Low	2	257	0.282	0.092
Medium birds	Moderate	7	446	0.675	0.080
Medium birds	High and very high	17	364	0.868	0.039
Medium birds and raptors	High and very high	23	406	0.848	0.031
Medium birds	Total	26	1,067	0.771	0.046
Large birds	Low and Moderate	29	1,650	0.711	0.038
Large birds	High and very high	14	517	0.837	0.036
Large birds and raptors	High and very high	20	559	0.886	0.030
Large birds	Total	43	2,167	0.752	0.029
Small raptors	High	6	42	0.750	0.091
Medium raptors	High	6	42	0.788	0.045
Large raptors	High	6	42	1.000	0.000
"Birds"[a]	Low	11	690	0.390	0.074
"Birds"[a]	Moderate	38	2,796	0.509	0.031
"Birds"[a]	High and very high	56	2,805	0.676	0.029
"Birds"[a]	Total	105	6,291	0.585	0.023

[a] Some trials used "birds," without specifying which species were used. I assumed these were all small and medium-sized birds, so I lumped these trials with those involving small and medium birds. This category would be useful when fatality reports do not specify species of birds comprising the fatality rate estimate.

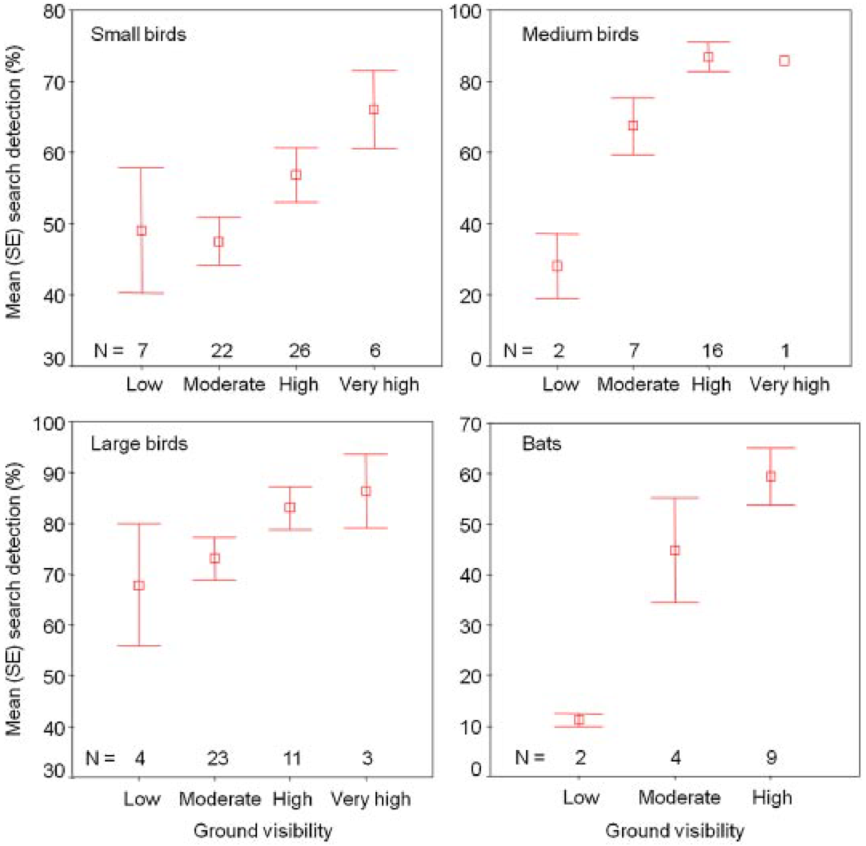

Figure 3. Mean searcher detection rates from trials at wind farms across North America increased with an index of ground visibility for carcasses of small birds (top left graph: ANOVA $F = 5.21$, df $= 2, 68$, $P < 0.01$, low and moderate visibility classes combined), medium-sized birds (top right: ANOVA $F = 12.51$, df $= 2, 31$, $P < 0.001$), large birds (bottom left: ANOVA $F = 11.28$, df $= 1, 48$, $P < 0.005$, low and moderate visibility classes combined and high and very high visibility classes combined), and bats (bottom right: ANOVA $F = 6.46$, df $= 2, 14$, $P < 0.05$).

Table 2. Average accumulated proportion of carcasses remaining each day into a removal trial and corresponding with the number of days in an average fatality search interval, where the averages were derived from removal trials reported throughout North American wind projects (from data in references in Appendix 1 [online]: 1, 3–11, 13, 14, 16, 16.1, 17, 20, 23–29, 31–34, 36–38, 40–44, 47–53).

Interval (days)	Proportion remaining				
	Bats	Birds	Large birds	Rock pigeons	Small birds
1	0.78	0.76	0.85	0.89	0.78
2	0.72	0.70	0.81	0.86	0.72
3	0.68	0.65	0.78	0.84	0.68
4	0.64	0.61	0.75	0.82	0.64
5	0.61	0.58	0.73	0.80	0.61
6	0.58	0.55	0.71	0.78	0.58
7	0.56	0.52	0.69	0.77	0.55
8	0.54	0.50	0.68	0.76	0.53
9	0.52	0.48	0.66	0.75	0.51
10	0.50	0.46	0.65	0.74	0.50
11	0.48	0.44	0.64	0.73	0.48
12	0.47	0.43	0.63	0.72	0.46
13	0.45	0.41	0.62	0.71	0.45
14	0.44	0.40	0.61	0.70	0.44
15	0.43	0.39	0.60	0.70	0.43
28	0.32	0.27	0.51	0.63	0.31
30	0.30	0.26	0.51	0.62	0.30
90	0.12	0.09	0.35	0.50	0.12

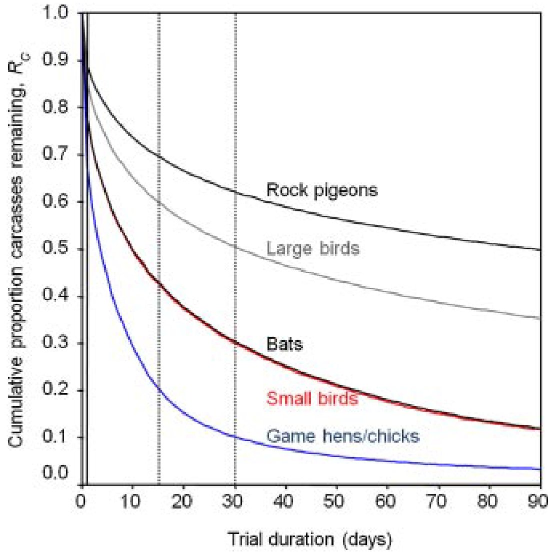

Figure 4. Based on trials performed at wind farms across North America, mean carcass persistence rates, R_C, declined most quickly for game hens and chicks, next most quickly for small birds and bats, and slowest for rock pigeons. Vertical dashed lines depict search intervals of 15 and 30 days, which were commonly used in fatality monitoring.

2010) and with trials of other large birds. Persistence rates at 30 days averaged 46% lower for large raptors and other large birds combined (Fig. 4) than they did for large raptors in Smallwood (2007). The mean accumulated carcass persistence rate of bats was 30% at 30 days into the trial, equaling the persistence rate of small birds (Fig. 4).

Maximum Search Radii

I collected 9,174 distances from turbines of bird and bat carcasses reported from fatality monitoring at wind-energy projects across North America. Distances from wind turbines did not vary by size class of birds, so I pooled all size classes. Logistic functions fit to cumulative sum fatalities of birds and bats indicated that the maximum search radius used in fatality monitoring was usually short of the distance at which the logistic functions predicted an asymptote in the cumulative number of fatalities that could have been found (Tables 3 and 4; Figs. 5 and 6). Best-fit logistic functions predicted that searches extending to the maximum search radius found, on average, 88% (range = 72–94%) of birds and 99% (range = 96–100%) of bats available to be found within the distance asymptote.

Gaps between the maximum search radii and the predicted distance asymptotes lessened with increasing tower height for birds, but there was no trend for bats (Fig. 7). For birds, the predicted distance asymptotes increased with both tower height and maximum search radius, but more of its variation was explained by maximum search radius

Table 3. Cumulative sum bird fatalities (derived from removal trials reported throughout North American wind projects; Appendix 1, online) regressed on distance from wind turbines, where r^2 was coefficient of determination, RMSE was root mean square error, *u* was upper bound of the logistic function used to fit the data, and *a* and *b* were fitted coefficients. Distance to asymptote was where the proportion of carcasses with increasing distance from the turbine reached 1.0.

Tower ht (*m*)	Max. search radius (*m*)	r^2	RMSE	*u*	*a*	*B*	Distance (*m*) to asymptote	Proportion of predicted fatalities found in max. search radius
19.0	38	0.99	0.125	73	0.088	0.912	78	0.84
19.0	50	0.98	0.186	2,345	0.002	0.921	86	0.91
21.3	50	0.97	0.326	337	0.021	0.911	78	0.94
24.0	38	0.96	0.273	36	0.446	0.907	83	0.72
24.0	50	0.94	0.421	1,639	0.007	0.907	80	0.92
26.4	50	0.95	0.341	686	0.016	0.911	82	0.91
30.5	50	0.96	0.317	93	0.116	0.907	79	0.93
40.0	50	0.97	0.305	53	0.472	0.889	73	0.93
40.0	63	0.97	0.305	84	0.410	0.912	96	0.91
50.0	50	0.95	0.337	22	0.907	0.844	49	
50.0	63	0.96	0.348	261	0.068	0.920	99	0.91
50.0	75	0.95	0.329	101	0.314	0.938	137	0.79
50.0	90	0.98	0.214	35	1.589	0.944	149	0.76
60.0	75	0.98	0.250	231	0.083	0.932	117	0.91
60.0	90	0.97	0.230	35	0.489	0.940	131	0.94
67.5	90	0.92	0.440	39	0.295	0.947	136	0.92
67.5	110	0.97	0.296	99	0.252	0.950	150	0.92
80.0	90	0.97	0.309	205	0.120	0.943	139	0.89
80.0	105	0.97	0.226	408	0.079	0.956	156	0.78
80.0	120	0.97	0.288	83	0.260	0.957	155	0.90

Table 4. Cumulative sum bat fatalities (derived from removal trials reported throughout North American wind projects; Appendix 1, online) regressed on distance from wind turbines, where r^2 was coefficient of determination, RMSE was root mean square error, *u* was upper bound of the logistic function used to fit the data, and *a* and *b* were fitted coefficients. Distance to asymptote was where the proportion of carcasses with increasing distance from the turbine reached 1.0.

Tower ht (*m*)	Max. search radius (*m*)	r^2	RMSE	*u*	*a*	*B*	Distance (*m*) to asymptote	Proportion of predicted fatalities found in max. search radius
40	63	0.93	0.553	86	0.211	0.895	74	0.98
50	30	0.99	0.246	152	0.071	0.796	34	0.99
50	50	0.97	0.359	45	0.474	0.759	31	1.00
50	60	0.97	0.256	13	1.401	0.858	54	1.00
50	63	0.88	0.841	294	0.027	0.867	52	1.00
50	90	0.97	0.266	23	1.202	0.930	118	0.96
60	75	0.97	0.325	126	0.143	0.913	91	0.98
60	90	0.82	0.717	28	0.346	0.925	98	0.99
67.5	50	0.93	0.534	71	0.173	0.876	59	0.98
67.5	60	0.95	0.447	64	0.178	0.884	63	0.99
67.5	90	0.91	0.492	20	0.594	0.909	82	1.00
67.5	110	0.98	0.213	33	0.370	0.911	84	1.00
80	60	0.99	0.215	181	0.096	0.868	58	1.00
80	90	0.96	0.369	109	0.167	0.923	103	0.99
80	105	0.98	0.229	97	0.398	0.931	126	0.98
80	120	0.92	0.434	35	0.234	0.936	112	1.00

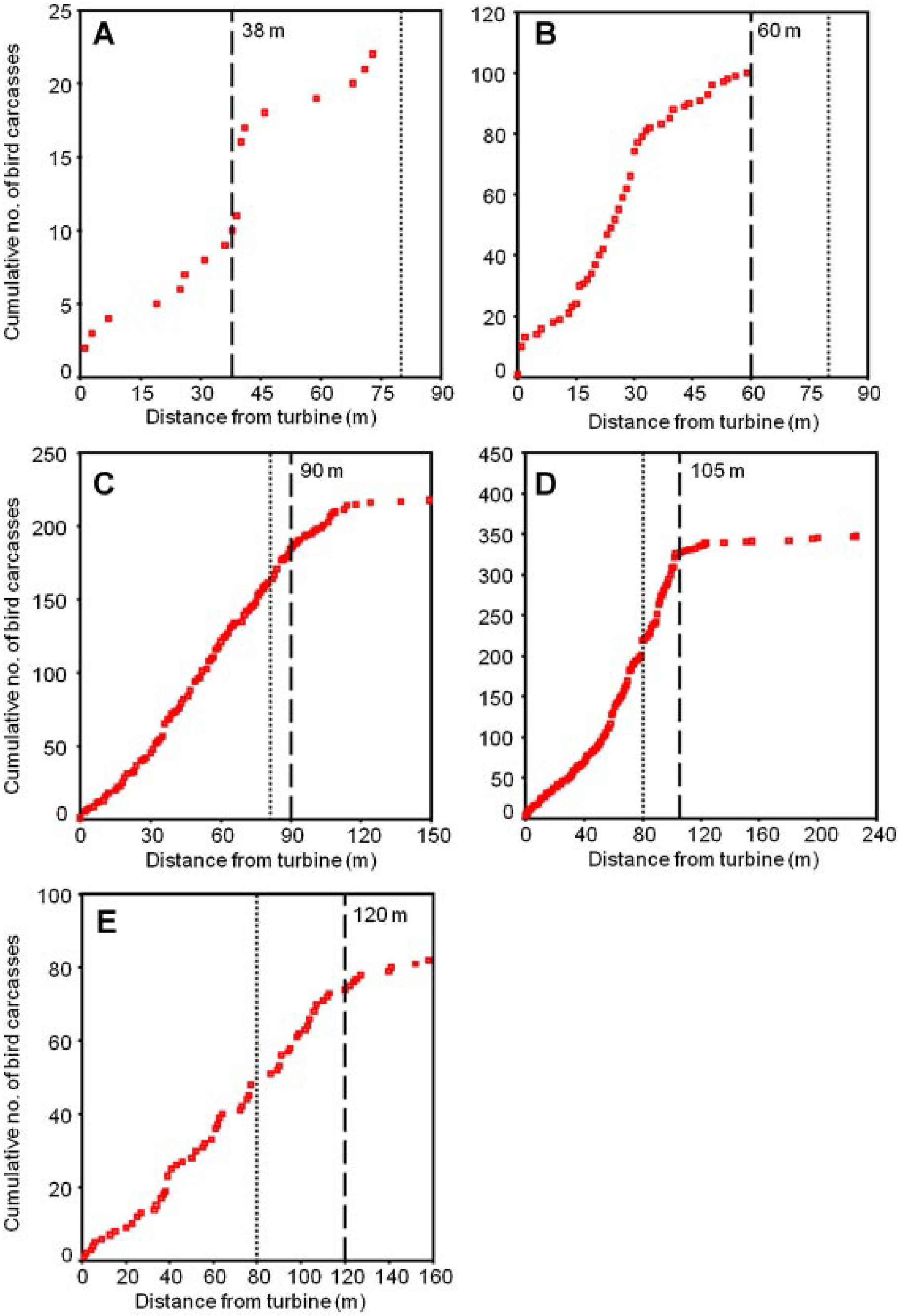

Figure 5. Examples of cumulative bird carcasses increasing at 1-m increments from wind turbines on 80-m towers (dotted line) and with maximum search radii (dashed lines) of 38 m (A), 60 m (B), 90 m (C), 105 m (D), and 120 m (E). The study with a 60-m search radius did not report found carcasses beyond the radius. Data were from wind projects across North America.

(Fig. 8). For bats, the predicted distance asymptotes increased with maximum search radius, but not with tower height (Fig. 8).

Fatality Rate Estimates

Projecting estimates of mean and SE fatalities/MW/year in Appendix 2 (online) to the estimated installed capacity of wind energy in the United States in 2012, I estimated annual fatalities of about 651,000–888,000 bats (with and without the 19 wind projects in the Altamont Pass Wind Resource Area, respectively), nearly 83,000 raptors, and about 573,000 birds of all types (Table 5). Including fatality rate estimates from the Altamont Pass Wind Resource Area lowered the 2012 fatality projection across the United States by 27% for bats and increased it by 78% for raptors.

Red-tailed hawk (*Buteo jamaicensis*) and all raptor fatality rates correlated inversely with increasing wind-turbine size (Figs. 9A,B), but bat fatality rates did not correlate with turbine size. Avian fatality rates in the Altamont Pass Wind Resource Area strongly influenced the relationship, and were the only fatality rates to correlate with wind-turbine size when all birds were included (Fig. 9C).

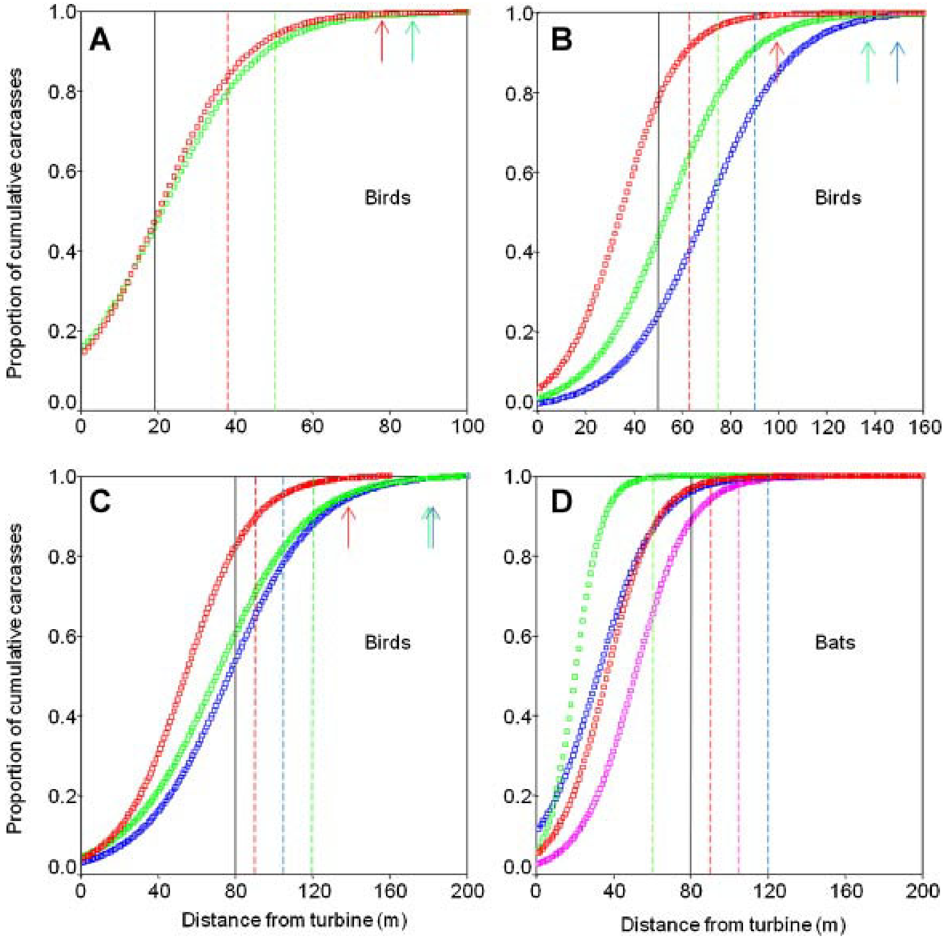

Figure 6. Examples of logistic functions fit to data that were normalized to asymptotes equal to 1.0 at tower heights (solid vertical lines) of 18.5 m (A), 50 m (B), and 80 m for bird carcasses (C) and bat carcasses (D). Color-coded to correspond with the cumulative carcasses detected at each radius, dashed vertical lines identify maximum search radii and arrows point out to asymptotes of each corresponding logistic function. Data were from wind projects across North America.

Where monitoring was performed long enough to notice, raptor fatality rates exhibited high inter-annual variation (Fig. 10). Relying on a single year of monitoring in the Altamont Pass Wind Resource Area, for example, could yield fatality-rate point estimates that vary 9-fold for golden eagle (*Aquila chrysaetos*) when ignoring the 1999 estimate (when no golden eagle fatalities were found), 4-fold for red-tailed hawk, 5.5-fold for American kestrel (*Falco sparverius*), and >8-fold for burrowing owl (*Athene cunicularia*).

Bat fatality rates correlated inversely with search interval (Fig. 11), even though the bat fatality rates had been adjusted for variation in search interval in the carcass removal adjustment. Fatality rates of none of the bird species or bird groups correlated with search interval.

DISCUSSION

Erickson et al. (2001) estimated annual deaths of 33,000 (range = 10,000–40,000) birds, including 488 raptors, in 2001. Erickson et al. (2005) estimated annual deaths of 20,000–37,000 birds, including 933 raptors, at the 6,374 MW of capacity that had been installed in the United States by the end of 2003. After taking measures to estimate comparable fatality rates among wind-energy projects, I estimated 888,000 bat and 573,000 bird fatalities/year, including 83,000 raptor fatalities, at 51,630 MW of installed wind-energy capacity in the United States. My fatality rate estimate was 20× greater than Erickson et al.'s estimate for all birds and 89× greater for raptors, even though the installed capacity of wind energy increased only 8.1-fold from 2003 to 2012. My increased estimates were likely due to improved estimation methods and many more wind-energy projects having been monitored and found to cause higher fatality rates than averaged by Erickson et al. (2001, 2005).

Thousands of additional MW of capacity were planned or under construction in 2012, meaning that the annual toll on birds and bats will increase. However, the expected increase of raptor fatalities could be offset by reductions of raptor fatalities as older wind projects are repowered to new, larger wind turbines, especially if the opportunity is taken to carefully site the new wind turbines (Smallwood and Karas 2009, Smallwood et al. 2009). Further reductions in fatality rates could be gained by adopting a new wind-turbine model that causes fewer fatalities.

My estimates of fatality rates across the United States were likely biased by the availability of fatality reports. Many reports of fatalities have been kept confidential, including

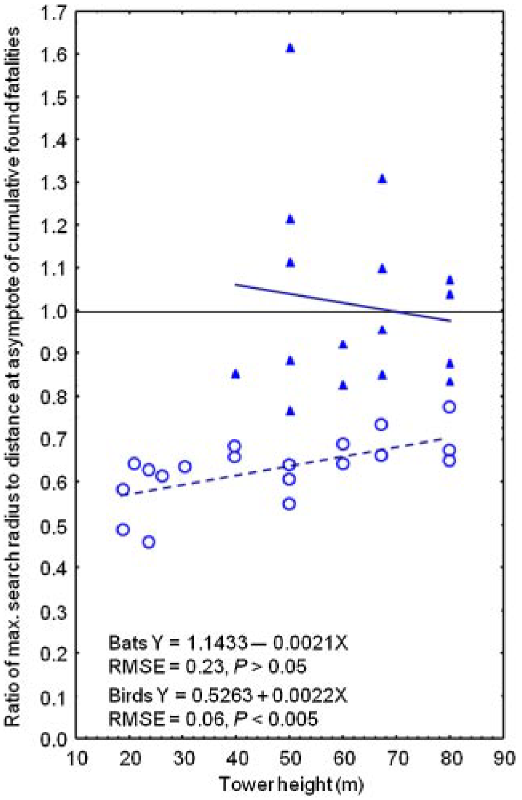

Figure 7. The search radius bias has decreased for bird carcasses with increasing tower height, because the corresponding maximum search radii have increased with tower height more substantially than have the model-fit distance asymptotes at which no more carcasses were found. No trend in search radius bias was evident for bats. Data were from wind projects across North America, model fits were logistic functions fit to cumulative carcasses detected at 1-m distance increments from the turbine, and RMSE was root mean square error.

reports of monitoring at most wind-energy projects in Texas. Also, high inter-annual variation in fatality rates, such as those seen in the Altamont Pass Wind Resource Area, raise questions about how representative many of the fatality rate estimates might have been, especially those based on only 1 year or even a fraction of a year. Additionally, and despite my efforts to use consistent methods and assumptions, fatality-rate adjustment factors most likely continue to pose large biases.

One remaining bias appears to be the search interval applied to bat fatality monitoring. Searcher detection of aged bat carcasses might decline much faster than it does for aged bird carcasses, so bat carcasses missed in the first search since deposition might more often be missed in subsequent searches than are bird carcasses when search intervals are longer than 1–3 days. This bias was reflected in the top panel of figure 1 in Korner-Nievergelt et al. (2011), which summarized simulations of fatality rate estimates of carcasses assumed to be removed quickly (mean removal = 3 days) over a range of search intervals. With a 1-day interval, Korner-Nievergelt et al. reported a small positive bias, but the bias was increasingly negative at 7-day and 14-day intervals. Overall, the pattern of bias depicted in Korner-Nievergelt et al. (2011) resembled the pattern of fatality rates of bats plotted against search interval in Figure 11.

Adjustment Factors

Searcher detection.—I could explain variation in searcher detection rates by body size and my index of ground visibility, but not by season. However, searcher detection trials have not represented the types of evidence typically found during fatality monitoring at wind projects. Carcasses found during standard searches often consist of feathers or a body part, are often faded in color due to exposure, and are smaller due to decomposition. In contrast, carcasses placed in detection trials are usually fresh and whole, and used to test searchers during one standard search. Searcher detection rates calculated from repeated visits to ovenbird (*Seiurus aurocapilla*) carcasses yet to be removed by scavengers declined in a pattern resembling scavenger removal curves. The decline indicated that searchers miss more carcasses as the carcasses decay. Longer average search intervals probably increase the discrepancies in detection rates between carcasses deposited by wind turbines and those used in trials, as was suggested by the decline of bat fatality-rate estimates as search intervals increased.

Scavenger removal.—Removal trials are prone to various potential biases and sources of uncertainty (Smallwood 2007), all of which are in need of research. Removal rates can be slowed artificially by swamping scavengers with too many carcasses placed at once (Smallwood et al. 2010), by using found carcasses already decayed one or a few days, or by using rock pigeons as surrogates for other species of the same size class, because rock pigeons more frequently leave feathers for searchers to detect. Removal rates can be quickened artificially by using chicks as surrogates for small birds or game hens as similar-sized species, or by placing carcasses whole rather than dismembered to mimic the condition of many carcasses deposited by wind turbines. Whole carcasses are more likely than pieces to be picked up intact and removed at once by a single scavenger. Furthermore, calculating the proportion of carcasses remaining at pre-defined time intervals rather than at exact times of carcass removals tends to right-shift the data distribution, resulting in a biased representation of removal rates in the first few days after carcass placement (Smallwood et al. 2013).

Reports of removal trials have been unclear whether or how detection rates are managed during the trials. Standard fatality searches have searchers walking a comfortable pace with a certain distance separating transects, whereas removal trials often have select investigators returning to check on the status of placed carcasses. In removal trials, those making carcass status checks know what the carcass looked like and where it was placed. If the carcass is not initially detected during a status check, it is common for the ground to be intensively searched within 20 m or 30 m of the placement site. If available to be found, placed carcasses are much more likely to be detected during status checks than during routine fatality monitoring. At no point in fatality rate estimation is there an adjustment for the inflated detection rates in carcass removal trials.

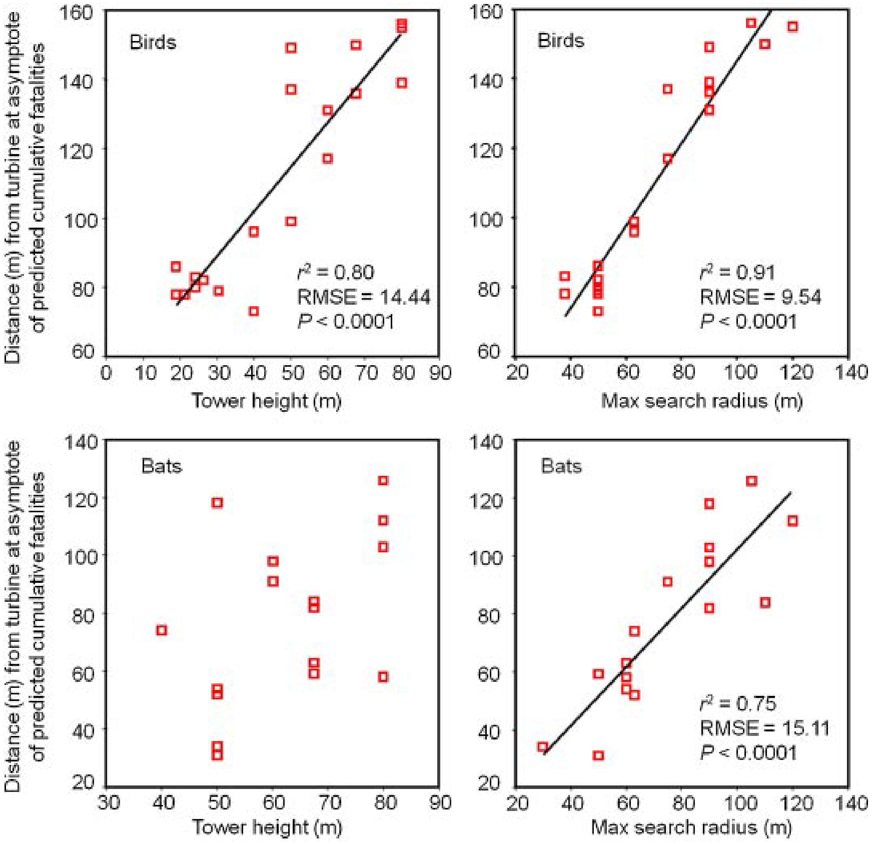

Figure 8. For birds, the distance from the turbine corresponding with model-fit asymptotes of found carcasses was slightly more responsive to maximum search radius (top right graph) than to tower height (top left), but for bats it was responsive only to maximum search radius (bottom right). Data were from wind projects across North America, model fits were logistic functions fit to cumulative carcasses detected at 1-m distance increments from the turbine, and RMSE was root mean square error.

During the past few years, some fatality monitors at wind projects have used the same placed carcasses for both removal trials and detection trials. This approach is more efficient than using separate groups of carcasses for each trial, but it still fails to account for the increased detection rates of placed carcasses in the removal trial. A more realistic approach to quantifying the proportion of carcasses not detected by searches would be to fully integrate the trials into standard fatality monitoring:

$$F_A = \frac{F_U}{D \times d}$$

where D is the proportion of placed carcasses that is detected by searchers performing standard fatality searches throughout a given monitoring period, and d is the adjustment factor for search radius bias (also see Smallwood et al. 2013). Using this approach, the investigator does not care whether carcasses were undetected due to searcher error or scavenger removal, and there is no added detection likelihood resulting from performing status checks on placed carcasses. Neither does the average search interval or number of searches matter, so long as the search interval varies little. The approach would also eliminate variation in inter-transect distance as a bias. To be effective, searchers should be naïve to the trial carcass placements, carcasses of species typically killed by the wind turbines should be placed one or a few at a time throughout the monitoring period, placements should be randomized by days within the search intervals and by monitored turbines and coordinates within the search area, placed carcasses should be dismembered in proportion to the rates of found carcasses that are dismembered, and all found carcasses

Table 5. Estimates of fatalities per year found at 51,630 megawatts of installed capacity of wind-energy projects across the United States in 2012 with and without including estimates from the Altamont Pass Wind Resource Area (APWRA). The installed capacity was reported by the American Wind Energy Association in December 2012.

	Deaths/year, excluding APWRA			Deaths/year, including APWRA		
Group	$\bar{x}$	90% LCL	90% UCL	$\bar{x}$	90% LCL	90% UCL
All bats	888,036	384,643	1,391,428	650,538	352,427	948,650
All raptors	46,467	26,590	66,344	82,608	56,123	109,094
All birds	531,789	419,183	644,394	573,093	467,097	679,089

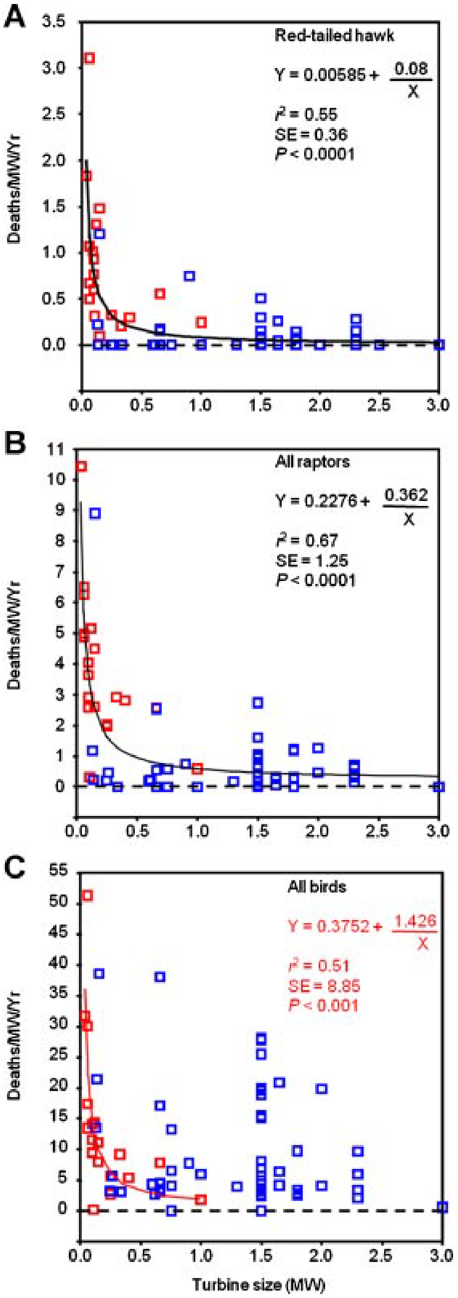

Figure 9. Fatality rates correlated inversely with wind-turbine size (red symbols represented wind turbines in the Altamont Pass Wind Resource Area [APWRA], and blue symbols represented wind turbines in all other wind-energy projects across North America) for red-tailed hawks (*Buteo jamaicensis*; (A), all raptors as a group (B), and all birds as a group (C) only within the APWRA (red symbols and text).

should be left in the search areas. This approach should eliminate the positive bias of finding carcasses in the second or subsequent searches after they were missed during the first search since deposition (Korner-Nievergelt et al. 2011).

Search radius.—Patterns in the data indicated that the maximum search radius around wind turbines have usually been sufficient for bats, but have likely left varying proportions of birds undetected and estimates of avian fatality rate biased low. Distances from the turbines predicted to correspond with an asymptote of found carcasses have usually been farther from the turbines than actually searched, more so for turbines on shorter towers. This pattern revealed a bias in comparing fatality rates among wind projects composed of various tower heights. A search radius adjustment is needed to improve comparability.

Although less influential than search detection and scavenger removal of carcasses, the maximum search radius remains a source of bias and uncertainty in fatality rate estimation due to arbitrary, inconsistent implementation. This factor is in need of field research. The ground needs to be searched farther from turbines than has been searched thus far. Once the maximum search radii have been determined within which all carcasses can be found, investigators can establish shorter maximum search radii and apply superior adjustment factors into fatality rate estimates.

Recommendations on other study attributes.—During my review of the available fatality reports, I noticed a number of common shortfalls in study methodology and reporting. For example, clearing searches were often reported. Clearing searches typically consist of a single search prior to the first search of a routine monitoring program. Carcasses found in clearing searches are usually removed from the field and excluded from use in fatality rate estimation. Because clearing searches are not always used, fatality rate estimates inconsistently incorporate the first carcasses found. Clearing searches, however, probably rarely clear the search areas of available carcasses, because searchers are at least as prone to missing carcasses during clearing searches as they are during detection trials. With small bird detection rates averaging about 50%, and not uncommonly as low as 12–25%, clearing searches probably reduce rather than improve the accuracy of fatality rate estimates. A better alternative is to regard the first search as having followed an average search interval, which is how I treated all of my fatality rate estimates based on data in the reports I reviewed herein.

Fatality monitoring also varies in how incidental finds are processed. Incidental finds are carcasses found at wind turbines not being monitored or at monitored turbines at a time other than a routine search. Some investigators exclude incidental finds at monitored turbines, and some include them. I recommend including incidental finds at monitored turbines to prevent abuse, which can involve a push toward finding carcasses incidentally so that they can be excluded from fatality rate estimates. Another way to manage incidental finds is to leave them in the field so that they have an opportunity to be found during subsequent routine searches.

Fatality rate estimates vary in whether and to what degree they include carcasses found beyond the maximum search radius. Some monitors exclude all fatalities seen outside the search radius, but most include these finds. The monitors in the Altamont Pass Wind Resource Area include all carcasses found within 125 m of the turbines, even though the maximum search radius is usually 50 m. Some find it obvious that all carcasses found beyond the search radius should be excluded, but doubts about this policy usually change once the carcasses of rare or important animals are found beyond

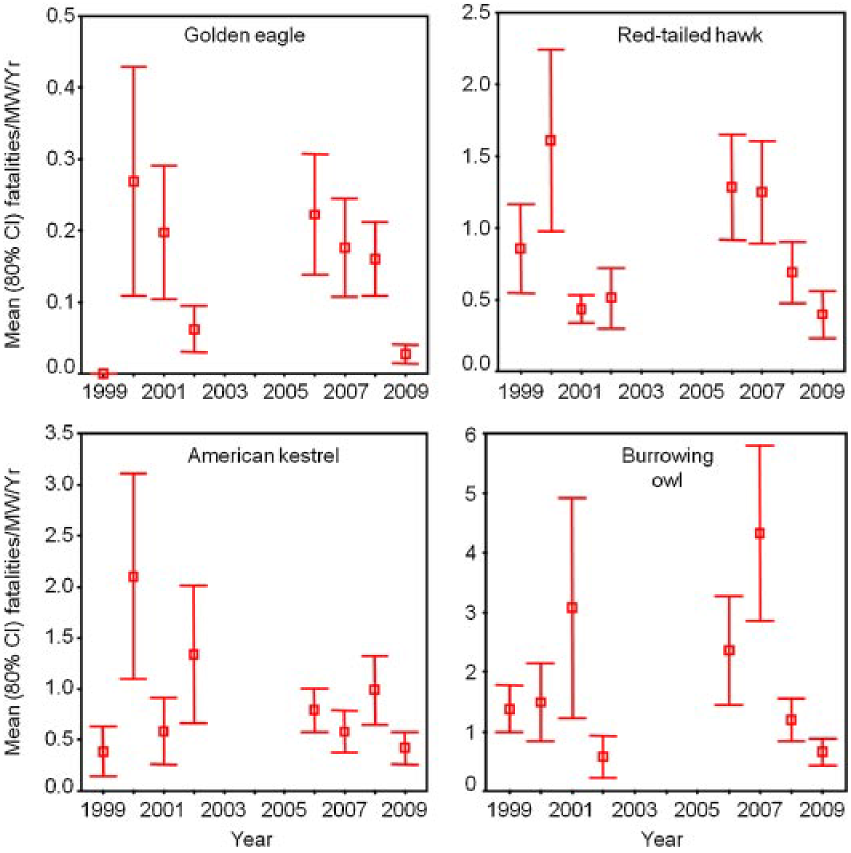

Figure 10. Fatality rates varied inter-annually for golden eagle (*Aquila chrysaetos*), red-tailed hawk (*Buteo jamaicensis*), American kestrel (*Falco sparverius*), and burrowing owl (*Athene cunicularia*) in the Altamont Pass Wind Resource Area, California, USA.

the search radius, such as golden eagles. In some cases, however, carcasses are highly unlikely to be found beyond the search radius due to low visibility in dense vegetation. Research needs to be directed toward the search radius bias and how to address it in fatality rate estimation.

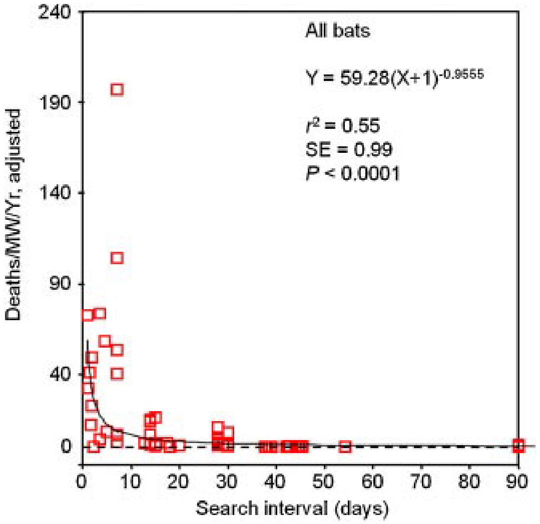

Figure 11. Bat fatality rates correlated as an inverse power function of average search interval (days), based on studies at wind-energy projects across North America.

Inter-transect distances vary among monitoring efforts, and sometimes within the search areas of individual wind turbines. The potential bias posed by this variation has yet to be quantified.

Many reports were of monitoring that lasted $\leq$1 year. Some monitoring efforts lasted only 6–8 weeks to capture the highest period of bat activity. However, longer term monitoring should be achieved for several reasons. In the case of bats, it may sometimes be incorrect to assume that fatalities are insubstantial during seasons other than late summer or autumn. Inter-annual variation in fatality rates can be high for both birds and bats, so relying on a single year of monitoring can be misleading. Finally, brief monitoring periods will obtain smaller numbers of found fatalities, which result in large error terms in the fatality counts, and hence large confidence ranges.

Using 2 search intervals emerged as a new trend in the Pacific Northwest, and has been spreading into California and probably elsewhere. Sometimes the monitored turbines are split into 2 groups, with one searched every 28 days and the other searched every 7 days. Sometimes all turbines are searched every 28 days, but a subset is searched every 7 days during spring and autumn. Every variation on the split interval approach poses significant problems, however. For example, split intervals need to be analyzed separately, which separates the sample of fatalities into smaller groups. Smaller samples of fatalities tend to result in relatively larger variance estimates, and hence larger confidence ranges. Also, arriving at ≥ 2 fatality rate estimates from ≥ 2 search intervals leaves the analyst questioning which fatality rate estimate to use. One can average the rates, but the analyst will know that the rates based on the shorter search interval will have been more accurately adjusted for removal rates, whereas the rates based on the longer search interval will have been based on a suite of species tending toward larger body sizes. Split intervals might be worthwhile when subsamples of monitored turbines are very large, but otherwise hinder fatality rate estimation.

In reporting of fatality rate estimates, it would be helpful if it always included wind turbine addresses with every fatality find, as well as distance and bearing from the wind turbine. The search schedule should be reported, as well as any disruptions to individual or collective wind-turbine operations. More detail is also needed in many reports of how variance exhaustion methods were used to generate standard error, and whether error terms were carried through the adjustments to fatality rate estimates.

Beginning in 2010, an increasing number of fatality monitoring reports have been kept confidential. Transparency is important to science, however, so this trend needs to be reversed. Furthermore, reports of fatality rate estimates need to be peer reviewed. Only a small fraction of the available reports have been peer reviewed, mainly those funded by public agencies.

MANAGEMENT IMPLICATIONS

Given high variability in field and analytical methods, it remains questionable whether valid comparisons can be made of reported fatality rate estimates among wind-energy projects. Whereas my estimates should be more comparable than the originally reported estimates, large biases remain unadjusted and uncertainties remain high. Most monitoring periods were too short, most search intervals were too long, and I was unable to make any adjustment for variation in inter-transect distance. Decision-makers need to be aware that much more scientific progress will be needed before variation in fatality rates can be conclusively attributed to wind-turbine models, environmental settings, mitigation measures, types of adjustment trials, or fatality rate estimators.

Fatality monitoring at wind-energy projects is in need of a radical change in direction, if comparable fatality rate estimates are to be obtained. Technical Advisory Committees and permitting agencies have been insisting on fatality monitors adopting field methods already used by other monitors. If those previously used methods were flawed, then using them again simply perpetuates the flaws. New field methods need to be tried, along with research. To fund research toward developing improved methodology, Technical Advisory Committees, permitting agencies, and regulatory agencies ought to encourage wind companies to allocate portions of their compensatory mitigation funds toward this methodological research.

Rather than continuing to attempt to develop fatality rate estimators that can adjust for the biases posed by conventional carcass removal and searcher detection trials, research should be directed toward developing detection trials that pose fewer, smaller biases to adjust. There is more opportunity to improve the accuracy of fatality rate estimates by incorporating detection trials into routine fatality monitoring than there is in post hoc mathematical adjustments for large biases introduced by detection trials that are decoupled from routine monitoring and that involve very different detection probabilities. Not only is the incorporation of detection trials prone to greater accuracy in fatality rate estimation, but the approach should cost less because carcass status checks by a designated biologist would be unnecessary.

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