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Bat mortality at Ontario wind farms quantified and compared using four candidate estimator equations

Bethany G. Thurber, 5 Best Avenue, Dundas, ON L9H 5Z1, Canada *bethany.thurber@gmail.com*
Catherine B. Jardine, Birds Canada, 4841 Delta St. #206, Delta, BC V4K 2T9, Canada
J. Ryan Zimmerling, Canadian Wildlife Service, Environment and Climate Change Canada, 351 St. Joseph Boulevard, Gatineau, QC K1A 0H3, Canada

Abstract: Wind farm development is expanding globally. While wind energy is a low-cost option for new electricity supply, the impacts to wildlife populations, including bats (Chiroptera), are of ecological concern. To quantify these impacts, scientists have developed estimator equations to estimate bat mortality, which vary in assumptions related to correction factors. We compared the results of 4 estimators applied to post-construction monitoring data from Ontario, Canada, wind farms to evaluate the effects of field methods and correction factors on estimator consistency. To conduct our study, we obtained data from 21 wind farms between 2011 and 2017 for a total of 26 wind farm survey years, because some wind farms supplied fatality monitoring data in >1 year, to estimate mortality. The Ontario Ministry of Natural Resources and Forestry estimator (OMNRF) tended to be highest, while the Huso, Schoenfeld-Erickson, and GenEst estimators produced similar results. Huso and Schoenfeld-Erickson estimates tended to fall within 95% confidence intervals for GenEst, while OMNRF estimates tended to be higher than the upper confidence interval for GenEst. The results from the OMNRF estimator were consistent with the other candidates when carcass persistence times were >6.5 days but inconsistent when carcass persistence times were shorter. Our results demonstrated the degree to which mortality estimates can vary among estimators and highlight the need for a consistent estimator in comparative studies. We recommend GenEst for such studies, as this estimator can incorporate more inputs with flexibility to reflect site-specific field conditions and produces highly consistent results. Conversely, the OMNRF estimator produced consistently higher estimates than the other candidate estimators, and assumptions related to carcass persistence were regularly violated. We recommend that these limitations be acknowledged when interpreting results from this estimator and that its use be reconsidered when assumptions related to carcass persistence are not met.

Key words: bat mortality, carcass persistence, Chiroptera, correction factor, estimator, Ontario, scavenger removal, searcher efficiency, wind energy, wind turbine

Wind farm development is expanding across Canada, where the total installed capacity reached 13,413 MW in 2019 with an anticipated addition of 510 MW/year until 2040 (Canadian Wind Energy Association [CanWEA] 2020). While wind energy is among the lowest-cost options for new electricity supply and is essentially emissions-free (National Energy Board [NEB] 2017), the impacts to wildlife populations are of ecological concern (Zimmerling et al. 2013, Zimmerling and Francis 2016). To understand the magnitude of potential effects, to perform comparative studies, and to implement meaningful management action through mitigation, it is imperative that consistent and representative estimates of mortality are reported.

Wind farms represent a substantial source of anthropogenic mortality to bat (Chiroptera) populations (Cryan and Brown 2007, Cryan 2011, O'Shea et al. 2016) via direct collision with rotating turbine blades (Horn et al. 2008, Rollins et al. 2012) or, potentially, barotrauma (Baerwald et al. 2008; Figure 1). Migratory tree bat species represent the majority of wind-related fatalities at Canadian wind farms (Zimmerling and Francis 2016), and it has been hypothesized that the magnitude of mortality may yield population-level effects for these species (Cryan 2011, Baerwald et al. 2014, Davy et al. 2020). For species that are facing population declines due to unrelated pressures such as white-nose syndrome (e.g., little brown myotis [*Myotis lucifugus*]), the additional mortality risk presented by wind farms may represent an additional threat to their survival and recovery (Environment and Climate Change Canada [ECCC] 2018).

Mortality caused by wind turbines cannot be accurately determined using raw counts

Figure 1. Silver-haired bat (*Lasionycteris noctivagans*) carcass found at the base of an operating wind turbine in southern Ontario, Canada, during fall 2012 (*photo courtesy of M. Anissimoff, Environment and Climate Change Canada*).

of carcasses alone. Rather, the number of carcasses recovered during post-construction fatality monitoring represents an unknown proportion of the total mortality. There are many factors that affect carcass detectability, such as carcass removal from the survey plot by scavengers before they are detected; imperfect searcher efficiency in searched areas; carcasses that fall beyond the survey plot and are therefore not available for counting; and the distribution of areas of the survey plot that include inaccessible terrain, forest, or otherwise dense vegetation that limit a searcher's ability to locate carcasses. Several estimator equations have been developed to adjust raw counts of animal carcasses for sampling bias introduced by these factors.

Broadly speaking, estimators differ in their approaches to correct for sampling bias. For example, the Huso (2011) and the Ontario Ministry of Natural Resources and Forestry (OMNRF) estimators assume constant searcher efficiency and scavenger removal rates (Huso 2011, Korner-Nievergelt et al. 2011). Other estimators allow for these correction factors to change through time (e.g., the Generalized Estimator [GenEst]; Dalthorp et al. 2018) to reflect empirical evidence that shows decreased searcher detection and scavenger removal with declining carcass condition (Labrosse 2008, Korner-Nievergelt et al. 2011, Warren-Hicks et al. 2013). The Huso and OMNRF estimators assume that if a carcass fails to be detected during the first search opportunity following its appearance in the search plot, it will not be available for detection in subsequent searches (Huso 2011, OMNRF 2011). Conversely, Schoenfeld-Erickson and GenEst allow for carcasses to persist from 1 search opportunity to the next (Schoenfeld 2004, Dalthorp et al. 2018). Under simulated conditions, the Schoenfeld-Erickson and Huso estimators were robust to variation in imperfect detectability (Schoenfeld 2004, Huso 2011), although applications of these estimators under field conditions revealed biases when search intervals were short, relative to mean carcass persistence times (Warren-Hicks et al. 2013). It is important to recognize that there will be variation among estimators for a given fatality dataset based on the way in which each incorporates information related to searcher efficiency and carcass persistence. As well, the choice of estimator will affect how the resulting estimates are used in studies that compare fatality rates among locations, evaluate the efficacy of mitigation measures or turbine design features, or inform operational curtailment requirements from provincial or state energy regulators.

In Canada, the largest proportion of operational wind farms are in the province of Ontario (CanWEA 2020). As of December 2019, there was an installed power capacity of 5,436 MW in Ontario, 3,882 MW in Quebec, and 4,095 MW distributed throughout the remainder of the provinces and territories. Wind farms in Ontario are required by regulation to follow guidelines set by the OMNRF that detail data collection standards for pre- and post-construction phases of wind farm development (OMNRF 2011). As part of the fatality monitoring protocol in a 3-year post-construction phase, these guidelines require that raw carcass counts and correction factor trial data are collected via standardized procedures. These data are submitted to OMNRF to be archived in the Canadian Wind Energy Bird and Bat Monitoring Database (Birds Canada 2019). This has resulted in a large, standardized dataset with which to investigate mortality estimation approaches.

Our objective was to utilize the extensive bat fatality dataset from Ontario wind farms and compare the results of 4 mortality estimator equations within years and wind farms. We tested whether variability in field methods and correction factor data explain differences in estimator output to assess estimator consistency.

Although birds are exposed to mortality risk at wind farms, wind turbines are responsible for a small percentage of the mortality caused by collisions with anthropogenic structures for birds (Calvert et al. 2013). For bats, wind turbines represent one of the largest sources of anthropogenic mortality (Cryan and Brown 2007, Cryan 2011, O'Shea et al. 2016), which is why bat mortality is the subject of our analyses. We selected candidate estimators that are widely used in the United States and Canadian provinces other than Ontario, Huso (Huso 2011) and Schoenfeld-Erickson (Schoenfeld 2004), a newly developed estimator with flexibility in the way in which correction factors are incorporated, GenEst (Dalthorp et al. 2018), and the estimator that is required by the provincial regulator in Ontario, OMNRF (OMNRF 2011). Detailed equations, summaries of assumptions, and definitions for input terms for each estimator are available online in supplemental information.

Study area

Fatality data were gathered between 2011 and 2017 from wind farms throughout the province of Ontario, Canada. Twenty-one wind farms had post-construction bat fatality data that contained complete searcher efficiency and carcass removal trial data as well as information on search schedule and proportion of area searched needed to satisfy the input requirements of all candidate fatality estimators. All wind farms included in our study used a search radius of 50 m and included a minimum of 10 carcasses/correction factor trial. The wind farms were primarily situated in agricultural landscapes that included corn (*Zea mays*), soybeans (*Glycine max*), and wheat (*Triticum* spp.) and were distributed throughout the Great Lakes Region of Ontario.

Methods

The Wind Energy Bird and Bat Monitoring Database is a centralized repository for post-construction environmental assessment data collected at wind farms in Canada. This database was established by Birds Canada, CanWEA, ECCC, and the OMNRF (department name was recently changed to the Ministry of Northern Development, Mines, Natural Resources and Forestry). The Wind Energy Bird and Bat Monitoring Database is not openly available to the general public; however, the database committee seeks to support collaborative studies through data sharing supported by confidentiality agreements to protect proprietary information (Birds Canada 2019). For our study, we extracted all bat fatality data from Ontario wind farms from the database, including raw carcass counts, proportion of area searched, and results from searcher efficiency and scavenger removal trials. Bat carcass data were collected using humane and ethical protocols that followed guidelines that were accepted by the provincial regulator at the time of data collection.

While all fatality monitoring was completed according to the Ontario provincial guidelines and included standardized search effort, correction factor trial sample sizes, and search radius, there was some variation among wind farms and years in the collection of scavenger removal and searcher efficiency data. There were differences in trial carcass type, number of trial carcasses, and total number of trials conducted. Correction factor trials included frozen and fresh carcasses with various species compositions, primarily combinations of birds and bats, and in rare circumstances, solely wild birds or domestic poultry chicks. Trial carcasses included raptors ($n = 10$), birds other than raptors ($n = 602$, of which 74 were poultry chicks), bats ($n = 323$), and unknown ($n = 80$). Carcass counts and correction factor data, along with the number of turbines searched (2–44 turbines) and whether those turbines were implementing operational curtailment to mitigate mortality for birds and/or bats are reported to the Wind Energy Bird and Bat Monitoring Database separately for spring (May and June), summer (July and August), and fall (September and October) monitoring seasons. Since the majority of bat fatalities at North American wind farms is reported in late summer and early fall (Arnett et al. 2008), and because bats in Canada tend to be inactive in the winter months, we assumed that very few fatalities occurred outside of May to October.

In a given monitoring season, some wind farms implemented operational curtailment (e.g., increased turbine cut-in speed of 5.5 m/second) at a subset of monitored turbines, while other wind farms implemented operational curtailment at all monitored turbines. In the situation where fatality monitoring occurred at turbines with different operations (i.e., undergoing and not undergoing curtailment), the wind farm reported separately carcass count and correction factor data for each set of monitored turbines. In all, fatality data were reported for 37 combinations of wind farm, year, and turbine operation, which means that mortality could be estimated for 37 fatality reporting units.

To generate annual mortality estimates, we summed mortality estimates from different fatality reporting units that were applied in the same year for each wind farm. This resulted in 26 individual years of data, or 26 "wind farm years." We report mortality as the estimated number of bat carcasses/turbine/year.

Correction factors

Area searched. Proportion of area searched was calculated as the proportion of the area searched within a 50-m radius of the turbine base. The GenEst has the option to include a more comprehensive and accurate means of correcting for area searched, density-weighted proportion, which represents the fraction of carcasses expected to arrive in the searched area based on the spatial distribution of areas searched around the turbine, and the distribution of carcasses found (Huso and Dalthorp 2014, Simonis et al. 2018). Unfortunately, information on the spatial distribution of area searched was not available, and density-weighted proportion could not be calculated. Rather, we used proportion of area searched in place of density-weighted proportion for all estimators.

Searcher efficiency. For the OMNRF, Huso, and Schoenfeld-Erickson estimators, searcher efficiency (*Se*) was calculated as the sum of the proportion of carcasses recovered by each individual during trial searches multiplied by the proportion of turbines searched by that individual:

$$Se = \sum_{i=0}^{n} \frac{p_i}{P_i} \times s_i \tag{1}$$

where P_i is the number of carcasses placed in trials completed by searcher i; p_i is the number of carcasses found by searcher i during trials; s_i is the proportion of turbines that were searched by searcher i; and n is the total number of searchers.

For GenEst, searcher efficiency depends on the conditional probability of detecting a carcass on the first search and the fractional change in probability that the carcass will be detected with each successive search:

$$Se = p_i k_i^{j-1} \tag{2}$$

where p_i is the probability that a carcass will be detected on the initial carcass search following placement and ki^{j-1} is the change in carcass detectability in subsequent searches. While GenEst can allow k to vary through time, the majority of wind farms reported searcher efficiency trials in which trial carcasses were retrieved by project staff after 1 search interval. Accordingly, we were constrained to hold k constant at 0.7 (Simonis et al. 2018), which has been shown to be a conservative estimate of k based on field data of bat fatalities (D. Dalthorp, U.S. Geological Survey, personal communication).

Scavenger removal. The scavenger removal correction factor used by the OMNRF estimator, *Sc*, was defined as the probability that a carcass present during 1 search opportunity was present on a subsequent visit:

$$Sc = \frac{n_1 + n_2 + n_3 + \cdots + n_i}{n_0 + n_1 + n_2 + \cdots + n_{i-1}} \tag{3}$$

where n_0 is the number of carcasses placed in scavenger removal trials and n_i is the number of carcasses that remain after visit i.

For the Huso and Schoenfeld-Erickson estimators, scavenger removal was corrected for by including a term that described the average time a carcass remained available to be found (t):

$$t = \frac{t_1 + t_2 + t_3 + \cdots + t_i}{i} \tag{4}$$

where ti is the day on which carcass i was removed and i is the number of carcasses.

Under the legislated guidelines of the OMNRF, carcass persistence was not assessed on a daily basis, and the resulting data did not directly allow for the calculation of t. Accordingly, we fit an exponential decay function to the scavenger removal trial data that were submitted to the database to create an appropriate but simulated dataset for carcass persistence. The simulated dataset was used to compute t for

Table 1. Correction factor assumptions for each candidate estimator used to estimate bat (Chiroptera) mortality at 21 Ontario, Canada, wind farms between 2011 and 2017, for a total of 26 wind farm survey years.

	Correction factor			
Estimator	Scavenger removal	Searcher efficiency	Search interval	Area searched
OMNRF[a]	Does not change through time	Consistent through time A carcass missed is not available for detection on a subsequent search	Twice per week (average 3.5-day intervals)	Proportion of target area searched
Schoenfeld-Erickson	Decreases exponentially through time	Consistent through time A carcass missed may be available for detection on a subsequent search	Consistent through time	Proportion of target area searched
Huso	Decreases exponentially through time	Consistent through time A carcass missed is not available for detection on a subsequent search	Consistent through time May invoke an optional term that estimates the effective search interval for studies with long search intervals	Proportion of target area searched
GenEst[b]	Decreases through time based on best fit distribution	May change through time A carcass missed may be available for detection on a subsequent search	Consistent through time	Density-weighted proportion based on carcass distribution around turbine base

[a]Ontario Ministry of Natural Resources and Forestry
[b]Generalized Estimator

the Huso and Schoenfeld-Erickson estimators and scavenger removal for the OMNRF estimator; the use of simulated data also ensured that the results from these estimators were comparable. For all wind farm years, the exponential decay curve provided an acceptable fit to the data (i.e., $R^2 > 0.7$). See supplemental material for exponential decay function coefficients and fitted curves.

The GenEst includes a term for carcass persistence that describes the probability that a carcass will persist for t or more days after arrival in the search plot. Carcass persistence was modeled separately with each of 4 possible distributions that include exponential, Weibull, log-normal, and log-logistic survival for each fatality reporting unit. The most appropriate distribution for carcass persistence was selected by comparing the models using Akaike's Information Criterion (AIC). The model with the lowest AIC was then selected to compute mortality estimates for each fatality reporting unit (Dalthorp et al. 2018).

Estimators

The GenEst is a recently developed framework for estimating mortality (Dalthorp et al. 2018). The output for GenEst includes an estimate of mean fatality as well as 5% and 95% confidence intervals to provide an estimate of precision within a given monitoring season. GenEst assumes that a carcass missed during 1 search may be available for detection on a subsequent search and allows for decreasing probability of discovery with carcass age (Table 1). Season was used as a predictor for searcher efficiency and carcass persistence models, and k was 0.7. The searcher efficiency and carcass

Table 2. Akaike's Information Criterion corrected for small sample sizes and model weight for 11 *a priori c*andidate models to explain the variation in Ontario Ministry of Natural Resources and Forestry (OMNRF) mortality estimates compared to Generalized Estimator (GenEst) confidence intervals. The estimates were based on bat (Chiroptera) fatality monitoring data from 21 Ontario, Canada, wind farms between 2011 and 2017, for a total of 26 wind farm survey years.

Model	Parameters	ΔAIC_c	w_i
M3	CP[a]	0	0.33
M9	CP + turbine capacity	0.87	0.21
M10	CP + hub height	2.11	0.11
M7	CP + Se[b]	2.21	0.11
M8	CP + Ps[c]	2.21	0.11
M1	Null	4.04	0.04
M5	Turbine capacity	5.15	0.02
M4	Ps	5.16	0.02
M2	Se	6.09	0.02
M6	Hub height	6.23	0.01
M11	CP + Se + Ps + hub height + turbine capacity	8.42	0

[a] Carcass persistence
[b] Searcher efficiency
[c] Proporation of area searched

persistence models with the lowest AIC were selected for each wind farm, year, and fatality monitoring unit.

The OMNRF estimator assumes that carcass removal rates do not change over time and that a carcass missed by a searcher will not be available for detection on a subsequent search (OMNRF 2011; Table 1). The Schoenfeld-Erickson estimator assumes that carcass removal rate is exponential and that a carcass missed during 1 search may be detected during a subsequent search; that carcass age does not affect searcher efficiency and carcass removal rates; and that search intervals, scavenger removal, and search efficiency are constant through time (Shoenfeld 2004; Table 1).

The Huso estimator is similar to the Schoenfeld-Erickson estimator in that scavenger removal rates are constant through time (Huso 2011; Table 1). Like the OMNRF estimator, it also assumes that a carcass missed on 1 search is not available for detection on a subsequent search (Table 1). The Huso estimator includes an optional term that represents an estimate of the effective search interval, defined as the length of time beyond which the probability of a carcass persisting is <1%. This term is applied when a carcass search protocol has a relatively long search interval or high scavenger removal rate (Huso 2011).

The GenEst fatality estimates were derived using the "GenEst" package (v. 1.2.1) described by Simonis et al. (2018) in R 3.5.2 (R Development Core Team 2019), with 1,000 iterations and a confidence limit of 0.9. Bat mortality for the other candidate estimators was also estimated using program R.

Data analysis

We tested for differences among estimators at the wind farm year level using an analysis of variance (ANOVA) and Tukey HSD test, and pair-wise comparisons were considered significant when $P < 0.05$. We also used Pearson-moment correlation tests to describe the degree of correlation between each pair of estimators and visualized those relationships using linear regression. To evaluate estimator consistency, we applied generalized linear modeling with binomial error structure to test whether variability in correction factors, field data collection methodology, and turbine characteristics could

Table 3. Correction factor data and mortality estimates for a series of 21 Ontario, Canada, wind farms that reported bat (Chiroptera) fatality monitoring data between 2011 and 2017, for a total of 26 wind farm survey years. Carcass count is the number of bat carcasses found between May and October; searcher efficiency (proportion), carcass persistence (days), scavenger removal (proportion), and area searched (proportion) are reported as the medians from values reported to the Canadian Wind Energy Bird and Bat Monitoring Database for that wind farm and year; Huso, Schoenfeld-Erickson, Ontario Ministry of Natural Resources and Forestry (OMNRF), and Generalized Estimator (GenEst) are mortality estimates generated by each candidate estimator, presented as bat carcasses/turbine/year.

Wind farm ID	Year	Carcass count	Searcher efficiency	Carcass persistence	Scavenger removal	Area searched	Huso	Schoenfeld-Erickson	OMNRF	GenEst
A	2016	11	0.6	7.0	0.6	0.8	3.95	4.93	6.13	4.37
B	2011	52	0.8	3.5	0.3	0.3	4.73	4.53	8.38	2.73
C	2016	8	0.9	8.8	0.8	0.7	5.01	5.21	5.66	7.17
C	2017	2	0.8	10.3	0.8	0.6	1.28	1.41	1.43	0.92
D	2016	17	0.8	6.6	0.6	1.0	2.57	2.87	3.94	2.95
E	2016	57	0.8	9.2	0.8	1.0	4.77	4.19	5.00	4.47
F	2016	37	0.9	9.0	0.8	1.0	4.92	4.52	6.84	5.82
G	2016	66	1.0	9.8	0.8	1.0	6.22	6.06	6.51	0.40
H	2016	17	0.9	1.0	0.0	1.0	15.05	15.12	Infinity	5.55
I	2016	85	0.9	7.4	0.7	0.9	5.17	4.70	6.66	4.73
J	2016	8	0.7	5.4	0.5	0.9	2.67	3.15	3.97	4.02
K	2015	13	0.8	7.0	0.6	1.0	3.52	4.20	4.55	3.26
K	2016	12	0.6	4.0	0.4	1.0	6.15	7.60	13.29	4.17
K	2017	4	0.7	9.9	0.8	1.0	1.12	1.24	1.49	0.96
L	2017	2	1.0	1.8	0.1	0.5	3.91	3.92	17.12	2.45
M	2015	40	0.7	7.0	0.7	0.9	9.37	7.57	11.46	12.39
M	2016	65	1.0	9.1	0.8	0.9	7.46	7.27	8.47	10.18
N	2016	14	0.7	5.1	0.5	0.9	2.04	1.81	3.79	2.36
O	2016	95	1.0	6.1	0.6	1.0	6.59	6.43	8.01	9.94
P	2016	7	0.6	4.4	0.4	1.0	2.83	3.56	5.57	1.86
P	2017	7	0.8	9.4	0.8	1.0	1.98	2.45	2.72	1.89
Q	2015	11	0.4	7.1	0.7	0.8	4.29	2.69	5.21	5.40
R	2016	59	0.9	8.4	0.7	1.0	7.88	7.56	23.34	6.54
S	2016	31	0.8	3.1	0.3	0.9	7.85	8.17	21.24	6.64
T	2016	13	0.9	5.1	0.4	0.9	4.14	4.33	6.14	3.24
U	2016	3	0.8	6.6	0.6	0.9	2.86	3.20	5.09	2.04

be used to predict when the OMNRF estimates were within GenEst confidence intervals. The binomial response was "1" when the OMNRF estimates were within the GenEst confidence intervals and "0" when the OMNRF estimates were higher or lower than the GenEst confidence intervals for each fatality reporting unit. The Tukey HSD tests revealed that estimators Huso, Schoenfeld-Erickson, and GenEst produced results that were not significantly different from one another, so we assumed that if the OMNRF estimates were within the GenEst confidence intervals, they were also consistent with the results from Huso and Schoenfeld-Erickson.

To explain the variation in OMNRF consistency with the other candidate estimators, we constructed 11 *a priori* models to test our hypotheses related to correction factors, field data collection methodology, and turbine characteristics (Table 2). Variables included searcher efficiency and carcass persistence as medians for a fatality reporting unit, proportion of area searched for a fatality reporting unit, turbine power capacity (MW), and hub height (m). Wind farms included in our study tended to be composed of a single turbine model. Project N, however, was composed of two turbines with different capacities and hub heights; we therefore used the average power capacity and average hub height for this wind farm. Model fit was visually assessed by plotting fitted values versus residuals.

We used Akaike's Information Criterion corrected for small sample sizes (AICc) to assess support among candidate models (Hurvich and Tsai 1989). The most parsimonious model was the one with the lowest AICc, but models within 2 AICc units were considered competitive (Burnham and Anderson 2002). All statistical analyses were conducted in R 4.0.5 (R Development Core Team 2021); package "AICcmodavg" was used to conduct model selection (Mazerolle 2019).

Results

There was sufficient data for fatality search protocol and correction factors to satisfy the input requirements of all 4 candidate estimators for data collected at 21 Ontario wind farms between 2011 and 2017, for a total of 26 wind farm survey years (Table 3). The OMNRF estimator produced the highest estimates in 19 wind farm years, while GenEst frequently produced the lowest estimates (n = 14 wind farm years). In 1 wind farm year, the OMNRF estimator encountered a simulated value of 0 for scavenger removal (i.e., all carcasses were removed on the first day of scavenger removal trials), and therefore a denominator of 0 caused the estimator to fail; the other estimators did not experience this issue (Table 3).

In 37 fatality reporting units, most wind farms reported an average search interval of 3.5 days (n = 36). Fatality searches were completed once per week for the remaining fatality monitoring unit. Proportion of area searched was also consistent among fatality monitoring units, ranging between 0.31 and 1.00 with median 0.93. Searcher efficiency reports were 0.39–1.00, median 0.80. Carcass persistence was the most variable field method or correction factor among fatality monitoring units, ranging 1.00–11.80 days, median 6.60. Despite the relatively high variation, carcass persistence times exceeded the average search interval in 79% of fatality monitoring units, such that the majority of carcasses were deposited and persisted in the searched area to be identified by field staff that were conducting the fatality monitoring.

In pair-wise comparisons, results from the Huso and Schoenfeld-Erickson estimators were strongly and positively correlated (Pearson's product-moment correction, $r = 0.97$, $P < 0.01$; Figure 2). While estimates based on the OMNRF estimator were positively correlated with those by Huso ($r = 0.71$, $P < 0.01$) and Schoenfeld-Erickson ($r = 0.74$, $P < 0.01$), the slopes of the lines of best fit were <0.30 (Table 4). GenEst results were moderately associated with all other estimates (r = 0.39–0.61), although the slope for the line of best fit with the OMNRF estimator was just 0.21 (Table 4).

Huso and Schoenfeld-Erickson estimates were within the confidence intervals for GenEst in 76% and 78% of fatality monitoring units, respectively, while 59% OMNRF estimates were within range and tended to be higher than the other candidates (Figure 2B). An ANOVA corroborated these observations; while there was significant variation among the estimators (df = 3, $F = 3.32$, $P = 0.0257$), a post-hoc Tukey HSD test showed that the OMNRF estimates tended to be higher than all other candidate estimators (Table 4). There was no difference among GenEst, Huso, and Schoenfeld-Erickson (Table 4).

The most parsimonious model to describe when the OMNRF estimates were within GenEst confidence intervals included only carcass persistence (Table 2). For fatality monitoring units in which carcass persistence was long (e.g., >6.5 days), the OMNRF estimates were more likely to be within the confidence intervals than in fatality monitoring units when carcass persistence was shorter (e.g., 4 days; Figure 3A). The OMNRF estimates tended to decrease as carcasses persisted for longer in the searched area (Figure 3B).

Discussion

All of the wind farms that were included in our study followed the OMNRF Renewable Energy Approval guidelines for post-construction

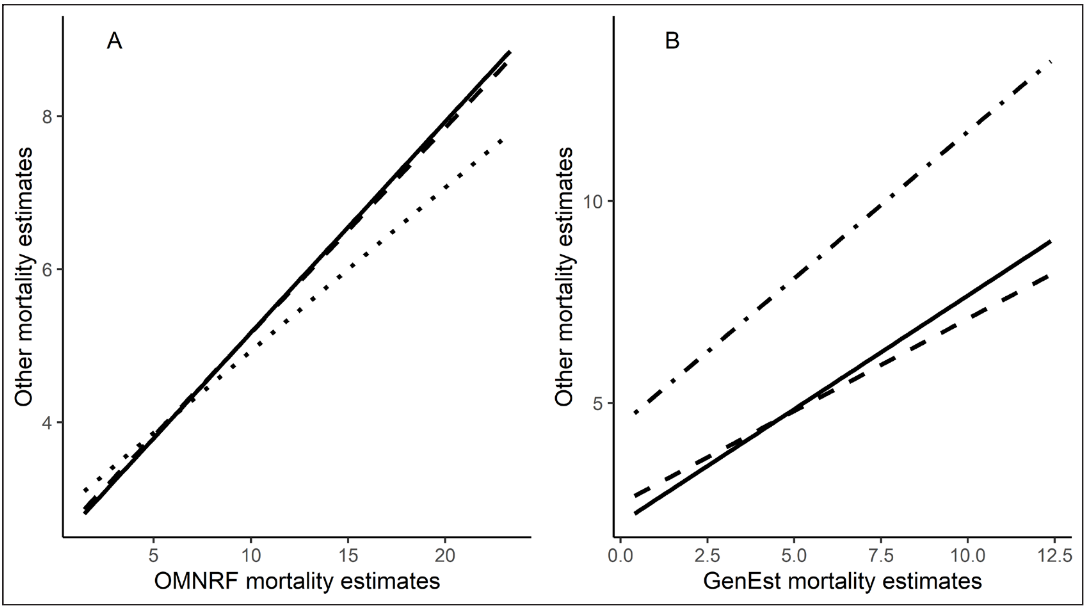

Figure 2. Comparisons of bat (Chiroptera) mortality (bat carcasses/turbine/year) between 4 estimator equations. (A) Plots of the lines of best fit for Huso (solid), Schoenfeld-Erickson (hatched), and GenEst (dotted) vs. the Ontario Ministry of Natural Resources and Forestry (OMNRF) estimates. (B) Plots of the lines of best fit for Huso, Schoenfeld-Erickson, and OMNRF (alternating hatches and dots) vs. Generalized Estimator (GenEst) estimates. Each estimator was applied to a common dataset of bat fatality collected at 21 Ontario, Canada, wind farms between 2011 and 2017, for a total of 26 wind farm survey years.

Table 4. Pair-wise comparisons of 4 candidate mortality estimators by Tukey HSD test and linear regression. Tukey HSD test outputs include difference in observed means, lower and upper endpoints of interval, and adjusted *P*-value. The line of best fit is the result of regressing the mortality estimates of each candidate estimator against the others. The estimates were based on bat (Chiroptera) fatality monitoring data from 21 Ontario, Canada, wind farms between 2011 and 2017, for a total of 26 wind farm survey years.

Estimator comparison	Difference in observed means	Lower endpoint of interval	Upper endpoint of interval	Adjusted *P*-value	Line of best fit
Huso – GenEst[a]	0.17	-0.09	0.43	0.31	0.61x + 2.20
OMNRF[b] - GenEst	0.55	0.29	0.81	<0.05	0.21x + 2.79
Schoenfeld-Erickson - GenEst	0.19	-0.07	0.44	0.22	0.51x + 2.68
OMNRF - Huso	0.38	0.12	0.64	<0.05	0.28x + 2.41
Schoenfeld-Erickson - Huso	0.02	-0.24	0.27	0.10	1.00x - 0.05
Schoenfeld-Erickson - OMNRF	-0.36	-0.62	-0.10	<0.05	0.27x + 2.48

[a] Generalized Estimator
[b] Ontario Ministry of Natural Resources and Forestry

monitoring (OMNRF 2011). Despite the resulting similarities in data collection methods, we found variation in mortality among estimators within wind farm years, which highlights the importance of correction factors and how they are incorporated into mortality estimates. In particular, our results demonstrate that assumptions related to carcass persistence affect the consistency of mortality estimates.

Other studies have shown consistency between the Huso and Schoenfeld-Erickson estimators when search intervals are shorter than the length of time that carcasses persist in the searched area (Huso 2011, Warren-Hicks et al. 2013). These estimators will deviate in their results when the search interval is long because

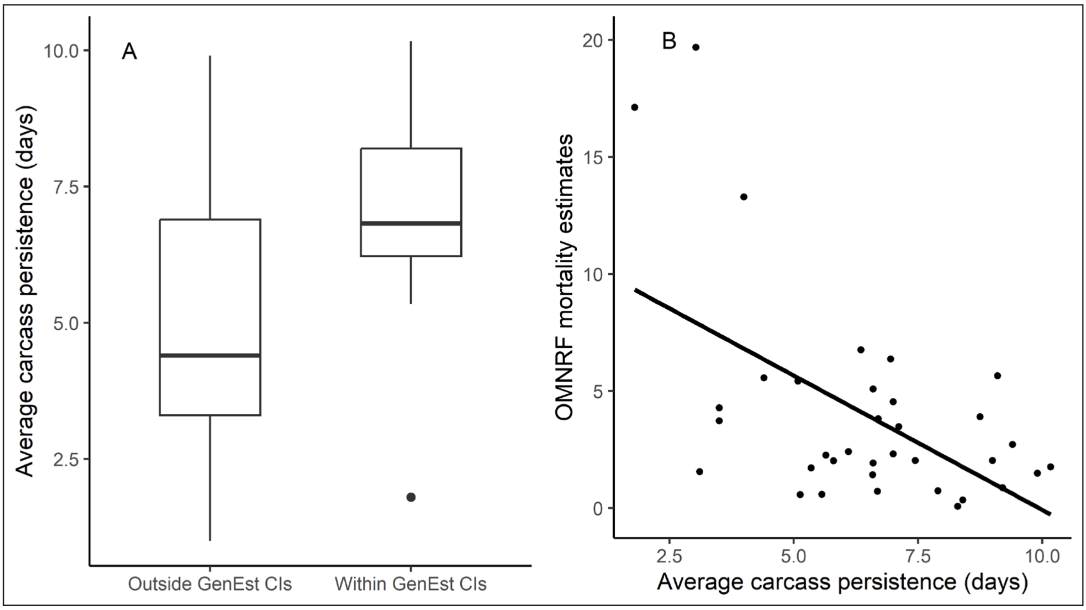

Figure 3. (A) Bat (Chiroptera) carcass persistence times (days) for fatality monitoring units in which the Ontario Ministry of Natural Resources and Forestry (OMNRF) estimator results were within (*n* = 22) or outside (*n* = 15) of the GenEst confidence intervals. (B) OMNRF mortality estimates vs. carcass persistence, including line of best fit. Bat fatality data were collected at 21 Ontario, Canada, wind farms between 2011 and 2017. There were 37 fatality monitoring units in 26 wind farm survey years.

the Huso estimator can leverage an optional term to represent an estimate of the effective search interval, defined as the length of time beyond which the probability of a carcass persisting is <1% (Huso 2011). Given that all the wind farms included in our study used short search intervals, this optional term was not invoked.

Estimator accuracy and consistency are equally important to understand mechanisms of wildlife mortality at wind farms. A number of factors contribute to the accuracy of any fatality estimation approach, including the use of a sufficiently large search area, short search intervals, and highly efficient searchers (Huso 2011, Korner-Nievergelt et al. 2011, Santos et al. 2017). Empirical studies of bat mortality show that rates of searcher efficiency and scavenger removal are not constant through time (Kerns et al. 2005, Warren-Hicks et al. 2013). Scavenger removal rates are generally higher in high visibility ground conditions (Kerns et al. 2005, Smallwood 2013) for fresh carcasses compared to decayed carcasses (based on studies of bird fatality; Labrosse 2008) and have been shown to follow a Weibull distribution (Warren-Hicks et al. 2013). The Huso and Schoenfeld-Erickson estimators, however, assume that scavenger removal is exponentially distributed. For GenEst, carcass persistence is not limited to a particular distribution. Rather, scavenger removal trial data are modeled using each of 4 candidate distributions, and the distribution that best fits the data is selected based on model comparison via AIC (Simonis et al. 2018). In our study, carcass persistence was exponentially distributed in 23 of 37 fatality monitoring units, followed by lognormal (*n* = 8), loglogistic (*n* = 3), and Weibull (*n* = 3). The OMNRF estimator was the only estimator to not include a function of increasing carcass persistence over time. It follows, then, that variation in carcass persistence best predicted when the OMNRF estimates were consistent with the other candidate estimators.

We found that the Huso, Schoenfeld-Erickson, and GenEst estimators produced consistent results when search intervals were relatively short, as was the case with the field data used in this study. Given that there is not yet a widely accepted carcass persistence distribution curve for bats (Warren-Hicks et al. 2013), assumptions related to carcass persistence could create additional conditions for estimator inconsistency. These assumptions, however, were violated for the Huso and Schoenfeld-Erickson estimators in ~1/3 of the wind farm years, yet the resulting estimates were similar to one another and to GenEst, where distribution curves were selected based on fit. This suggests that the distribution for carcass persistence can deviate from the assumed exponential and that search interval likely affects consistency between Huso and Schoenfeld-Erickson at the wind farm year level.

Conversely, carcass persistence did explain the variation between the OMNRF and GenEst estimates. When carcass persistence was longer, the OMNRF estimates were more likely to fall within the GenEst confidence intervals than when carcass persistence was shorter. The shape of the carcass persistence distribution curve, however, was not a contributing factor, as wind farms for which there was inconsistency between these estimators had carcass persistence distributions that were modeled as Weibull, exponential, or log-normal.

To date, GenEst has only been applied in technical reports (e.g., Rabie et al. 2021), but it produced results consistent with the widely used Huso and Schoenfeld-Erickson estimators, which lends to its credibility as a reliable candidate for mortality estimation. Importantly, GenEst can incorporate variability in fatality search protocols and can accept more inputs to adjust for sources of bias than other estimators. Although we could not capitalize on 2 particular inputs that capture variability in field methods, the raw data to determine these inputs are often collected by developers but are not required for submission to the Canadian Wind Energy Bird and Bat Monitoring Database. Inclusion of density-weighted proportion to describe the area searched will increase the utility of this estimator in comparative studies, as it will allow developers to more comprehensively estimate mortality in terrain that is difficult to search, at wind farms with variable turbine heights, and would account for carcasses that fall beyond the searched area. Accounting for carcasses that fall beyond the searched area (e.g., 50-m search radius) is important, given that 18% of bat carcasses were found >50 m from turbines across Canadian wind farms (Zimmerling and Francis 2016) and because carcasses may fall >60 m depending on local wind conditions (M. M. Huso, U.S. Geological Survey, unpublished data). Despite the facts that the wind farms in our study were able to achieve high proportions of area searched and the proportions of recovered carcasses falling within 5-m distance bands began to decrease beyond 40 m from the turbine base, some carcasses were undoubtedly missed. Furthermore, GenEst can be tailored to local differences in carcass removal rates and searcher efficiency, has a built-in calculation of precision, a key component missing from other estimation methods, and is implemented using an open source R package with a user-friendly graphical user interface. This offers a streamlined approach to fatality estimation, including the potential for time and cost savings during the data analysis phase of post-construction monitoring.

Increasingly, mortality estimates from wind facilities are being used to evaluate landscape-level questions (e.g., to quantify regional levels of mortality [Davy et al. 2020] or to test for effects of variation in turbine specifications on mortality [Choi et al. 2020], efficacy of mitigation [Davy et al. 2020; J. R. Zimmerling, ECCC, unpublished data]), or efficacy of pre-construction acoustic survey data to predict mortality [Solick et al. 2020]). These studies rely on the assumption that the reported mortality estimates are accurate and that variation in mortality levels between wind farms is a result of project characteristics and not due to inconsistencies in the equations used to derive those estimates. We acknowledge that precision among estimators is not an indication of accuracy. Likewise, the use of a single estimator does not guarantee accuracy but, rather, improves precision. It is therefore imperative that a consistent estimator be used in comparative studies. To facilitate this, regulators should ensure that raw post-construction monitoring data are collected and made available so that mortality estimates can be re-calculated for all wind farms using 1 estimator in comparative studies. For Canadian wind farms, these raw data should be submitted to the Wind Energy Bird and Bat Monitoring Database with the fatality monitoring correction factor and carcass count data to facilitate these analyses.

Management implications

As regulators work to establish a standardized approach for estimating mortality, we encourage stakeholders to consider the implications of all approaches. Collectively, the more traditional options such as the OMNRF estimator used in Ontario and the Huso and

Schoenfeld-Erickson estimators used elsewhere offer a simple approach to correct for some factors that are known to bias estimates of fatality: carcass removal by scavengers and imperfect searcher efficiency. The relatively new GenEst produced consistent results with the Huso and Schoenfeld-Erickson estimators, but with a key benefit for wildlife managers: confidence intervals to indicate estimate certainty, which can be invaluable for determining appropriate mitigation measures. On the other hand, the OMNRF estimator consistently produced the highest mortality estimates and was higher than the upper GenEst confidence limit in 41% of fatality monitoring units. This is of particular interest, as Ontario has the highest amount of installed wind energy capacity in Canada, as well as the highest mortality rates in comparison to other provinces and territories (Zimmerling and Francis 2016). Based on these results, our recommendations are 2-fold. Although we recognize that the use of the OMNRF estimator is a regulatory requirement in some jurisdictions, we first recommend that its use should be reconsidered when assumptions related to carcass persistence are not met, as this leads to inconsistency and bias. Second, because GenEst can incorporate more inputs with flexibility to reflect site-specific field conditions, includes a built-in indication of precision, and produces highly consistent estimates, we recommend its use in comparative studies.

Supplemental material

Supplemental material can be viewed at https://digitalcommons.usu.edu/hwi/vol16/iss1/9.

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Associate Editor: Larry Clark

BETHANY G. THURBER earned an M.Sc. degree in ecology from the University of Western Ontario in 2010. In the 10+ years that have followed, she has specialized in using remote sensing technologies like radar and radio-telemetry to track landscape scale movements of migratory birds all over the world, with a focus on movements around airports, wind farms, and oil and gas installations. Currently, she is a self-employed wildlife biologist, working on issues that range from measuring long-term changes in waterfowl migration phenology to mortality mitigation for migratory birds and species at risk bats at wind farms in Canada.

CATHERINE B. JARDINE is a data analyst at Birds Canada. She manages the National Wind Energy Bird and Bat Monitoring Database and is responsible for the recruitment, standardization, and management of post-construction monitoring data collected at facilities in Canada.

J. RYAN ZIMMERLING is manager of migratory birds and wildlife health for the Canadian Wildlife Service of Environment and Climate Change Canada and has >20 years of experience as a wildlife biologist. He earned a Ph.D. degree in zoology from the University of Western Ontario. His current research is focused on the assessment and mitigation of impacts of wind turbines on bats and other wildlife in Canada.