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Original Research Article

# The management utility of large-scale environmental drivers of bat mortality at wind energy facilities: The effects of facility size, elevation and geographic location

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ABSTRACT

Wind power development can cause direct mortality of both birds and bats through collisions with turbines, but the estimates of mortality necessary to evaluate the impact of this mortality are unavailable for many facilities and regions. We used monitoring surveys from the majority of facilities in a contiguous region spanning 800 km of southwest-northeast distance and almost 900 m of elevation (Quebec, Canada) to produce estimates of mortality per facility. The distribution of these estimated mortalities is skewed low with more than two thirds of facilities having annual mortalities of less than 50 individuals. We then used this set of estimated annual mortalities to explore how changes in installed capacity (megawatts), elevation and geographic position affected estimated annual mortality, with the goal of providing guidance to conservation mangers attempting to find strategies for minimizing mortality. More installed capacity (MW) correlated with higher mortality, but installed capacity alone was a poor predictor of estimated mortality. Medium-sized facilities were the best management strategy to minimize per MW mortality. Mortality decreased with increasing elevation and decreased from southwest to northeast within this region. The cumulative effects of this mortality have the potential to be devastating for bats, particularly migratory species, which account for the majority of carcasses observed. Our results also highlight the necessity of monitoring at all facilities in order to identify the small number of high mortality facilities for effective application of mitigation measures.

## 1. Introduction

Bats play a key role in Earth's ecosystems. In North America, ecological services provided by bats have been valued at \$3.7 to \$53 billion USD per year (Boyles et al., 2011). They are major predators of nocturnal insects and contribute to the regulation of epidemic outbreaks in agricultural fields and managed forests, as well as to the control of insects transmitting diseases to humans (Reiskind and Wund, 2009). Despite both their ecological and economic importance, however, bat populations are declining in many regions and it is essential that conservation measures effectively address mortality caused by human activities. In the north-eastern part of the continent alone, six species of bat have demonstrated a degradation of their

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conservation status since 2000 (Hammerson et al., 2017). To date, many threats and limiting factors facing bat populations have been identified, including white-nose syndrome, colony eradication, disturbance during hibernation, habitat loss, changes in forest structure, chemical contamination, decreases in insect abundance and wind turbines (Boyles and Brack, 2009; COSEWIC, 2013; Frick et al., 2010; Hickey et al., 2001; Johnson et al., 1998; Kunz et al., 1977; Mann et al., 2002).

Negative effects of wind power development include a loss or alteration of habitat caused by the construction, installation, and operation of wind power facilities (Kuvlesky et al., 2007) and direct mortalities of both birds and bats caused by collisions with the turbines themselves, principally the spinning blades, which are estimated to kill hundreds of thousands of bats annually (Arnett et al., 2008; Arnett and Baerwald, 2013; Hayes, 2013; Kunz et al., 2007; Orloff and Flannery, 1992; Smallwood, 2013). These numbers, combined with the swift and continued growth of the wind industry worldwide, have caused growing concern that some bat populations might be pushed toward extinction (Frick et al., 2017). The cumulative effects of bat fatalities at wind farms must, therefore, urgently be assessed in order to determine their impacts on bat populations.

However, estimating cumulative impacts is extremely difficult for two reasons. Firstly, accurate estimates of bat population sizes are lacking for most species world-wide (see, however, Frick et al., 2017). Secondly, accurate estimates of mortality at large scales are essential, and important variability in mortality estimates between facilities may impair our capacity to produce consistent estimates of mortality across large areas. In addition, although general guidelines are available (e.g., see Strickland et al., 2011), survey methodologies frequently differ between facilities or regions, further complicating our ability to accurately estimate cumulative impacts. Consequently, the three different studies that have estimated bat mortality caused by wind energy production in the contiguous United States reported results that ranged from 196 000 to 880 000 individuals killed annually (Arnett and Baerwald, 2013; Hayes, 2013; Smallwood, 2013).

Estimation of mortality at wind farms is a significant challenge. The number of carcasses observed around the bases of turbines represents a varying proportion of total mortality. For example, vegetation may influence the probability of carcass detection by observers, and predators may remove carcasses prior to the survey, thus reducing their probability of persistence through time. The number of observed carcasses must be adjusted using site- and year-specific correction parameters (Huso, 2011; Rogers et al., 1977). Furthermore, a wider understanding of bat mortality at wind farms should correct for potential bias due to different methodologies across facilities.

In addition, environmental factors may also influence mortality at spatial scales ranging from turbine-scale to regional- or continental-scale. For example, mortality is higher closer to roosting sites (Ferreira et al., 2015), maternity sites (Piorkowski and Connell, 2010), or migration corridors (Baerwald et al., 2014). One recent study found that mortality was inversely correlated with the proportion of grassland habitat surrounding wind energy facilities (Thompson et al., 2017). However, the specific role of environment in modifying mortality rates remains largely unexplored at these different spatial scales, as does the potential to mitigate impacts by avoiding higher-risk locations or habitats.

A better understanding of the impacts of environmental factors at the spatial scale of provinces/states is particularly important because this is the scale at which much of the regulation and management decisions are made. At a regional scale, geographic variables are often used to approximate habitat patterns. For example, elevation and latitude are responsible for many well-documented patterns of species distribution and ecology (e.g., Lomolino, 2001; Willdenow, 1805). Fatalities of bats have already been noted to decrease with increasing latitude in one region, the Northeastern Deciduous Forest (Arnett and Baerwald, 2013). A clear understanding of what correlates with high-risk facility placement at a regional scale could contribute to better regulation and management decisions, and ultimately favor the sustainable development of this industry.

To date, the majority of North American studies on bat mortality in wind-energy facilities have been conducted in the United States (but see Zimmerling and Francis, 2016). However, Canada is increasingly becoming a major player in wind energy production; the country is now ranked ninth in the world for its total installed onshore capacity with 12 816 MW as of December 2018 (Canadian Wind Energy Association, 2018). Canada mostly regulates wind farm projects at the provincial scale, and among the provinces, Quebec accounts for a third of the country's installed capacity (3882 MW in 2018). Additionally, in Quebec post-construction mortality surveys are required to be conducted using a standardized methodology. However, only one published study documented bat fatalities in this vast province and results were based on only three facilities whereas the province now has more than 30 facilities in operation (Zimmerling and Francis, 2016).

In this paper, we took advantage of the unique opportunity presented by having mortality surveys carried out using a standardized methodology at all facilities in a large contiguous area to document bat mortality within and across 30 wind farms. Lastly, we evaluated the effects of facility size, geographic position and elevation on annual bat mortality in order to determine whether these parameters could be used to inform management decisions. This study contributes to a better understanding of patterns in bat mortality associated with wind-energy facilities and helps managers to design effective and targeted mitigation measures to preserve threatened bat populations.

## 2. Material and methods

Eight bat species are found in Quebec. Five are resident in the province, roost in colonies in caves, mines, or buildings and are active from May until October: the northern myotis (*Myotis septentrionalis*), the eastern small-footed myotis (*Myotis leibii*), the little brown myotis (*Myotis lucifugus*), the tri-colored bat (*Perimyotis subflavus*) and the big brown bat (*Eptesicus fuscus*) (Clare et al., 2014; Fabianek et al., 2015, 2011; MMACH, 2018). Three species are tree-roosting and migratory, spending only the summer months in this region: the silver-haired bat (*Lasionycteris noctivagans*), the hoary bat (*Lasiurus cinereus*) and the eastern red bat (*Lasiurus borealis*). These migratory species are generally first detected in Quebec in May and gone by the end of September (MMACH, 2018). Quebec's wind energy facilities are distributed across almost 5 degrees of latitude and 10 degrees of longitude (almost 1000 km of distance southwest-northeast) and include facilities ranging from 0 to 900 m in elevation (Fig. 1).

### 2.1. *Carcass surveys and data compilation*

All data were gathered according to a standardized protocol published by the provincial government in Quebec in 2008 (MRNF, 2008) and subsequently updated (MDDEFP, 2013). This protocol stipulated that any new facility built was to conduct carcass surveys, carcass persistence trials and searcher efficiency trials seasonally for the first three years of operation and submit reports containing both results of surveys and trials as well as estimated fatalities to the provincial government. Among the differences between the original and updated protocols, the search interval between visits was reduced from 7 to 3 days, the surveyed area was reduced from 120 × 120 m to 80 × 80 m and the spacing between transects was reduced from 10 to 5 m. All details regarding the methodology can be found in the published protocols (MDDEFP, 2013; MRNF, 2008).

Searcher efficiency ($p$) trials were conducted during each season of monitoring (spring, summer and fall) using decoys (small bird- or mouse-type decoys). Each searcher efficiency trial involved placing the decoys inside the sampling plots at a facility before a regularly scheduled carcass search; decoys were placed by someone not involved in carrying out the carcass search. From 1 to 30 decoys were used per trial, with the majority of trials using between 5 and 10. No field data from Quebec exist that would allow estimation of the parameter describing how searcher efficiency changes through time for carcasses that are missed during a search (bleed-through sensu Wolpert). We therefore adopted the value of 0.674 suggested by Dalthorp and Huso (2017) as the best approximation.

Carcass persistence trials were also carried out once during each season of monitoring by placing carcasses (small mouse and bird carcasses) below turbines in areas to be searched and monitoring them until disappearance or for a maximum of 28 days. Fitting a model to the raw data and determining the underlying distribution is the best way to summarize carcass

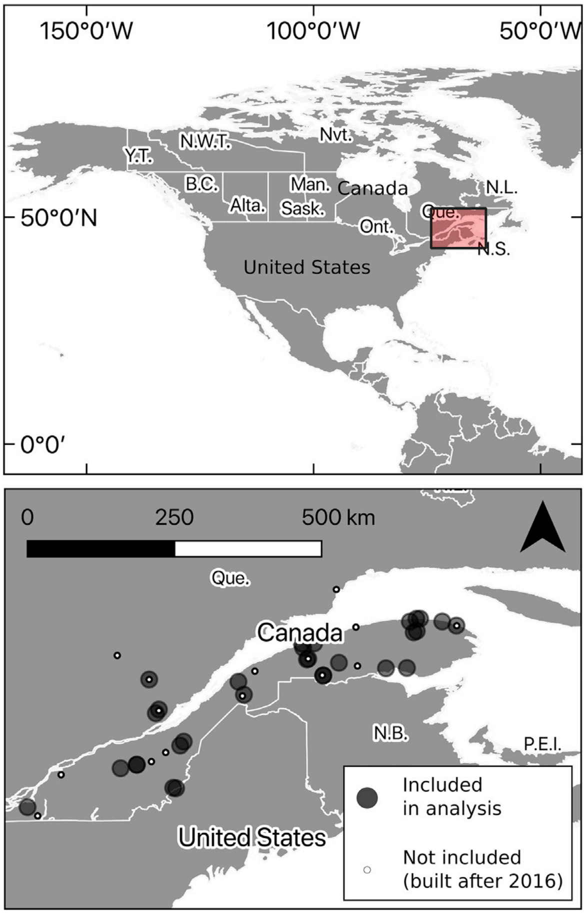

**Fig. 1.** Map of the study area in the province of Quebec (Canada). Wind-energy facilities are shown, distributed from the southwest to the northeast in the province.

persistence (Bispo et al., 2013). Very few surveys (15 of 65) reported raw data, however, so we parameterized a exponential distributions using the reported means ($\bar{t}$) and associated variances.

We estimated a spatial correction factor ($a$) that combined three sub-parameters: 1) the proportion of turbines monitored, 2) the proportion of area under each turbine that was included in carcass searches, and 3) the proportion of carcasses expected to fall into this searched area. We identified conservative values for the proportion of carcasses falling into concentric circular zones around the turbine base (60% from 0 to 40 m and 40% from 40 to 80 m) based on the published literature (Hull and Muir, 2010; Huso and Dalthorp, 2014; Korner-Nievergelt et al., 2016; Zimmerling and Francis, 2016).

The dataset available to us therefore comprised 65 annual carcass monitoring surveys carried out at 30 wind energy facilities (Fig. 1). This represents all but three facilities in operation in the province during and prior to 2015, although additional facilities have been built since (Fig. 1). The number of carcasses found per season, the searcher efficiency ($p$), the carcass persistence, a spatial correction factor ($a$) and an ordered sequence of consecutive search intervals ($I$) were extracted from each available report. Sometimes, parameters were missing for a particular survey (e.g., no trial for searcher efficiency carried out in the spring or no carcass persistence trial reported) and the nearest comparable estimate was used (e.g., results from a trial carried out in another year, or from a nearby facility; see Supplementary Material A for details).

## 2.2. Mortality estimates

### 2.2.1. Mortality estimates at the facility scale

We used the statistical package Evidence of Absence (eoa) to implement the Dalthorp estimator because low numbers of carcasses were found overall. Fewer than 10 surveys reported more than 15 bat carcasses and there were a large number of zero observations with 26 of 65 surveys finding no bat carcasses at all (Dalthorp, 2016; Huso et al., 2015; R Core Team, 2016). As suggested by Dan Dalthorp (personal communication), we used a three-step strategy to combine the season-specific correction factor estimates with reported carcass counts to produce estimates of mean annual mortality for each facility*-year combination. First, we used the Single Year Module to estimate a facility-specific global probability of detection ($g_{season}$) for each of the three monitored seasons (Spring [March 15th – June 1st]; Summer [June 1st – Aug 1st]; and Autumn [Aug 1st – Nov 15th]). Next, we used the Multiple Class Module to combine these three seasonal probabilities of detection into a single yearly probability of detection for each facility ($g_{year}$) using the expected proportion of carcasses arriving in each season to weight (DWP) the relative contributions of the seasons. We weighted the two monitoring seasons that covered reproductive and migratory periods (Summer and Autumn) with 45% of annual carcasses each, and the Spring period at 9% to represent early arriving or awakening individuals. The remaining 1% of annual mortality was attributed to the ‘winter’ falling outside of monitored periods. We recorded the median point estimate (M-50) from the discrete posterior distribution produced at this step, along with the yearly probability of detection and associated 95% confidence intervals. We then used the Multiple Years Module along with carcass counts (yearly totals) and the $\alpha$ (Ba) and $\beta$ (Bb) parameters describing the distribution of yearly probabilities of detection ($g_{year}$) to produce an estimate of the average annual fatality rate ($\lambda$) and associated 95% Credible Intervals for each facility using all years of available data (years weighted equally; $\rho = 1$).

### 2.2.2. Mortality estimates at the regional scale

We estimated 95% Credible Intervals on combined annual mortality for the thirty facilities included in this study using the Multiple Class Module of the Evidence of Absence package. Although this module is designed to combine classes such as different types of vegetation, it can also be used to produce a single regional estimate using facilities as ‘classes’, since all facilities were monitored. This estimate weights the contribution of each facility ($\rho$) by the number of turbines installed. We also tried weighting facilities by estimated mortality; this produced results that were consistent with those obtained using size of facility and we therefore present only the results weighted by facility size. We then calculated mortality per MW using the total installed capacity accounted for by the facilities in this study (2777 MW). We used this per MW estimate of mortality in our region and the installed capacity per year to calculate one regional estimate for each of the 17 years (1999–2016; Canadian Wind Energy Association, 2016; TechnoCentre éolien, 2017). Lacking any species-specific correction parameters, we assumed that the proportion of carcasses found per species reflected the proportion of bats killed of that species to describe general trends of mortality per species in the region.

## 2.3. Large-scale environmental drivers of mortality

We then extracted installed capacity (megawatts) and geographic position directly from facility reports and elevation from the provincial government’s digital elevation model using ArcGIS (Ministère d’énérgie et ressources naturelles, 2009). Pairwise analysis of explanatory variables revealed that longitude and latitude co-varied too tightly to include both in analyses (the most northerly facilities were also those furthest to the east; coefficient of variation 0.89). The facilities in our region were distributed along a gradient not only from south to north but simultaneously from west to east that follows the geography of the Saint Lawrence river, estuary and gulf; this gradient of geographic location represents a dominant geographic pattern in the region (Fig. 1). We therefore used a ‘distance to the northeast’ variable representing the linear distance from a chosen origin in the southwest of the province near Montreal (45.5 N, –73.5 W). This variable therefore represents geographic position along a southwest-northeast gradient; small values indicate facilities in the southwest of the province and larger values indicate increasing distance to both the north and east.

In order to examine the effects of facility size, elevation and geographic position on estimated mortality, we used the mortality estimates per facility (annual mortality estimated per facility for $n = 30$ facilities as the median of a discrete posterior distribution based on multiple years of surveys) as the response variable in an analysis of environmental factors. Since there is a portion of the variance in point estimates of mortality that depends on detection probability, we weighted mortality estimates within this analysis using global detection probabilities. Mortality estimates were distributed in a skewed manner with many low values and Poisson models were extremely over dispersed ($\widehat{c}$ values $> 30$) so we used a negative binomial distribution with a log-link function. We tested which combination of our three environmental factors (MW, elevation and geographic gradient) best explained variations in mortality using a model selection framework based on corrected Aikaike's Information Criterion ($AIC_c$). We created a set of 8 models (Table 1); all models included a weights argument based on the global probability of detection at that facility (a relative ranking of global probabilities of detection). We fit a global model using the glm.nb function (MASS package) in order to estimate a global shape parameter (theta), verified model suppositions graphically, then used this theta parameter to refit negative binomial models using the glm function and calculate $AIC_c$ values, delta $AIC_c$, and model weights for our candidate model set (Table 1). We retained all models having a $\Delta$ $AIC_c$ of less than 2 (Burnham and Anderson, 2002) and used the AICcmodavg package (Mazerolle, 2015) to produce model-averaged estimates of parameters and predicted values.

## 3. Results

### 3.1. Carcass surveys and correction factors

The majority (72%) of the 268 carcasses found during surveys were migratory bats (Supplementary Material B). Of these, the most common species found was the hoary bat (47% of carcasses, found at 21 out of 30 facilities), while the silver-haired bat accounted for 18% of carcasses and the eastern red bat 6%. The three species of resident bat found during surveys (the big brown bat, the northern myotis and the little brown bat) together accounted for 18% of carcasses found overall, and were found at fewer facilities than the migratory species (7 out of 30 facilities for all resident species combined; Supplementary Material B). Two resident species (the tri-colored bat and the eastern small-footed myotis) were never identified in carcass surveys, although one individual of the tri-colored bat was detected outside of scheduled carcass surveys. Most carcasses were found in July and August (69%).

Searcher efficiencies ranged from 0.1 to 1; mean seasonal efficiencies were between 0.5 and 0.7. Reported carcass persistence values ranged from 0 to 25 days; mean values ranged from 3 to 8 days. Spatial correction factors ranged from 0.11 to 0.57 (mean ± 1 sd: 0.27 ± 0.11). Seasonal temporal correction factors ranged from 0.18 to 1 (mean ± 1 sd: 0.84 ± 0.18).

### 3.2. Mortality estimates

#### 3.2.1. Mortality estimates at the facility scale

Mean annual estimated bat mortality per facility in Quebec ranged from 3 to 287 individuals while the upper limits of the 95% Credible Intervals ranged from 14 to 725 individuals (Fig. 3A–C). Mean annual mortality per MW ranged from 0.03 to 2.62 individuals. The distribution of these estimated mortalities was heavily skewed; more than two thirds of facilities had estimated mean mortalities lower than 100 individuals per year and only three had annual mortalities greater than 250 individuals per year.

The mean annual estimate was calculated from all available annual median estimated mortalities per facility (M-50), which were generally consistent between consecutive years of surveying at the same facility (Fig. 2A). Global probabilities of

**Table 1**

Candidate model set and $AIC_c$ table for model selection testing the effects of installed capacity (MW), geographic position (Geog), and elevation (Elev) on estimated annual bat mortality ($\lambda$) per facility ($n = 30$ facilities). All models having a $\Delta$ $AIC_c$ of less than 2 (shown in bold) were retained and used to produce model-averaged parameter estimates.

| Model | K | $AIC_c$ | $\Delta$ $AIC_c$ | $AIC_c$ weight | LL |
|---|---|---|---|---|---|
| **$\lambda \sim$ MW + Geog + Elev** | **5** | **125.59** | **0.00** | **0.41** | **−56.55** |
| **$\lambda \sim$ MW + Geog** | **4** | **126.06** | **0.47** | **0.32** | **−58.23** |
| **$\lambda \sim$ MW + Elev** | **4** | **127.32** | **1.73** | **0.17** | **−58.86** |
| $\lambda \sim$ Elev + Geog | 4 | 130.47 | 4.87 | 0.04 | −60.43 |
| $\lambda \sim$ MW | 3 | 130.76 | 5.17 | 0.03 | −61.92 |
| $\lambda \sim$ Geog | 3 | 131.28 | 5.69 | 0.02 | −62.18 |
| $\lambda \sim$ Elev | 3 | 134.14 | 8.55 | 0.01 | −63.61 |
| $\lambda \sim$ 1 | 2 | 137.43 | 11.84 | 0.00 | −66.49 |

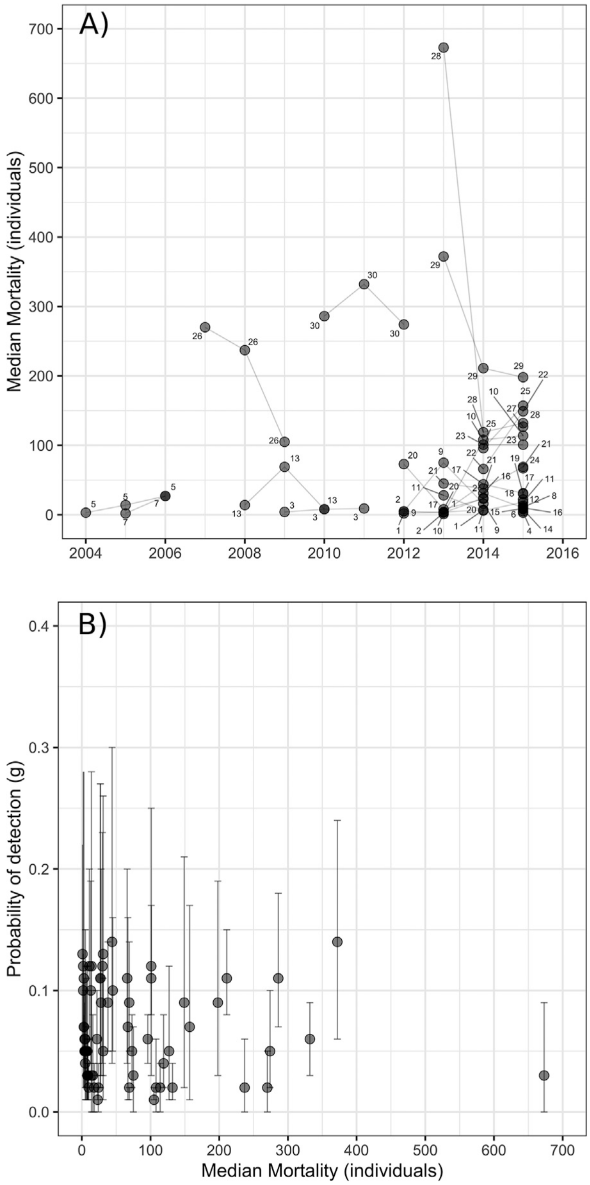

**Fig. 2.** (A) Median of the discrete posterior distribution of mortality per carcass survey. Facilities are identified (1–30) and consecutive years of surveys at the same facility indicated by connecting lines. (B) Probability of detection as a function of estimated mortality. Probabilities of detection, shown with 95% Confidence Intervals, are universally low (<0.3) but there is no relationship with median estimates of mortality.

detection (*g*) per facility*year combinations (n = 65 carcass surveys at 30 separate facilities) were very low (<0.3). However, there was no relationship between the point estimate of median mortality and the probability of detection (Fig. 2B).

### 3.2.2. *Mortality estimates at the regional scale*

Total bat mortality for 2016 in the province of Quebec falls within the 95% Credible Interval [4526, 6455], which gives an estimate of mortality per MW which falls in the interval [1.29, 1.84]. Lacking species-specific detection probabilities, the best we can do is assume that the relative proportion of carcasses found per species reflects the real proportions of species killed. If this is the case, 2016 mortality of hoary bats in Quebec (47% of carcasses) would fall in the interval [2128, 3035] individuals. At the other end of the spectrum, the eastern small-footed myotis and the tri-colored bat were never identified in carcass surveys; however, 11% of carcasses were not identifiable to species, accounting for [490, 699] individuals killed in 2016 alone. Using yearly installed capacities from 1999 to 2016, we estimated that cumulative mortality in Quebec since the first wind energy installations in this region up until 2016 falls within the interval [18 186, 25 941].

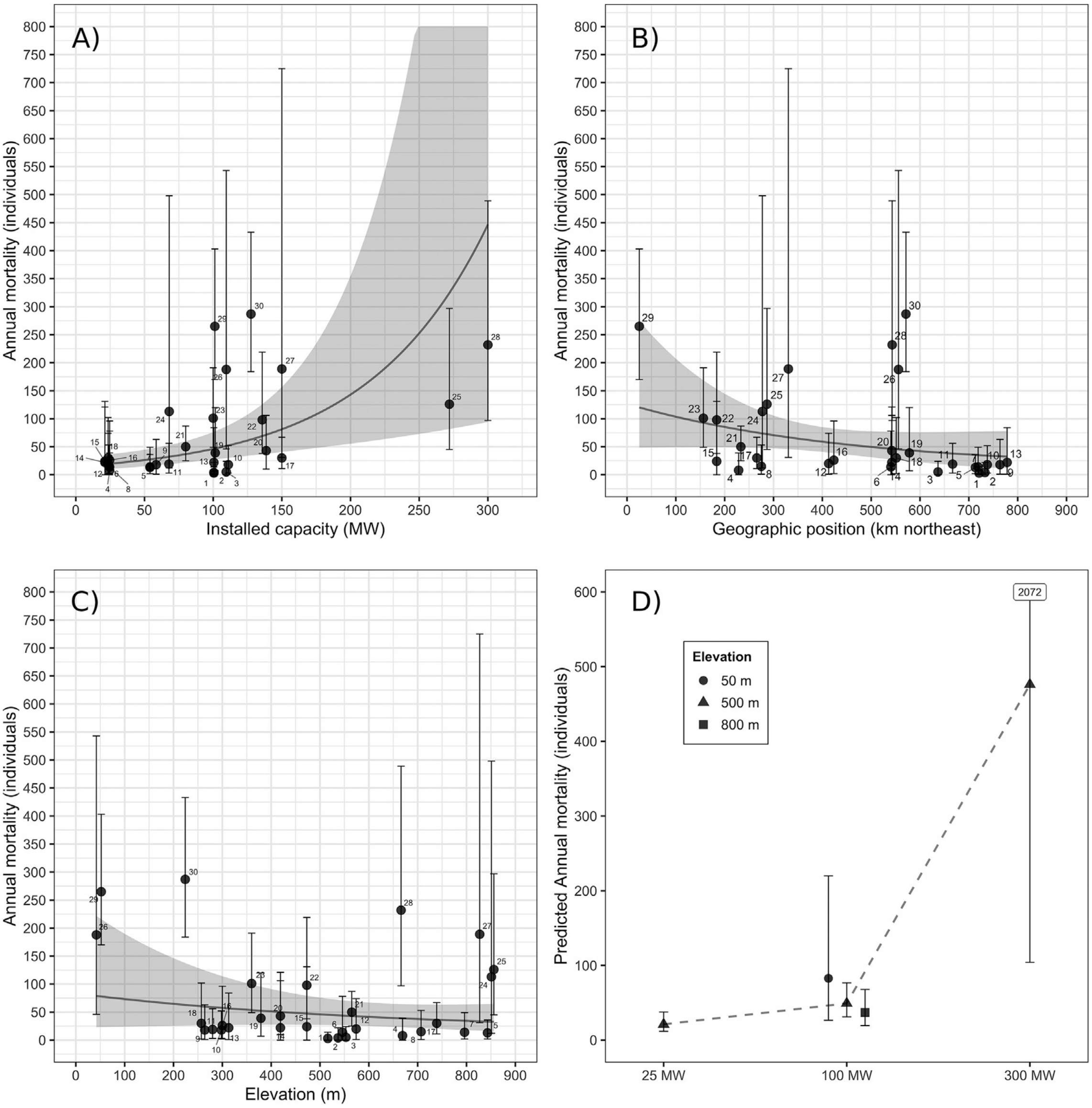

**Fig. 3.** Median point estimates of mortality and 95% Credible Intervals for each of the 30 facilities included in this analysis and model-averaged predictions for the effect of (A) installed capacity, (B) geographic position and (C) elevation on annual mortality. Facilities are identified (1-30) to correspond with Fig. 2 and supplementary material B. Solid lines are predictions based on the median values for the other two variables (100 MW median installed capacity; 495 m median elevation; 542 km median distance to the northeast) and shaded areas indicate the 95% confidence intervals around these predictions. (D) Predictions based on management scenarios are shown for three representative facility sizes (25 MW, 100 MW and 300 MW). For mid-sized facilities, three elevations are shown (50, 500 and 800 m). All predictions are for a median distance to the northeast (542 km).

### 3.3. *Large-scale environmental drivers of mortality*

The scale parameter (theta) for the global model was 2.13 indicating a manageable level of overdispersion and graphical model verification revealed no serious patterns in the residuals. The model selection based on $AIC_c$ showed that three models had an important level of empirical support with $\Delta AIC_c < 2$ (Table 1). The three top models had an $AIC_c$ weight of 90%, and all included installed capacity; the best-ranked model included all three variables ($AIC_cWt = 0.41$). Of the three variables, installed capacity had the strongest effect on bat mortality at wind energy facilities, with larger facilities having higher mortalities (Table 2; Fig. 3A).

In addition, facilities further to the northeast tended to have lower mortality than those to the southwest (Fig. 3B). Similarly, mortality tended to decrease with increasing elevation but the relationship was also weak (Fig. 3B). At low elevations (<250 m), mortality at two facilities was higher than expected by the predictions of model averaging and at high

**Table 2**
Model-averaged parameter estimates from models with $\Delta$ AIC$_c$ < 2 and upper and lower bounds of a 95% Confidence Limit for the main effects of installed capacity, geographic position, and elevation on annual bat mortality. Confidence Intervals that do not overlap with zero indicate significant effects.

| | ***exp***($\beta$) | Lwr 95CL | Upr 95CL | units |
|---|---|---|---|---|
| Intercept | 63.85 | 17.78 | 229.28 | |
| Installed capacity (MW) | 1.011 | 1.005 | 1.018 | **megawatts** |
| Geographic position (Geog) | −0.998 | −0.996 | 0.999 | **kilometers** |
| Elevation (Elev) | −0.998 | −0.997 | −1.000 | **meters** |

elevations (>650 m), mortality at four facilities was higher than expected (Fig. 3C). The relationships with these three environmental variables appear to be weak at least partly because those facilities with higher than average mortality (the few facilities at the high end of the skewed distribution of mortality) are poorly predicted by the models.

## 4. Discussion

This study is unique both in having access to surveys following a standardized methodology within a large contiguous area, and in applying a single estimator appropriate for low or zero counts to all surveys. Although robust estimates of bat mortality due to wind energy at spatial scales relevant to bat populations are arguably a prerequisite for effective conservation actions, extrapolating single-facility estimates of mortality to regional or continental scales is often problematic. We found that per-facility bat mortality was influenced not only by installed capacity, but also by geographic position, and elevation. These results support the hypothesis that environmental variables and spatial context can drive variation in bat mortality, but also highlight that the few facilities with higher-than-average mortality are generally poorly predicted by these large-scale environmental variables. These results show the utility of using easily available facility descriptors such as elevation and geographic location as an inexpensive way for managers concerned about conservation to include basic environmental factors in considerations of mortality risk at wind energy facilities, but also point to the need for a more in-depth understanding of the determinants of higher-than-average mortality.

### *4.1. The skewed distribution of mortality among facilities: a small number of facilities account for a large proportion of regional mortality*

Many wind energy facilities in our region had low estimated bat mortality (both annual and per Megawatt) and may be considered bat-friendly. This has important implications for monitoring and conservation; in particular, it indicates that monitoring at all facilities is critical in order to correctly identify those facilities with higher-than-average mortality and those facilities which are bat friendly. Effective regional or national management and mitigation measures should target those areas or facilities with high or potentially high mortality in order to have the most impact on reducing population-level mortality. Our estimate of the cumulative regional mortality for bats for the period from 1999 to 2016 was between 18 186 and 25 941 individuals. The majority of wind energy facilities in Quebec were built in the latter half of this period and the estimated regional mortality in 2016 alone accounts for approximately a fifth of this total cumulative mortality. The fact that several facilities contributed disproportionately to this mortality, however, while other facilities had both very low per Megawatt and annual mortalities, indicates that management, conservation and mitigation efforts should focus on those facilities with higher-than-average mortality. Accurate facility-by-facility estimates are therefore critical for effective conservation and management; this clearly points to the risk of using estimates from one or several facilities to extrapolate to unmonitored facilities or areas.

### *4.2. Regional context: large-scale environmental gradients as determinants of mortality*

Many syntheses have noted variations in mortality among regions (e.g., Arnett and Baerwald, 2013). Differences in habitat availability and use and the placement of both wind energy facilities and individual turbines within facilities are likely to play a role in these differences. The results of the present study clearly show that environmental context has an important influence on mortality. Indeed, since the operational life of a facility is generally at least 25 years, and there is no plan to decommission any existing wind energy facilities over the short term (increases in installed capacity have occurred every year in this region), the estimated 2016 mortality can be used as a minimum annual mortality for future years, resulting in at least an estimated 45 260 to 64 550 bat mortalities for the next ten years in Quebec (2016–2025). This estimated mortality is low when compared to estimates produced for many other North American regions (e.g. (Arnett and Baerwald, 2013; Hayes, 2013; Smallwood, 2013; Zimmerling and Francis, 2016), and it is possible that Quebec, because it includes the northern limits of bat distributions in North America, represents a region with less bat habitat, lower population densities, and therefore lower observed mortalities overall. However, this cumulative mortality is still considerable when placed in the context of bat populations which are typically slow-growing and are facing many additional threats across their ranges.

Mortality within our study region is highest in the southwest and decreases to the northeast. The geography of the province of Quebec is dominated by the Saint Lawrence river, estuary and gulf, which extends from the southwest to the northeast. This creates a region-specific gradient of geography that contains elements of both latitude and longitude, and it is probable that the decrease in mortality further to the northeast corresponds to a regional gradient of habitat types. In the southwest of the province, agricultural areas and patches of deciduous forest dominate; this is part of the Mixedwood Plains ecozone. Further to the northeast, the river becomes the estuary and then widens into the gulf; the proportion of farmland decreases, and deciduous forests become mixed with more boreal coniferous habitats. This portion of the province falls within the Atlantic Maritime ecozone (Ecological Stratification Working Group, 1995). The significant effect of geographic position on mortality could therefore result from a decrease in high quality bat habitat in the Altantic Maritime ecozone as compared to the Mixedwood Plains ecozone. For example, large diameter trees, essential for cavity-roosting bats (Fabianek et al., 2015), are more common in the deciduous forests that dominate the Mixedwood Plains ecozone. Additionally, bat flight activity has been observed to be higher over trails and still bodies of water, and on the edges of forest stands (Krusic et al., 1996); all of these features are more abundant in the southwest of the province.

There is a well-recognized gradient in habitat with higher elevations having increasingly lower temperatures, precipitation and productivity (McCain, 2009; McVicar and Körner, 2013; Pan et al., 2016). Increasing elevations generally have lower proportions of agricultural land, fewer water features such as streams or lakes and fewer edge habitats between forest and meadow, all of which are important determinants of bat habitat use (Arnett and Baerwald, 2013; Rydell et al., 2010; Thompson et al., 2017). Mortality in our region decreased overall at higher elevations, but individual facilities with high mortality appeared to be either at low or high elevations, and not at mid-elevation sites. There did not appear to be a pattern in species-specific mortality (i.e., based on carcasses found, specific species or types – e.g., migratory bats - were not found principally at either low or high elevations); however, facilities with higher mortality tended to have more species represented in carcass surveys. This may indicate use of these sites by a larger number of bat species. In a recent study of bird diversity across an elevational gradient, temperature, precipitation and habitat heterogeneity were important determinants of species diversity (Pan et al., 2016). While both temperature and precipitation decreased with increasing elevation, habitat heterogeneity displayed a hump-shaped relationship with elevation (the highest habitat heterogeneity was found at mid-range elevations). Although the range of elevations examined in our study is much smaller than that in Pan et al. (2016), it is possible that a pattern wherein, for example, edge habitats or prime foraging areas are abundant at both low and high elevations could drive the observed pattern of bat mortality. Facilities with higher mortality at both high and low elevations may therefore be a result of increased probability of overlap between facilities and habitats used by multiple bat species. Our study provides evidence that elevation is indeed correlated with mortality and could therefore be used as a partial proxy for bat habitat. The relationship is not a simple one, however, and variability between individual facilities remains important.

### *4.3. Management perspectives*

The best description of mortality in our region was not based on installed capacity alone; models including both elevation and geographic position were also retained in our model selection process. Indeed, it has already been suggested that mortality is correlated with aspects of both behavior and habitat use (e.g., foraging strategies) in both North America (Cryan and Barclay, 2009; Thompson et al., 2017) and Europe (Rydell et al., 2010). Our results indicate that using mortality per MW from one or several facilities as a basis for predicting the impact of unmonitored facilities will do a poor job of explaining patterns in mortality because it implicitly assumes that mortality can be linearly scaled based oninstalled capacity and ignores environmental differences between facilities. The relationship between installed capacity and mortality was not a clear-cut case of each successive increase in installed capacity resulting in an incremental increase in estimated mortality. Small facilities (25 MW) had low annual mortality; increasing capacity fourfold (100 MW) resulted in a doubling of estimated mortality, but further increases in capacity resulted in much larger increases in mortality. This may indicate that the larger a facility is, the more important specific spatial and environmental context becomes in determining bat mortality. The high variability among larger facilities is possibly due to differences in environmental factors such as proximity to roosting sites, migratory routes or foraging habitat, which then can magnify differences in mortality due to installed capacity, elevation and other large-scale habitat features. Some large facilities, however, have low mortality and others have very high mortality; from a management perspective, large facilities are therefore associated with a much larger gamble than multiple small facilities. Given the difficulty of obtaining and analyzing detailed spatial habitat information, our results show that even very basic environmental proxy variables such as elevation and geographic position can greatly increase our ability to explain variation in the magnitude of mortality between wind energy facilities. Using this approach to include basic information on environmental variables will allow managers to more clearly evaluate the potential mortality risk posed by proposed wind energy facilities.

From the perspective of minimizing bat mortality, our results indicate that mid-sized facilities are the best management scenario. Although annual mortality is slightly higher than at small facilities, the increase is negligible when compared with the added capacity (i.e., 1 facility of 100 MW has much less than 4× the mortality of a 25 MW facility) and the uncertainty in the upper threshold of the estimate (upper limit of the 95% Confidence Intervals) does not increase substantially. Large facilities, however, have much higher mortality and a large uncertainty associated with them (extremely high upper limit of the 95% Confidence Intervals) which indicates that they are a much riskier management scenario. Incorporating marginal decreases in mortality by targeting higher elevations and regions further to the northeast could then further reduce mortality at these medium-sized facilities.

## 5. Conclusions

This study is the first to document patterns of bat mortality in a contiguous region spanning 800 km of southwest-northeast distance and almost 900 m of elevation, where all facilities in the region were monitored. We showed that mortality was distributed unevenly among facilities and that cumulative mortality was relatively low as compared to other regions. In addition, we identified three predictors of bat mortality (installed capacity, elevation and geographic position) that can be used in combination by managers to more effectively take mortality risk for bat populations into account when planning wind energy facilities. We showed that: (i) more installed capacity (MW) does correlate with higher mortality, but that capacity alone is a poor predictor of estimated mortality; (ii) mortality overall decreased with increasing elevation; and (iii) mortality decreased further to the northeast. The small proportion of high risk facilities or those that observe high total bat mortality should be targeted for the application of mitigation measures during operation, in order to reduce impacts on bat populations. Although detailed information about habitat directly surrounding individual turbines may provide the best explanations of mortality, both elevation and geographical position provide useful proxies for environmental variation that can be used by mangers on provincial/state spatial scales before a more detailed understanding of how environment modifies mortality risk at the turbine scale is attained.

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## Appendix A. Supplementary data

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## References

Arnett, E.B., Baerwald, E.F., 2013. Impacts of wind energy development on bats: implications for conservation. In: Adams, R.A., Pedersen, S.C. (Eds.), Bat Evolution, Ecology, and Conservation. Springer Science Business Media, New York, NY, pp. 435–456.

Arnett, E.B., Brown, W.K., Erickson, W.P., Fiedler, J.K., Hamilton, B.L., Henry, T.H., Jain, A., Johnson, G.D., Kerns, J., Koford, R.R., Nicholson, C.P., O'Connell, T.J., Piorkowski, M.D., Tankersley, R.D., 2008. Patterns of bat fatalities at wind energy facilities in North America. J. Wildl. Manag. 72, 61–78. https://doi.org/10.2193/2007-221.

Baerwald, E.F.F., Patterson, W.P., Barclay, R.M.R., 2014. Origins and migratory patterns of bats killed by wind turbines in southern Alberta: evidence from stable isotopes. Ecosphere 5, 1–17. https://doi.org/10.1890/ES13-00380.1.

Bispo, R., Bernardino, J., Marques, T.A., Pestana, D., 2013. Modeling carcass removal time for avian mortality assessment in wind farms using survival analysis. Environ. Ecol. Stat. 20, 147–165. https://doi.org/10.1007/s10651-012-0212-5.

Boyles, J.G., Brack, V., 2009. Modeling survival rates of hibernating mammals with individual-based models of energy expenditure. J. Mammal. 90, 9–16. https://doi.org/10.1644/08-MAMM-A-205.1.

Boyles, J.G., Cryan, P.M., McCracken, G.F., Kunz, T.K., 2011. Economic importance of bats in agriculture. Science 332, 41–42. https://doi.org/10.1126/science.1201366 (80-.).

Burnham, K.P., Anderson, D.R., 2002. Model Selection and Multimodel Inference: A Practical Information-Theoretic Approach, second ed. Springer.

Canadian Wind Energy Association, 2018. Powering Canada's future [WWW Document]. URL. https://canwea.ca/wp-content/uploads/2019/02/powering-canadas-future-web.pdf. accessed 4.16.19.

Canadian Wind Energy Association, 2016. Puissance de demain [WWW Document]. URL. https://canwea.ca/wp-content/uploads/2013/12/Canada-Current-Installed-Capacity_f.pdf. accessed 1.8.18.

Clare, E.L., Symondson, W.O.C., Broders, H., Fabianek, F., Fraser, E.E., Mackenzie, A., Boughen, A., Hamilton, R., Willis, C.K.R., Martinez-Nuñez, F., Menzies, A.K., Norquay, K.J.O., Brigham, M., Poissant, J., Rintoul, J., Barclay, R.M.R., Reimer, J.P., 2014. The diet of Myotis lucifugus across Canada: assessing foraging quality and diet variability. Mol. Ecol. 23, 3618–3632. https://doi.org/10.1111/mec.12542.

COSEWIC, 2013. COSEWIC Assessment and Status Report on the Little Brown Myotis (Myotis Lucifugus), Northern Myotis (Myotis Septentrionalis) and Tri-colored Bat (Perimyotis Subflavus) in Canada. Ottawa (ON).

Cryan, P.M., Barclay, R.M.R., 2009. Causes of bat fatalities at wind turbines: hypothesis and predictions. J. Mammal. 90, 1330–1340. https://doi.org/10.1644/09-MAMM-S-076R1.1.

Dalthorp, D., 2016. Eoa: Wildlife Mortality Estimator for Scenarios with Low Fatality Rates and Imperfect Detection. R package version 0.2.11.

Dalthorp, D., Huso, M.M., 2017. Chapter 4. In: Perrow, M. (Ed.), Wildlife and Wind Farms: Conflicts and Solutions, Volume 2: Onshore: Monitoring and Mitigation. Pelagic Publishing, Exeter, United Kingdom.

Ecological Stratification Working Group, 1995. A National Ecological Framework for Canada. Ottawa.

Fabianek, F., Gagnon, D., Delorme, M., 2011. Bat distribution and activity in Montréal island green spaces: responses to multi-scale habitat effects in a densely urbanized area. Ecoscience 18, 9–17. https://doi.org/10.2980/18-1-3373.

Fabianek, F., Simard, M.A., Desrochers, A., 2015. Exploring regional variation in roost selection by bats: evidence from a meta-analysis. PLoS One 10, 1–22. https://doi.org/10.1371/journal.pone.0139126.

Ferreira, D., Freixo, C., Cabral, J.A., Santos, R., Santos, M., 2015. Do habitat characteristics determine mortality risk for bats at wind farms? Modelling susceptible species activity patterns and anticipating possible mortality events. Ecol. Inf. 28, 7–18. https://doi.org/10.1016/j.ecoinf.2015.04.001.

Frick, W.F., Baerwald, E.F., Pollock, J.F., Barclay, R.M.R., Szymanski, J.A., Weller, T.J., Russell, A.L., Loeb, S.C., Medellin, R.A., McGuire, L.P., 2017. Fatalities at wind turbines may threaten population viability of a migratory bat. Biol. Conserv. 209, 172–177. https://doi.org/10.1016/j.biocon.2017.02.023.

Frick, W.F., Reynolds, D.S., Kunz, T.H., Frick, W.F., Reynolds, D.S., Kunz, T.H., 2010. Influence of climate and reproductive timing on demography of little brown myotis (Myotis lucifugus). J. Anim. Ecol. 79, 128–136.

Hammerson, G.A., Kling, M., Harkness, M., Ormes, M., Young, B.E., 2017. Strong geographic and temporal patterns in conservation status of North American bats. Biol. Conserv. https://doi.org/10.1016/j.biocon.2017.05.025.

Hayes, M.A., 2013. Bats killed in large numbers at United States wind energy facilities. Bioscience 63, 975–979. https://doi.org/10.1525/bio.2013.63.12.10.

Hickey, M.B.C., Fenton, M.B., MacDonald, K.C., Soulliere, C., 2001. Trace elements in the Fur of bats (Chiroptera: Vespertilionidae) from Ontario and Quebec, Canada. Bull. Environ. Contam. Toxicol. 66, 699–706. https://doi.org/10.1007/s001280065.

Hull, C.L., Muir, S., 2010. Search areas for monitoring bird and bat carcasses at wind farms using a Monte-Carlo model. Australas. J. Environ. Manag. 17, 77–87. https://doi.org/10.1080/14486563.2010.9725253.

Huso, M.M.P., 2011. An estimator of wildlife fatality from observed carcasses. Environmetrics 22, 318–329. https://doi.org/10.1002/env.1052.

Huso, M.M.P., Dalthorp, D., 2014. Accounting for unsearched areas in estimating wind turbine-caused fatality. J. Wildl. Manag. 78, 347–358. https://doi.org/10.1002/jwmg.663.

Huso, M.M.P., Dalthorp, D., Dail, D., Madsen, L., 2015. Estimating wind-turbine-caused bird and bat fatality when zero carcasses are observed. Ecol. Appl. 25, 1213–1225. https://doi.org/10.1890/14-0764.1.sm.

Johnson, S.A., Brack, V.J., Rolley, R.E., 1998. Overwinter weight loss of Indiana bats (Myotis sodalis) from hibernacula subject to human visitation. Am. Midl. Nat. 139, 255–261. https://doi.org/10.1674/0003-0031 (1998)139[0255:OWLOIB]2.0.CO;2.

Korner-Nievergelt, F., Niermann, I., Behr, O., Etter, M.A., Brinkmann, R., Korner, P., Hellriegel, B., Huso, M.M.P., Dalthorp, D., 2016. Package ' Carcass ' : Estimation of the Number of Fatalities from Carcass Searches.

Krusic, R.A., Yamasaki, M., Neefus, C.D., Pekins, P.J., 1996. Bat habitat use in white mountain national. J. Wildl. Manag. 60, 625–631.

Kunz, T.H., Anthony, E.L.P., Rumage, W.T.I., 1977. Mortality of little Brown bats following multiple pesticide applications. J. Wildl. Manag. 41, 476–483.

Kunz, T.H., Arnett, E.B., Erickson, W.P., Hoar, A.R., Johnson, G.D., Larkin, R.P., Strickland, M.D., Thresher, R.W., Tuttle, M.D., 2007. Ecological impacts of wind energy development on bats: questions, research needs, and hypotheses. Front. Ecol. Environ. 5, 315–324.

Kuvlesky, W.P., Brennan, L.A., Morrison, M.L., Boydston, K.K., Ballard, B.M., Bryant, F.C., 2007. Wind energy development and wildlife conservation: challenges and opportunities. Wildl. Res. 71, 2487–2498. https://doi.org/10.2193/2007-248.

Lomolino, M.V., 2001. Elevation gradients of species-density: historical and prospective views. Glob. Ecol. Biogeogr. 10, 3–13.

Mann, S.L., Steidl, R.J., Dalton, V.M., 2002. Effects of cave tours on breeding *Myotis velifer*. J. Wildl. Manag. 66, 618–624.

Mazerolle, M.J., 2015. Package 'AICcmodavg.

McCain, C.M., 2009. Global analysis of bird elevational diversity. Glob. Ecol. Biogeogr. 18, 346–360. https://doi.org/10.1111/j.1466-8238.2008.00443.x.

McVicar, T.R., Körner, C., 2013. On the use of elevation, altitude, and height in the ecological and climatological literature. Oecologia 171, 335–337. https://doi.org/10.1007/s00442-012-2416-7.

MDDEFP, 2013. Protocole de suivi des mortalités d'oiseaux de proie et de chiroptères dans le cadre de projets d'implantation d'éoliennes au Québec. Québec.

Ministère d'énergie et ressources naturelles, 2009. Géoboutique Québec [WWW Document]. Modèles numériques d'altitude à l'échelle 1/20 000. URL. http://geoboutique.mern.gouv.qc.ca/html/MNA-20K_fiche.htm. accessed 3.20.19.

MMACH, 2018. Banque de données sur les micromammifères et les chiroptères du Québec, 1996-2018. Gouvernement du Québec, ministère des Ressources naturelles et de la Faune, Direction de l'expertise sur la faune et ses habitats. Quebec, Quebec.

MRNF, 2008. Protocole de suivi des mortalités d'oiseaux de proie et de chiroptères dans le cadre de projets d'implantation d'éoliennes au Québec.

Orloff, S., Flannery, A., 1992. Wind Turbine Effects on Avian Activity, Habitat Use, and Mortality in Altamont Pass and Solano County Wind Resource areas: 1989-1991. A report prepared for the California Energy Commission, pp. 1–199.

Pan, X., Ding, Z., Hu, Y., Liang, J., Wu, Y., Si, X., Guo, M., Hu, H., Jin, K., 2016. Elevational pattern of bird species richness and its causes along a central Himalaya gradient, China. PeerJ 4, e2636. https://doi.org/10.7717/peerj.2636.

Piorkowski, M.D., Connell, T.J.O., 2010. Spatial pattern of summer bat mortality from collisions with wind turbines in mixed-grass prairie. Am. Midl. Nat. 164, 260–269. https://doi.org/10.1674/0003-0031-164.2.260.

R Core Team, 2016. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing version 3.3.1 (2016-06-21) – "Bug in Your Hair.".

Reiskind, M.H., Wund, M.A., 2009. Experimental assessment of the impacts of northern long-eared bats on ovipositing Culex (Diptera: Culicidae) mosquitoes. J. Med. Entomol. 46, 1037–1044.

Rogers, S.E., Cornaby, B.W., Rodman, C.W., Sticksel, P.R., Tolle, D.A., 1977. Environmental Studies Related to the Operation of Wind Energy Conversion Systems. Columbus, Ohio.

Rydell, J., Bach, L., Dubourg-Savage, M.-J., Green, M., Rodrigues, L., Hedenström, A., 2010. Bat mortality at wind turbines in Northwestern Europe. Acta Chiropterol. 12, 261–274. https://doi.org/10.3161/150811010X537846.

Smallwood, K.S., 2013. Comparing bird and bat fatality-rate estimates among North American wind-energy projects. Wildl. Soc. Bull. 37, 19–33. https://doi.org/10.1002/wsb.260.

Strickland, M.D., Arnett, E.B., Erickson, W.P., Johnson, G.D., Morrison, M.L., Shaffer, J.A., Warren-Hicks, W., 2011. Comprehensive guide to studying wind energy/wildlife interactions. Front. Ecol. Environ. 5, 315–324.

TechnoCentre éolien, 2017. TechnoCentre éolien [WWW Document]. URL. https://www.eolien.qc.ca/fr/eolien-quebec/liste-complete-des-parcs.html. accessed 6.20.12.

Thompson, M., Beston, J.A., Etterson, M., Diffendorfer, J.E., Loss, S.R., 2017. Factors associated with bat mortality at wind energy facilities in the United States. Biol. Conserv. 215, 241–245. https://doi.org/10.1016/j.biocon.2017.09.014.

Willdenow, K.L., 1805. The Principles of Botany, and Vegetable Physiology. Blackwood, Cadell and Davies, London.

Zimmerling, J.R., Francis, C.M., 2016. Bat mortality due to wind turbines in Canada. J. Wildl. Manag. 1–10 https://doi.org/10.1002/jwmg.21128.