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Techniques and Technology Article

Estimating Wind Turbine–Caused Bird Mortality

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ABSTRACT Mortality estimates are needed of birds and bats killed by wind turbines because wind power generation is rapidly expanding worldwide. A mortality estimate is based on the number of fatalities assumed caused by wind turbines and found during periodic searches, plus the estimated number not found. The 2 most commonly used estimators adjust mortality estimates by rates of searcher detection and scavenger removal of carcasses. However, searcher detection trials can be biased by the species used in the trial, the number volitionally placed for a given fatality search, and the disposition of the carcass on the ground. Scavenger removal trials can be biased by the metric representing removal rate, the number of carcasses placed at once, the duration of the trial, species used, whether carcasses were frozen, whether carcasses included injuries consistent with wind turbine collisions, season, distance from the wind turbines, and general location. I summarized searcher detection rates among reported trials, and I developed models to predict the proportion of carcasses remaining since the last fatality search. The summaries I present can be used to adjust previous and future estimates of mortality to improve comparability. I also identify research directions to better understand these and other adjustments needed to compare mortality estimates among wind farms. (JOURNAL OF WILDLIFE MANAGEMENT 71(8):2781–2791; 2007)

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KEY WORDS bird carcass, fatality monitoring, mortality estimate, scavenger removal, searcher detection, wind turbine.

Wind turbines for electric power generation are rapidly increasing in size, number, and worldwide distribution, appearing where wind resources are suitable. Wind turbines kill birds and bats, usually because the wind turbine blades strike birds and bats flying into the rotor zone, the portion of the sky swept by the rotor blades. Wind turbine–caused mortality of birds and bats has been estimated at some wind power sites (wind farms), and some of these estimates were high enough to cause concern (e.g., J. Kerns and P. Kerlinger, FPL Energy, unpublished report [Table 1]; Smallwood and Thelander 2004).

Mortality estimates at wind farms can be expressed as the annual number of fatalities or as the annual number of fatalities per unit representing the size or magnitude of the wind farm. These estimators inform society of the direct impacts caused by particular projects. They can be compared in research designs to assess the efficacy of mitigation measures, and they can be compared seasonally or annually to detect trend. Mortality estimates compared to site utilization or to relative abundance estimates can measure relative collision risk or indicate biological impacts. Mortality estimates provide the basis for assessing liability in enforcement actions pursuant to the Migratory Bird Treaty Act or to other environmental or business laws. Finally, mortality estimates facilitate comparison of wind turbine–caused impacts to direct impacts caused by other forms of energy generation or other human activities.

The 2 crudest measures of wind turbine–caused mortality are the number of fatalities per carcass search and the annual number of fatalities in the wind farm. Both are limited in their use. The number of fatalities per carcass search does not account for search frequency, wind farm size, or monitoring duration. It would be useful if all fatality monitoring programs were performed in exactly the same manner. The annual number of fatalities does not account for wind farm size, so might only be useful for assessing liabilities or comparing mortality at the same wind farm through time. Both measures of mortality are biased low when unadjusted by the carcasses undetected by searchers, removed by scavengers prior to searches, and for other reasons.

Estimates of wind turbine–caused mortality have been highly uncertain and prone to biases. Considering adjustments for searcher detection error and scavenger removal rate alone, the number of carcasses found during searches may need to be increased only slightly or by a factor of 40, depending on vegetation cover, the bird or bat species deposited, season, and the local abundance and composition of scavenger species. Some scavengers, such as common raven, learn quickly of carcass availability (Kerns 2005). When searchers are estimated to have missed half the available carcasses during search detection trials, mortality estimates would be double the number of carcasses actually found. When scavengers remove 90% of trial carcasses during a time period equal to the interval between fatality searches, then mortality estimates would be 10 times the number of carcasses remaining. Search detection error, scavenger removal of carcasses, and the mortality estimators are the 3 principal sources of error and bias to date.

Scavenger removal trials at wind farms usually treated body size as the only variable besides season that matters to scavenger removal rates. For example, Young et al. (2003) used house sparrows (*Passer domesticus*) and juvenile quail as small birds, rock doves (*Columba livia*) as medium-sized birds, and mallards (*Anas platyrhynchos*) as large birds. W. P. Erickson, K. Kronner, and B. Gritski (WEST, Inc., unpublished report, page 4 [Table 1]) used 16 species of songbirds and game birds (chicks) to represent "small birds and bats," and 9 species of adult game birds, chickens, and frozen raptors to represent "medium and large birds." Additionally, trial duration has varied, as have time intervals between carcass searches, numbers of carcasses deployed at once, and the metric used to measure carcass removal rate.

My objectives were to identify known sources of error in

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Table 1. Unpublished reports of bird collision studies at wind farms in the United States, from which I used data on reported searcher detection and scavenger removal rates.

Report	Reference
1	Erickson, W. P., G. D. Johnson, M. D. Strickland, and K. Kronner. 2000. Final report: avian and bat mortality associated with the Vansycle Wind Project, Umatilla County, Oregon: 1999 study year. Umatilla County Department of Resource Services and Development, Pendleton, Oregon, USA.
2	Erickson, W. P., K. Kronner, and B. Gritski. 2003. Nine Canyon Wind Power Project avian and bat monitoring report. Report to Nine Canyon Technical Advisory Committee, Energy Northwest. WEST, Cheyenne, Wyoming, USA.
3	Erickson, W. P., J. Jeffrey, K. Kronner, and K. Bay. 2004. Stateline wind project wildlife monitoring final report, July 2001–December 2003. Technical Report submitted to FPL Energy, the Oregon Energy Facility Siting Council and the Stateline Technical Advisory Committee. WEST, Cheyenne, Wyoming, USA.
4	Howell, J. A., and J. E. Didonato. 1991. Assessment of avian use and mortality related to wind turbine operations, Altamont Pass, Alameda and Contra Costa Counties, California, September 1998 through August 1989. Final report submitted to U.S. Windpower, Livermore, California, USA.
5	Howell, J. A., and J. Noone. 1992. Examination of avian use and mortality at a U.S. Windpower wind energy development site, Montezuma Hills, Solano County, California. Final report. Prepared for Solano County Department of Environmental Management, Fairfield, California, USA.
6	Johnson, G. D., W. P. Erickson, J. White, and R. McKinney. 2003. Avian and bat mortality during the first year of operation at the Klondike Phase I Wind Project, Sherman County, Oregon. Northwestern Wind Power, Goldendale, Washington, USA.
7	Kerlinger, P., R. Curry, L. Culp, A. Jain, C. Wilkerson, B. Fischer, and A. Hasch. 2006. Postconstruction avian and bat fatality monitoring study for the High Winds Wind Power Project, Solano County, California: two-year report. High Winds, LLC and FPL Energy, Juno Beach, Florida, USA.
8	Kerns, J., and P. Kerlinger. 2004. A study of bird and bat collision fatalities at the Mountaineer Wind Energy Center, Tucker County, West Virginia: annual report for 2003. Report to FPL Energy and Mountaineer Wind Energy Center Technical Review Committee. FPL Energy, Juno Beach, Florida, USA.
9	Koford, R., A. Jain, G. Zenner, and A. Hancock. 2005. Avian mortality associated with the Top of Iowa Wind Farm. Horizon Wind Energy, Houston, Texas, USA.
10	WEST, Inc. 2006. Diablo Winds wildlife monitoring progress report: March 2005–February 2006. WEST, Cheyenne, Wyoming, USA.

the available estimators, to quantify biases where feasible, and to develop the means to predict the proportion of carcasses remaining after various periods intervening carcass searches, when scavenger removal trials were not performed or will not be performed on site. My goals were to establish a basis to adjust previous mortality estimates so they are comparable and to identify productive research directions to improve the accuracy and precision of wind turbine–caused mortality estimates.

METHODS

Most wind turbine–caused mortality estimates factor in wind farm size and are adjusted for the 2 most widely recognized sources of error. One estimator of adjusted mortality, M_A, is the following:

$$M_A = \frac{\bar{c}}{\left(\frac{\bar{t}\times p}{I}\right)\left(\frac{e^{I/\bar{t}}-1}{e^{I/\bar{t}}-1+p}\right)} \quad (1)$$

where $\bar{c}$ is average number of carcasses observed per year, $\bar{t}$ is mean number of days until carcass removal, p is observer efficiency rate, and I is search interval in days (WEST, Inc., unpublished report 10; Table 1). This version of the estimator was revised from a previous version after Shoenfeld (West Virginia Highlands Conservancy, unpublished report) concluded it biased mortality estimates low about 23%.

Another widely used estimator of adjusted mortality is the following:

$$M_A = \frac{M_U}{R\times p}, \quad (2)$$

where M_U is unadjusted mortality expressed as either number of fatalities per wind turbine per year or number of fatalities per megawatt (MW) of rated capacity per year, R is proportion of carcasses remaining since the last fatality search and is estimated by scavenger removal trials, and p is proportion of carcasses found by fatality searchers during searcher detection trials. Additional adjustments could be incorporated into equation 2, such as background mortality (M_B), crippling bias (M_C), and search radius bias (M_S):

$$M_A = \frac{M_U}{R\times p} - M_B + M_C + M_S. \quad (2b)$$

Background mortality is the natural rate of fatalities, the rate not caused by wind turbines or their infrastructure. Crippling bias refers to the number of animals injured by the wind turbines but that die elsewhere, undetected. Search radius bias refers to the number of animals thrown by the wind turbines outside the search area and never found. Attempts to estimate M_B, M_C, and M_S would also require adjustments by R and p. My study does not quantify M_B, M_C, or M_S because they are either relatively small or unknown in their magnitudes due to insufficient field research.

Searcher Detection

I collected data on searcher detection rates from Orloff and Flannery (1992), Kerlinger et al. (2000), Johnson et al. (2002), Young et al. (2003), Anderson et al. (2004, 2005), and unpublished reports 1–3, 6, 7, 9, and 10 (Table 1). I categorized vegetation stature based on reported descriptions of the study areas. Short-stature vegetation included annual grassland and short–mid-grass prairie. Intermediate stature vegetation included grassland and shrub-steppe, small shrubs and grass, small shrubs, mowed within forest, and forest clearings. Taller stature vegetation included mixed-grass prairie and sagebrush shrub-land, wheat (*Triticum aestivum*), wheat and grassland, hayfield, ruderal, creosote bush (*Larrea tridentate*), brittlebush (*Encelia farinose*), scalebroom (*Lepidospartum* spp.), wetland, and grassland and forest.

Searcher detection rates were typically reported as percentages of volitionally placed carcasses found. I converted the percentages found to proportions for use in mortality estimation (eq 1 and 2). In comparing results from searcher detection trials, I assumed the methods used would have produced equal likelihoods the trial carcasses would be found. Distances between transects and time spent searching likely varied by terrain, vegetation, and visibility, but if these variations produced unequal detection probabilities, then my comparison of detection rates could be biased.

Scavenger Removal

Mean time to removal.—I collected estimates of mean number of days to carcass removal from reports of scavenger removal trials. Data on rock doves were from Kerlinger et al. (2000), Johnson et al. (2002), Young et al. (2003), and unpublished reports 1, 2, 6, and 10 (Table 1). Data from other medium- and large-sized birds were from Kerlinger et al. (2000) and reports 1–3 and 6 (Table 1). Data on small birds were from Kerlinger et al. (2000), Johnson et al. (2002), Young et al. (2003), Anderson et al. (2005), and reports 1–3, 6, and 10 (Table 1). From reports that presented mean time to removal both seasonally and averaged among seasons, I used only the latter estimates. I used mean time to removal specific to one season when no average was reported among seasons.

I related mean time to removal to the scavenger removal trial's duration, and I tested multiple functions for best fit to the data. I assessed best fit by the magnitude of the coefficient of determination, the root mean-square error, the *P*-value, sample size (df), whether the *y*-intercept was reasonably close to 100% of carcasses remaining, whether the residuals were homoscedastic when plotted against the predictor variable, and interpretability of the model.

Proportion of carcasses remaining.—I obtained percentages of bird carcasses remaining in scavenger removal trials from tables in reports, when available, but sometimes I took them from graphs using a ruler. Estimates for small birds were from Kerlinger et al. (2000), Kerlinger (2002), Johnson et al. (2002), Young et al. (2003), Anderson et al. (2005), and reports 1–3, 6–8, and 10 (Table 1). Estimates for medium and large birds were from Orloff and Flannery (1992), Kerlinger et al. (2000), Johnson et al. (2002), Schmidt et al. (2003), Young et al. (2003), Kerns (2005), Anderson et al. (2005), and reports 1–3, 6, 7, and 9 (Table 1). Estimates for rock doves were from Johnson et al. (2002), Young et al. (2003), and report 10 (Table 1). Estimates for chickens and game hens were from Orloff and Flannery (1992), and Anderson et al. (2005), and report 4 (Table 1). Estimates for small, medium, and large raptors were from Orloff and Flannery (1992), and on medium and large raptors were from reports 5 and 10 (Table 1), the latter of which had a sample size of 3. All the raptor data were from the Altamont Pass and the Solano wind farms, California.

I took means from data spanning multiple seasons. Generally, I summarized the reported percentages of carcasses remaining per study site. I visually examined plots of these data to select mathematical functions to fit them. I assessed model fits using the same standards used for mean time to carcass removal, described above.

Season effect.—I saved the unstandardized residuals from the best-fit models of mean days to carcass removal related to number of days into the scavenger removal trial, and I also saved the residuals from the percent of carcasses remaining related to number of days into the trial. I then tested these residuals for a seasonal effect using one-way analysis of variance (ANOVA). Only estimates associated with month or season of the year could be used, so I excluded from the tests estimates reported as annual or from multiple seasons.

Proportion of accumulated carcasses remaining.—Assuming wind turbines operate consistently from day to day and assuming birds and bats fly in similar manners and frequencies each day, wind turbine collisions have a similar probability of depositing carcasses on the ground from one day to the next. In addition to the carcasses possibly deposited since the last fatality search, say 30 days ago, the analyst needs to consider the number deposited 29 days ago, 28 days ago, and so on until one and zero days ago. To estimate the accumulated percentage of carcasses remaining after various search intervals, and assuming a steady state of carcass deposition, I relied on the following equation:

$$R_C = \frac{\sum_{I}^{i=1} R_i}{I \times 100}, \quad (3)$$

where R_C was the cumulative carcasses remaining, R_i was the percent of carcasses remaining by the *i*th day following the initiation of a scavenger removal trial, and *I* was the duration of a scavenger removal trial corresponding with the fatality search interval used during a mortality monitoring effort. Thus, the expected percentage of bird carcasses remaining by the next fatality search should be R_C corresponding with the fatality search interval, *I*.

RESULTS

Searcher Detection

Searcher detection of volitionally placed carcasses varied by species group (ANOVA $F = 24.87$, df = 5, 127, $P < 0.001$), averaging 100% for large raptors, 80% for large nonraptor birds, 79% for medium-sized raptors, 78% for medium-sized nonraptor birds, 75% for small raptors, and 51% for

Table 2. Logistic growth curve models fit to the mean time to removal of bird carcasses deployed in scavenger removal trials and trial duration, where RMSE represented root mean-square error, the intercept and slope parameters were represented by *a* and *b*, respectively. Data were insufficient to fit models for raptors. The data were gathered from reports of scavenger removal trials performed 1989–2006 throughout the United States.

Model	r^2	RMSE	*n*	*P*-value	*a*	*b*
Medium and large birds[a]	0.91	0.32	16	<0.001	4.2000	−27.4795
Rock dove	0.91	0.29	4	<0.05	4.3294	−29.7639
Small birds	0.60	0.40	9	<0.05	2.9297	−14.1678

[a] Small birds are typically songbirds, medium birds are typically the size of rock doves, and large birds are typically ducks, herons, buteo hawks, and eagles.

small nonraptor birds. Among small birds, percent searcher detection differed by stature of the vegetation cover in the search area (ANOVA $F = 13.12$, df = 2, 51, $P < 0.001$), averaging only 43% in short-stature vegetation, 65% in intermediate-stature vegetation, and 60% in relatively tall vegetation. Among medium- and large-sized nonraptor birds, searcher detection did not differ among categories of vegetation stature (ANOVA $F = 2.89$, df = 2, 57, $P = 0.064$).

Scavenger Removal

Mean time to removal.—Mean days to removal was a logistic growth function of the number of days in the scavenger removal trial (Table 2, Fig. 1):

$$\bar{t} = e^{a+b/d}, \tag{4}$$

where *t* was the mean time to removal, *d* was the number of days since the scavenger removal trial began, and *a* and *b* were fitted parameters. For example, applying the parameter estimates in Table 2 to the model in equation 4, a 62-day trial would predict an average 43 days to carcass removal of medium to large birds, but a 14-day trial would predict an average of only 9 days to carcass removal (also see Fig. 1). Thus, other factors held constant, the longer the trial the lower the mortality estimated by equation 1.

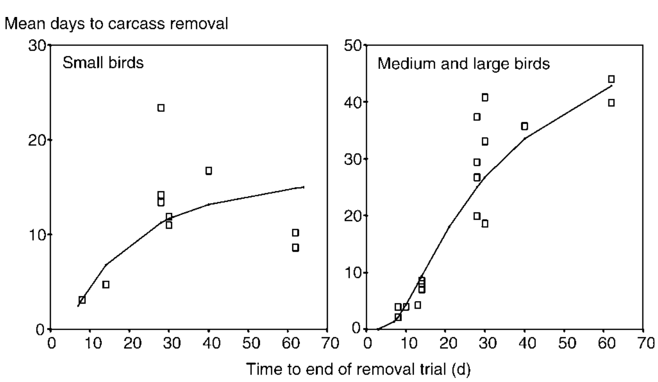

Figure 1. Logistic growth curve fitted to reports of mean days to small bird carcass removal (left graph) and medium and large bird carcass removal (right graph) as functions of the number of days to the end of the carcass removal trial. The data were gathered from reports of scavenger removal trials performed 1989–2006 throughout the United States.

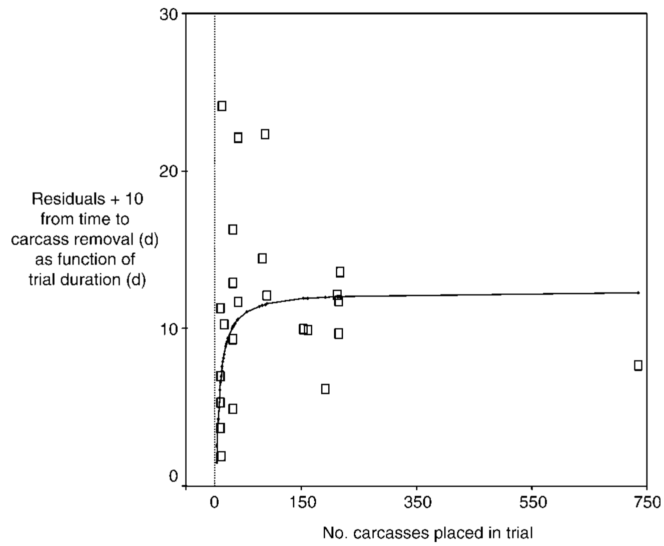

Figure 2. From logistic growth curves fit to the number of days to the end of the bird carcass removal trial, the unstandardized residuals increased rapidly with sample size of carcasses until about 50 carcasses were used in the removal trials performed 1989–2006 throughout the United States.

The sample size of carcasses in scavenger removal trials explained much of the remaining variation in mean days to carcass removal after accounting for trial duration (Fig. 2). The model fit was best for small birds (Table 3).

Proportion of carcasses remaining.—I fit the percentages of carcasses remaining by mathematical functions best representing the pattern in the data (Figs. 3 and 4). In most cases the logarithmic model fit best:

$$R_i = a + b \cdot \ln(i + 1), \tag{5}$$

where R_i was the percent of carcasses remaining on the *i*th day into the scavenger removal trial, and *a* and *b* were fitted parameters (Table 4).

Season effect.—After removing the effect of trial duration on mean days to carcass removal by fitting equation 4 fit to the data (Table 2), the unstandardized residuals did not relate to season of the year (ANOVA $F = 0.41$, df, = 2, 6, $P > 0.05$). However, after removing the effect of trial duration on percent of carcasses remaining by fitting equation 5 to the data (Table 5), the unstandardized residuals related to season of the year (ANOVA $F = 6.21$, df, = 3, 192, $P < 0.001$). Residuals from equation 5 averaged −7.09 during autumn, −1.10 during winter, −0.86

Table 3. Logistic growth curve models fit to trial duration-adjusted mean days to bird carcass removal and sample size of carcasses used in the scavenger removal trial, where RMSE represented root mean-square error and the intercept and slope parameters were represented by *a* and *b*, respectively. I added the value 10 to the residuals to eliminate negative values for the purpose of model fitting. Data were insufficient to fit models for raptors. The data were gathered from reports of scavenger removal trials performed 1989–2006 throughout the United States.

Model	r^2	RMSE	*N*	*P*-value	*a*	*b*
All birds	0.17	0.54	23	<0.05	2.5174	−6.3769
Small birds	0.64	0.34	8	<0.01	2.7496	−11.1947

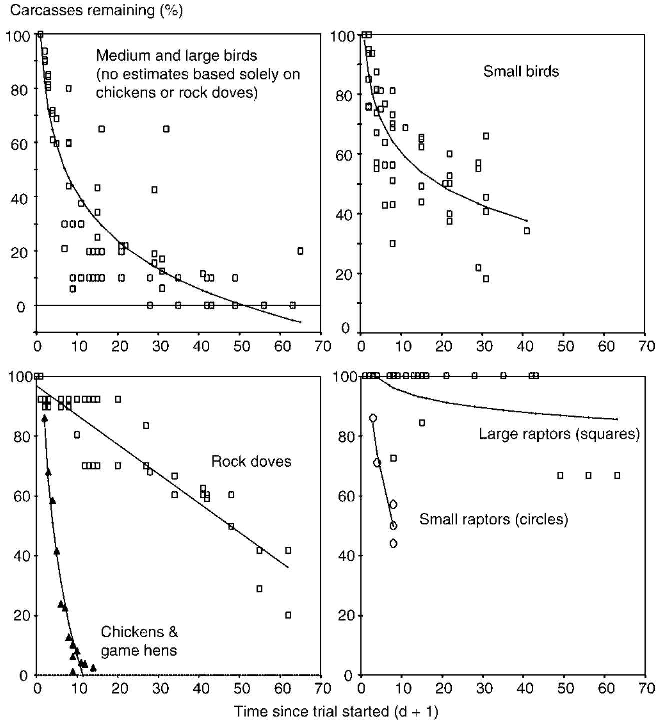

Figure 3. The percentage of carcasses remaining at trial's end as a function of trial duration for small nonraptor birds (upper left), large nonraptor birds (upper right), rock doves and chickens and game hens (lower left), and small and large raptors (lower right). All functions were logarithmic except for rock doves, which was linear. The data were gathered from reports of scavenger removal trials performed 1989–2006 throughout the United States.

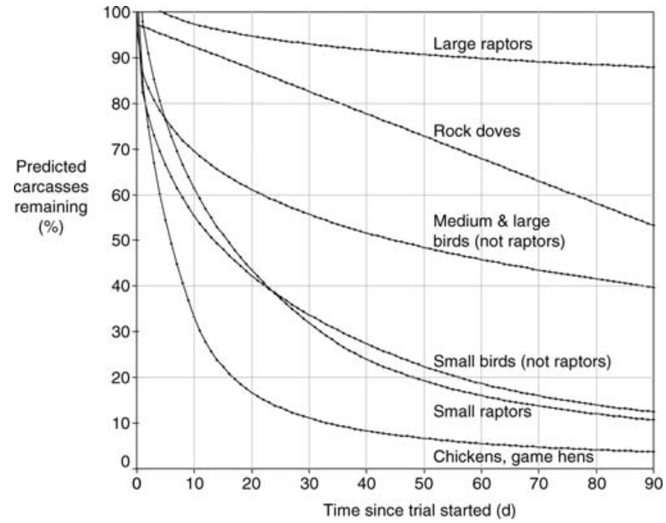

Figure 4. Predicted percentages of bird carcasses remaining each day into a scavenger removal trial or fatality search rotation, assuming a steady-state frequency of bird collisions at wind turbines and using equation 3:

$$R_C = \frac{\sum_{I}^{i=1} R_i}{I \times 100},$$

where R_C was the cumulative carcasses remaining, R_i was the percent of carcasses remaining by the ith day following the initiation of a scavenger removal trial, and I was the duration of a scavenger removal trial corresponding with the fatality search interval used during a mortality monitoring effort. The underlying data used for predictions were gathered from reports of scavenger removal trials performed 1989–2006 throughout the United States.

during spring, and 6.35 during summer. Scavengers removed more carcasses during autumn and fewer during summer.

Proportion of accumulated carcasses remaining.—By applying predictions from equation 5 (Table 4) to equation 3, I obtained estimates of the cumulative percentages of carcasses remaining on any of 90 days since the last fatality search (Fig. 4; Appendix). As an example, the percentage of small raptor carcasses remaining 3 days since the last fatality search can be obtained by using the small raptor model in Table 4 to estimate the percentages after 1 day, 2 days, and 3 days. After the first day since the last fatality search, or after the first day into the removal trial ($i = 1$), the percentage of carcasses remaining would be estimated as:

$$R_1 = 121.86 - 34.54 \cdot \ln(1 + 1) = 97.9\%.$$

After 2 days in the field $R_2 = 83.9\%$ and after 3 days $R_3 = 74.0\%$. Applying these predictions to equation 3 yields the following estimate of the cumulative percentage of carcasses remaining at the end of the 3-day interval since the last fatality search:

$$R_C = \frac{97.9 + 83.9 + 74.0}{3 \times 100} = 85.3\%.$$

This value is 0.3% larger than the value appearing in the Appendix because I rounded the values in the Appendix to the nearest 0.5%.

Thus, the Appendix and Figure 4 can be used to predict the percentage of carcasses remaining since the last fatality search, assuming a steady state of carcass deposition by wind turbines. For example, 51% of small-bodied raptor carcasses should remain to be found 15 days since the last fatality search (Appendix).

DISCUSSION

My comparisons of estimated searcher detection and scavenger removal rates revealed a strong bias in mean days to carcass removal, which contributes substantially to one of the most popular mortality estimators used to assess impacts of wind farms on birds and bats. The number of bird carcasses deployed at once during scavenger removal trials can also bias the resulting mortality estimates low. My comparisons also revealed differences among groups of species used in search detection and scavenger removal trials, indicating the use of surrogate species for those killed by wind turbines may be misleading. My comparisons of searcher detection and scavenger removal rates among both published and unpublished reports established a basis to adjust previous mortality estimates so they are comparable, and to adjust future mortality estimates at wind farms when searcher detection and scavenger removal trials will not be performed for whatever reason(s).

While comparing searcher detection and scavenger

Table 4. Percent of bird carcasses remaining regressed on the number of days since the start of the scavenger removal trial, where the intercept and slope parameters were represented by *a* and *b*, respectively. The data were gathered from reports of scavenger removal trials performed 1989–2006 throughout the United States.

Group	Model	r^2	*n*	*P*-value	*a*	*b*
Small birds	Logarithmic	0.77	68	<0.001	100.05	−25.48
Medium and large birds	Logarithmic	0.60	51	<0.001	97.85	−16.20
Chickens and game hens	Logarithmic	0.95	14	<0.001	118.22	−48.50
Rock doves	Linear	0.85	38	<0.001	97.81	−0.98
Small raptors	Logarithmic	0.93	6	<0.001	121.86	−34.54
Large raptors	Logarithmic	0.23	26	<0.05	106.43	−5.16

removal rates, I noticed investigators often sought trial results based on large sample sizes of bird carcasses but took few steps to better understand why birds are missed during searcher detection trials or what factors influence scavenger removal rates. Most fatality monitoring has been performed for permit compliance, and not for scientific research, and most reports were neither peer reviewed or published. Peer-reviewed research is needed, and it needs to be directed toward searcher detection, scavenger removal, and a suite of other sources of uncertainty and potential bias yet to be factored into most mortality estimates, to be discussed below.

Searcher Detection

Increasing body size of species used in searcher detection trials improved carcass detection around wind turbines, and large-bodied raptors were detected more often than large-bodied nonraptors. Finding small-bodied bird species at lower rates in short-stature vegetation might reflect a bias caused by vertebrate scavengers quickly removing small bird carcasses intended for searcher detection trials, even when scavenger removal and searcher detection trials are not performed simultaneously. However, my results should be interpreted within the range of vegetation statures used in searcher detection trials; significant differences might be found in other circumstances, such as on tilled fields, barren ground, or in tall, dense vegetation.

Searcher detection rates might be biased high due to insufficient search radius. The search radius bias might result from birds or bats thrown by the wind turbine blades beyond the boundary of the fatality search area. Strong wind gusts can boost bird carcasses beyond the search radius. Some, but probably not all, carcasses beyond the search radius are spotted by fatality searchers from within the search radius. Any carcasses landing outside the search area and going undetected will bias the corresponding mortality estimates low.

Scavenger Removal

Mean days to carcass removal.—The increase in mean days to carcass removal with increasing trial duration (Fig. 1) indicates the use of mean days to carcass removal can bias mortality estimates. I hypothesize that one of the mechanisms of this bias is scavenger swamping, similar to the phenomenon of predator swamping well described in the ecological literature. Giving scavengers more carcasses than they can remove and process increases the likelihood some carcasses will be left to decompose to the point of being unattractive as food. The difference between the observed and predicted mean days to carcass removal increased rapidly between 0 and 50 carcasses used in the trial (Fig. 2), meaning the vertebrate scavengers removed increasingly smaller percentages of trial carcasses from samples ranging up to about 50. Once remaining carcasses fill with maggots or dry to the hardness of leather, vertebrate scavengers likely leave them alone and the carcasses essentially mummify. Only a few mummified carcasses or feather and bone piles are needed to substantially increase the mean number of days to carcass removal because they will last as long as the trial is performed. To the 1 day, 2 days, or 3 days attributed to the removals of most bird carcasses, each mummified carcass will likely add the total number of days in the trial to the calculation of the mean number of days to carcass removal. Therefore, scavenger removal trials with mummified carcasses should increasingly reduce the mortality estimate the longer the trial lasts.

As an example of the consequence of scavenger swamping, 30 carcasses used in a field trial will average 2 days to carcass removal if all 30 carcasses are removed after 2 days, but if 4 (13%) of the carcasses mummify and remain until the end of a 15-day trial, then the mean days to carcass removal

Table 5. Percent of bird carcasses remaining during scavenger removal trials regressed on the number of days since the start of the trial but only for estimates associated with season of the year, where the intercept and slope parameters were represented by *a* and *b*, respectively. The data were gathered from reports of scavenger removal trials performed 1989–2006 throughout the United States.

Group	Model	r^2	*n*	*P*-value	*a*	*b*
Small birds	Logarithmic	0.66	78	<0.001	96.87	−23.62
Medium and large birds	Logarithmic	0.50	79	<0.001	114.83	−18.00
Rock doves	Linear	0.83	41	<0.001	97.85	−0.98
Small raptors	Logarithmic	0.93	7	<0.001	121.85	−34.54
Large raptors	Logarithmic	0.07	36	>0.05	101.75	−4.27

becomes 3.7 days, almost twice as long. Leaving these 4 mummified carcasses until the end of a 60-day trial shifts the mean days to carcass removal to 9.7 days, almost 5 times as long. Scavenger swamping likely biases the mortality estimator in equation 1 more than it biases the estimator in equation 2 because the value range of the mean days to carcass removal is unbounded whereas the value range of the proportion of carcasses remaining at trial's end is 0–1.

WEST, Inc. earlier relied on 14-day scavenger removal trials (Johnson et al. 2002) and later extended trials to 28 days (Young et al. 2003; reports 1 and 6 in Table 1), 30 days (report 2 in Table 1), 40 days (report 3 in Table 1), and 62 days (report 10 in Table 1), an average increase of 5 days per year over 7 years (Fig. 5). By increasing their trial durations West, Inc. also increased their mean time to carcass removal estimates, and they correspondingly underestimated mortality. As an example, using WEST, Inc.'s (report 10 in Table 1) estimated searcher efficiency of 0.76 for medium and large birds, and using predictions from equation 4 (Table 2) for the average time to removal of carcasses during a 62-day trial, their mortality estimator would adjust their raw estimate of 0.64 birds per MW per year to 1.03 birds per MW per year, whereas a 14-day trial would yield a predicted adjusted mortality estimate of 2.89 birds per MW per year. Thus, by extending their scavenger removal trial from 14 days to 62 days, WEST, Inc. reduced their medium–large-sized bird mortality estimate by 65%.

Proportion of carcasses remaining.—Rock doves were removed at a unique rate, though other species-specific patterns may appear similar to the rock dove pattern once sufficient species-specific trials are performed. Using the rock dove as a surrogate for raptors would tend to underestimate small-bodied raptor carcass removal and overestimate large raptor carcass removal. This is important because scavenger removal trials often use rock doves as surrogates for species killed by the wind farm. Scavenger removal trials are needed of raptors, and results need to be reported for individual species. If the rapid removal of small raptor carcasses (Fig. 3) is confirmed through additional scavenger removal trials, then Smallwood and Thelander's (2004, 2005) mortality estimates were too low for burrowing owl (*Athene cunicularia hypugea*) and American kestrel (*Falco sparverius*) in the Altamont Pass Wind Resource Area.

After accounting for trial duration, the percentage of carcasses remaining was significantly lower during autumn scavenger trials and higher during summer. Vertebrate scavengers might be more inclined to remove carcasses during autumn to build body fat for the winter.

Proportion of accumulated carcasses remaining.—Based on the rapid removal of chicken and game hen carcasses, leaving very small cumulative percentages after only a few days since the last search (Fig. 4), investigators should avoid using chickens or game hens as surrogate species for those typically killed by wind turbines. Also due to rapid removal rates, small birds, including small raptors, require careful scavenger removal trials to obtain accurate estimates, because small differences in time since the last fatality search can substantially shift cumulative percentages of carcasses remaining and subsequent mortality estimates. Considering only the effects of scavenger removal, the number of small birds found 30 days since the last search would need to be multiplied by 3 to account for the carcasses removed, and the number found after 90 days would need to be multiplied by nearly 10.

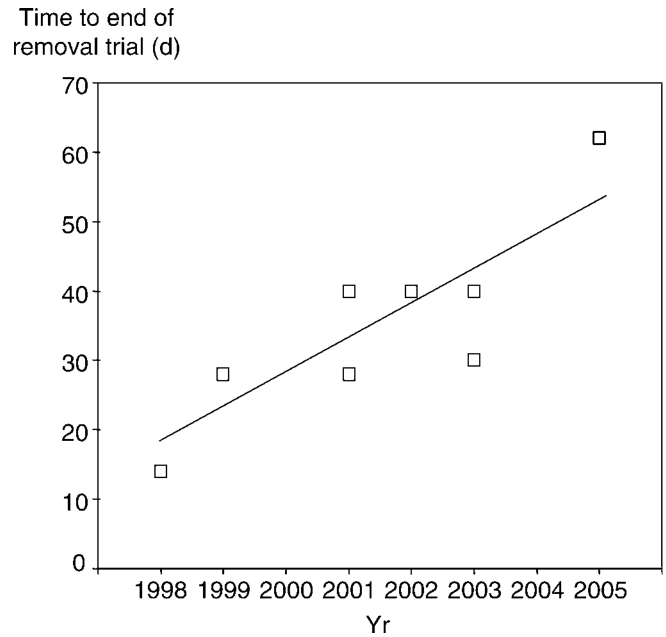

Figure 5. The number of days WEST, Inc. dedicated to scavenger removal trials of bird carcasses increased 5 days per year on average from 1998 until 2006, according to their reports of wind power studies in the western United States.

Other Biases

There are many potential sources of error and bias in the mortality estimators, especially in equation 1 (Table 6). Most of these error sources will bias the mortality estimate low, a few high, and others add imprecision with unknown bias. Most have not been quantified or used in mortality estimators; thus, mortality estimates calculated from equations 1 or 2 remain imprecise and biased low until directed field research leads to quantification of these sources of error.

Searcher detection trials can be biased by the searchers' becoming aware of the trial after noticing evidence left by the trial administrators, such as footfall depressions left in grass while depositing carcasses or tags on trial carcasses and by placing too many carcasses on the search area. Once aware of the trial, the searchers will likely increase their search vigilance and lower their miss rate. Encountering 20 or 30 carcasses during a single search rotation, as might happen during a search detection trial, is too great a deviation from the normal carcass discovery rate of 1 or 2 per search rotation to go unnoticed. Also, volitionally placed bird carcasses will often appear differently to searchers than carcasses deposited by wind turbines because wind turbines tend to knock feathers from the bird, dismember it, or splay it on the ground, whereas volitionally placed carcasses

Table 6. Potential biases and sources of error in adjustment terms used in mortality estimators of birds killed by wind turbines throughout the United States, 1988–2006.

Source of error or bias in mortality estimators	Likely effect on estimates
Choice of denominator in the ratio of fatalities to the incidence of the hazard under consideration (e.g., no. of wind turbines, megawatts [MW] of rated power output among sampled turbine[s], rotor-swept area by the turbine[s], kilowatt-hr since the last fatality search)	Increases or decreases uncertainty depending on circumstances; potential biases
Crippling bias	Bias low
Search radius bias	Bias low
Background mortality, though the few available estimates indicate the error due to inadvertent inclusion of background mortality is small	Slight bias high
$\bar{t}$ and p are derived from small samples of carcasses in field exp., usually performed concurrently	Add uncertainty and possible bias
Scavenger swamping	Bias low
Some carcasses not removed by vertebrate scavengers mummify and increase $\bar{x}$ d to carcass removal	Bias low
Use of inappropriate species misrepresents levels of detection and attractiveness to scavengers	Usually bias high, but could also bias low
Frozen or thawed carcasses less attractive to vertebrate scavengers	Bias low
Whole carcasses may not mimic dismembered carcasses and are more difficult to detect or to remove	Might bias low
Right-censored data (i.e., terminating trial before all carcasses removed)	Add uncertainty
Left-censored data (i.e., findings of zero fatalities not adjusted)	Bias low
Long search intervals in scavenger removal trials hamper best-fits of alternative mathematical functions	Add uncertainty
The use of $\bar{x}$ time to removal in eq 1 assumes exponential rate of carcass removal, whereas the available data indicate a nonconstant rate of carcass removal, not an exponential rate	Add uncertainty
Seasonal variation in scavenger activity	Add uncertainty
Site variation in scavenger activity	Add uncertainty
More vigilance among searchers aware of detection trials	Bias low
Searcher swamping can alert searchers to the trial	Bias low
Inappropriate species used in searcher detection trials can be more or less conspicuous or can alert searchers to the trial	Usually bias low
Marking carcasses can alert searchers to detection trial	Bias low
Searchers typically rely on multiple cues when detecting wind turbine–killed birds, but volitionally placed whole carcasses may not provide those cues	Bias high
Detection trials performed away from the wind turbines will alert searchers to the trial	Bias low
Seasonal variation in carcass detection by searchers	Add uncertainty
Site variation in carcass detection (e.g., due to vegetation ht)	Add uncertainty

usually are intact and do not disturb the vegetation (Orloff and Flannery 1992). To my knowledge Kerlinger et al. (2000) were the only investigators who reportedly placed carcasses to simulate carcass conditions typically found by searchers. They placed only 1–2 carcasses per wind turbine to minimize the chance the searchers would get wise to the trial, and Kerlinger et al. (2000) spread feathers around the carcass, and Kerlinger et al. (2004) tossed the carcasses over their shoulders to minimize their influence on the carcasses' disposition.

Perhaps one of the largest sources of uncertainty and of potentially high bias is the choice of denominator in expressing the number of fatalities relative to the incidence of the threat posed by wind turbines in the study area. Early estimates of bird mortality expressed mortality as the number of fatalities per wind turbine, but wind turbine size has increased 25- to 63-fold since the earliest estimates were made. Comparing fatalities per turbine can introduce bias when the comparison is between 40-kilowatt wind turbines in the Altamont Pass and 2.5-MW turbines in other wind farms. The larger wind turbines will probably kill more birds per turbine but not as many per MW of rated capacity. Fatalities per MW per year emerged as the most common metric but the difference between a wind turbine's rated and actual outputs can be large and can vary by wind turbine model, location, and season. The superior mortality metric will relate number of fatalities to the kilowatt-hours since the last fatality search, because it will account for both wind turbine size and level of operations since the last fatality search. This metric would eliminate much of the noise in comparisons of mortality estimates. To use it, wind turbine operators would need to provide researchers with power output data at sufficient resolution to tally output between fatality searches.

P. Shoenfeld (unpublished report) pointed out $\bar{t}$ and p are estimated from common field experiments involving small samples of carcasses, so knowledge of these parameters may be incomplete. He concluded bias can probably be found in how these parameters relate to the number of carcasses found and the estimated number killed, but he did not attempt to characterize the bias. The common practice of using the same carcasses simultaneously in searcher detection and scavenger removal trials can confound estimated searcher detection rates if scavengers remove carcasses prior to the next fatality search. The analyst may be unable to determine whether undetected carcasses resulted from search error or scavenger removal since carcasses were placed the preceding night or day. Indeed, carcasses missed due to search error can even be removed between the time of the searcher detection trial and the follow-up visit by those who placed the carcasses.

P. Shoenfeld (unpublished report) assumed all wind turbine–killed birds fall to the ground, but this assumption is false. Whereas some injured birds are found at wind turbines, others are likely never found and their eventual deaths never factored into the mortality estimate. This type of bias is referred to as crippling bias. Some unknown number of birds survive long enough to die outside the fatality search areas, and some unknown number likely survive for extended periods, though debilitated by their injuries. Therefore, all mortality estimates will remain conservative to an unknown degree until remote detection of turbine collisions is achieved.

Kerns (2005) reported faster removal of fresh compared to frozen carcasses, yet frozen carcasses are typically deployed in scavenger removal trials. Freezing carcasses might alter odor delivery and tissue attractiveness. Also, placing whole carcasses in removal trials falsely mimics the deposition of most wind turbine–killed birds, which are often cut in half or dismembered. Pieces of bird are easier for vertebrate scavengers to remove. Furthermore, wounds sustained by blade strikes might dispense odors alerting mammalian scavengers, common ravens (*Corvus corax*), turkey vultures (*Cathartes aura*), and other birds to the urgent availability of fresh food. Carcasses placed whole might reduce the pool of available scavenger species and the number of detections by scavengers, thus biasing mortality estimates low. A solution is to cut some fresh bird carcasses in half, and to cut one or both wings off, prior to placing carcass parts in the field.

Fitting the appropriate mathematical function to the scavenger removal data can be hindered by arbitrary termination of scavenger removal trials. Right-censoring of data hides part of the scavenger removal pattern that can be fit by a model, but this practice is common because budgets have not covered trials lasting as long as some of the carcasses are detectable. The problem of right-censored data could be eliminated by running scavenger removal trials until all carcasses degrade to the point of becoming undetectable.

Left-censoring of data can bias mortality estimates low because wind turbines represented by zero fatalities may have, in truth, deposited carcasses undetected due to searcher error, scavenger removal, or crippling bias. Turbines or turbine strings assigned zero-values will not be adjusted by scavenger removal rates or searcher detection bias unless these turbines are lumped with others for a pooled mortality estimate. In the case of Smallwood and Thelander's (2004, 2005) study, mortality was estimated for each turbine string separately because the turbines were searched unequally. All turbine strings with zero fatalities were estimated to have caused zero mortality because zero divided by scavenger removal and searcher detection terms yields zero.

MANAGEMENT IMPLICATIONS

Planners, decision-makers, and wind turbine operators should regard most, if not all, existing mortality estimates at wind farms as highly imprecise and potentially biased low. Past estimates need to be adjusted before being used to predict mortality at proposed new wind farms, and when formulating fatality monitoring guidelines, mitigation measures, and mortality or mortality-reduction thresholds prompting additional measures. Past and future estimates should be transformed to number of fatalities per kilowatt-hour since the last search, but this step requires that turbine owners share power output data with researchers. Scavenger removal trials need to be designed to prevent scavenger swamping, and should use species killed or likely to be killed by the wind turbines. Trial carcasses should be checked daily or placed in front of event-triggered cameras, and some should be cut or dismembered to simulate the effects of collisions. I recommend using equation 2 or 2b to minimize biasing mortality estimates low. If using equation 1, I recommend omitting carcasses left by vertebrate scavengers from the calculation of mean days to removal, using decision rules. To compare bird mortality estimates from wind farm studies lacking estimates of scavenger removal rates, or which vary in their fatality search intervals, Figure 4 and the Appendix can be used to adjust the estimates.

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Appendix. Daily predictions of percentages of carcasses remaining since the last search or since the start of a scavenger removal trial, based on calculations from equation 5,

$$R_i = a + b \cdot \ln(i + 1),$$

applied to equation 3:

$$R_C = \frac{\sum_{I}^{i=1} R_i}{I \times 100},$$

where R_i was the percent of carcasses remaining by the ith day following the initiation of a scavenger removal trial, R_C was the cumulative carcasses remaining, I was the duration of a scavenger removal trial corresponding with the fatality search interval used during a mortality monitoring effort, and a and b were fitted parameters.

Time since last search (d)	% of carcasses remaining					
	Small nonraptor birds	Large nonraptor birds	Small raptors	Large raptors	Chickens and game hens	Rock doves
1	82	87	98	103	85	97
2	77	83	91	102	75	96
3	73	81	85	101	67	96
4	70	78	81	100	60	95
5	67	77	76	100	54	95
6	64	75	73	99	49	94
7	61	73	70	99	45	94
8	59	72	67	98	41	93
9	57	71	64	98	37	93
10	55	69	61	97	33	92
11	54	68	59	97	30	92
12	52	67	57	97	28	91
13	51	66	55	96	26	91
14	49	66	53	96	24	90
15	48	65	51	96	22	90
16	47	64	50	96	21	89
17	45	63	48	95	20	89
18	44	62	46	95	19	89
19	43	62	45	95	18	88
20	42	61	43	95	17	88
21	41	60	42	95	16	87
22	40	60	41	94	15	87
23	39	59	40	94	14	86
24	38	59	38	94	14	86
25	38	58	37	94	13	85
26	37	58	36	94	13	85
27	36	57	35	93	12	84
28	35	57	34	93	12	84
29	34	56	33	93	11	83
30	34	56	32	93	11	83
31	33	55	31	93	11	82
32	32	55	30	93	10	82
33	32	54	29	93	10	81
34	31	54	28	92	10	81
35	30	54	27	92	10	80
36	30	53	27	92	9	80
37	29	53	26	92	9	79
38	29	52	25	92	9	79
39	28	52	25	92	9	78

Appendix. Continued.

Time since last search (d)	% of carcasses remaining					
	Small nonraptor birds	Large nonraptor birds	Small raptors	Large raptors	Chickens and game hens	Rock doves
40	27	52	24	92	8	78
41	27	51	23	92	8	77
42	26	51	23	91	8	77
43	26	51	22	91	8	76
44	25	50	22	91	8	76
45	25	50	21	91	7	75
46	24	50	21	91	7	75
47	24	49	20	91	7	74
48	23	49	20	91	7	74
49	23	49	20	91	7	73
50	22	48	19	91	7	73
51	22	48	19	91	7	72
52	22	48	18	91	6	72
53	21	48	18	90	6	71
54	21	47	18	90	6	71
55	20	47	17	90	6	70
56	20	47	17	90	6	70
57	20	47	17	90	6	69
58	19	46	17	90	6	69
59	19	46	16	90	6	68
60	19	46	16	90	6	68
61	18	46	16	90	5	67
62	18	45	16	90	5	67
63	18	45	15	90	5	66
64	17	45	15	90	5	66
65	17	45	15	89	5	65
66	17	44	15	89	5	65
67	17	44	14	89	5	64
68	16	44	14	89	5	64
69	16	44	14	89	5	64
70	16	44	14	89	5	63
71	16	43	14	89	5	63
72	16	43	13	89	5	62
73	15	43	13	89	5	62
74	15	43	13	89	5	61
75	15	43	13	89	4	61
76	15	42	13	89	4	60
77	15	42	12	89	4	60
78	14	42	12	89	4	59
79	14	42	12	89	4	59
80	14	42	12	88	4	58
81	14	41	12	88	4	58
82	14	41	12	88	4	57
83	13	41	12	88	4	57
84	13	41	11	88	4	56
85	13	41	11	88	4	56
86	13	40	11	88	4	55
87	13	40	11	88	4	55
88	13	40	11	88	4	54
89	13	40	11	88	4	54
90	12	40	11	88	4	53