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AVIAN CONSERVATION & ECOLOGY

Research Paper, part of a Special Feature on Quantifying Human-related Mortality of Birds in Canada

Avian mortalities due to transmission line collisions: a review of current estimates and field methods with an emphasis on applications to the Canadian electric network

Mortalité aviaire attribuable aux collisions avec les lignes de transport d'électricité : une revue des estimations actuelles et des méthodes de terrain avec un accent sur les applications au réseau électrique canadien

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ABSTRACT. Birds are vulnerable to collisions with human-made fixed structures. Despite ongoing development and increases in infrastructure, we have few estimates of the magnitude of collision mortality. We reviewed the existing literature on avian mortality associated with transmission lines and derived an initial estimate for Canada. Estimating mortality from collisions with power lines is challenging due to the lack of studies, especially from sites within Canada, and due to uncertainty about the magnitude of detection biases. Detection of bird collisions with transmission lines varies due to habitat type, species size, and scavenging rates. In addition, birds can be crippled by the impact and subsequently die, although crippling rates are poorly known and rarely incorporated into estimates. We used existing data to derive a range of estimates of avian mortality associated with collisions with transmission lines in Canada by incorporating detection, scavenging, and crippling biases. There are 231,966 km of transmission lines across Canada, mostly in the boreal forest. Mortality estimates ranged from 1 million to 229.5 million birds per year, depending on the bias corrections applied. We consider our most realistic estimate, taking into account variation in risk across Canada, to range from 2.5 million to 25.6 million birds killed per year. Data from multiple studies across Canada and the northern U.S. indicate that the most vulnerable bird groups are (1) waterfowl, (2) grebes, (3) shorebirds, and (4) cranes, which is consistent with other studies. Populations of several groups that are vulnerable to collisions are increasing across Canada (e.g., waterfowl, raptors), which suggests that collision mortality, at current levels, is not limiting population growth. However, there may be impacts on other declining species, such as shorebirds and some species at risk, including Alberta's Trumpeter Swans (*Cygnus buccinator*) and western Canada's endangered Whooping Cranes (*Grus americana*). Collisions may be more common during migration, which underscores the need to understand impacts across the annual cycle. We emphasize that these estimates are preliminary, especially considering the absence of Canadian studies.

RÉSUMÉ. Les oiseaux sont vulnérables aux collisions avec les structures fixes d'origine anthropique. Malgré le développement continuel et l'augmentation du nombre d'infrastructures, nous avons peu d'estimations sur l'ampleur de la mortalité par collision. Nous avons procédé à une revue de la littérature touchant la mortalité aviaire associée aux lignes de transport d'électricité et avons calculé une estimation préliminaire pour le Canada. L'estimation de la mortalité attribuable aux collisions avec les lignes électriques pose un défi en raison du manque d'études, particulièrement au Canada, et de l'incertitude quant à l'ampleur des biais dans la détection. La détection des collisions aviaires avec les lignes électriques varie en fonction du type d'habitat, de la taille de l'espèce et des taux de disparition des carcasses par les charognards. De plus, les oiseaux peuvent être blessés à la suite d'une collision et en mourir par la suite, mais les taux de blessures mortelles sont peu connus et rarement inclus dans les estimations. Nous avons utilisé des données existantes pour calculer différentes estimations de la mortalité aviaire attribuable à ce type de collision au Canada, en incluant les erreurs relatives à la détection, à la prédation par les charognards et aux blessures mortelles. Il y a 231 966 km de lignes de transport d'électricité au Canada, surtout situées en forêt boréale. Les estimations de la mortalité s'étendaient de 1 à 229,5 millions d'oiseaux par année, une fois les corrections faites pour tenir compte des erreurs. L'estimation la plus réaliste, en tenant compte de la variabilité du risque selon l'endroit au Canada, se situe entre 2,5 et 25,6 millions d'oiseaux morts par année. D'après des données issues de nombreuses études réalisées au Canada et dans le nord-est des États-Unis, les groupes d'oiseaux les plus vulnérables sont : 1) la sauvagine; 2) les grèbes; 3) les limicoles; et 4) les grues.

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Les populations de plusieurs groupes d'oiseaux vulnérables aux collisions sont en augmentation au Canada (p. ex. sauvagine, rapaces), ce qui indique que la mortalité attribuable aux collisions, selon les estimations actuelles, ne limite pas la croissance des populations. Toutefois, cette mortalité peut avoir un impact sur d'autres espèces en déclin, comme les limicoles et certaines espèces en péril, y compris le Cygne trompette (*Cygnus buccinator*) en Alberta et la Grue blanche (*Grus americana*) dans l'Ouest du Canada, espèce en voie de disparition. Il se peut que les collisions soient plus fréquentes durant les migrations, ce qui fait ressortir la nécessité de bien comprendre les impacts tout au long du cycle annuel. Nous insistons sur le fait que les estimations présentées sont préliminaires, surtout parce qu'il n'y a pas encore d'études canadiennes.

Key Words: *avian mortality; bird collision; Canada; electricity; incidental take; transmission lines*

INTRODUCTION

Birds are vulnerable to collisions with a range of fixed structures, such as buildings, towers, transmission lines, and wind turbines (Erickson et al. 2001, Manville 2005). Indeed, the dangers that collisions with electrical structures pose to birds have been known since the late 1800s (Coues 1876). Estimates of mortality due to collisions with power lines in the United States have ranged from hundreds of thousands to 175 million birds each year (Erickson et al. 2001). In Norway, annual estimates of tetraonid (e.g., grouse, ptarmigan) power line mortalities alone have ranged from 20,000 to 50,000 individuals (Bevanger 1995). As many as 245 species are known to collide with power lines, with shorebirds, waterfowl, cranes, herons, tetraonids, and passerines among the most common victims (Brown et al. 1987, Bevanger 1995, Bevanger 1998).

Many species of birds are especially vulnerable to collisions with high voltage transmission lines because of the height of these structures with respect to flight altitude, and because of their low visibility, whereas many species are potentially less vulnerable to collisions with distribution lines—the network of lower voltage lines that carry electricity to customers from load centers (Morkill and Anderson 1991, Savereno et al. 1996, Jenkins et al. 2010, APLIC 2012). Specifically, the shield wires, typically the highest wire found on transmission lines, are usually smaller in diameter than conductor wires, which renders them less visible (Brown et al. 1987, Faanes 1987). While shield wires can be found on some distribution lines, their configuration generally consists of phase conductors and a neutral wire either at the same level or lower (APLIC 2012). Given that Morkill and Anderson (1991) found that birds tend to increase altitude when reacting to power lines, this could explain the high frequency of collisions with static wires above the rest of the structure. However, it should be noted that in one study by Janss and Ferrer (1998), they found no difference between collisions on distribution and transmission lines, which suggests that the collision rates at distribution lines should not be overlooked.

Transmission lines not only cause direct mortality of birds, they can also cripple individuals, which can result in delayed and inhumane deaths (Bevanger 1998, Pandey et al. 2008). Mortality rates due to transmission lines are thought to be low for many species (Meyer 1978, Thompson 1978, James and Haak 1979, Beaulaurier 1981, Faanes 1983, 1987, Alonso and Alonso 1999), with the exception of a few species of conservation concern (notably Whooping Cranes [*Grus americana*] and Trumpeter Swans [*Cygnus buccinator*] in Canada, and elsewhere, Great Bustards [*Otis tarda*] and California Condors [*Gymnogyps californianus*] [Janss and Ferrer 2000, Alberta Trumpeter Swan Recovery Team 2006, COSEWIC 2010, APLIC 2012]) that are generally impacted due to their small populations and restricted geographical ranges (Bevanger 1998, APLIC 1994, 2012).

Collisions with power lines are rarely observed in the field (Beaulaurier 1981, Alonso and Alonso 1999); therefore, collision rates are estimated via direct searches for carcasses either by observers, or by observers with dogs. Consequently, estimates of collision rates are highly influenced by variation in detection rates. First, observer detection rates can be influenced by habitat type and size of species impacted (Bevanger 1995, Savareno et al. 1996, Janss and Ferrer 1998, Rubolini et al. 2005). Second, carcass detection is strongly influenced by scavenging rates (Bevanger 1999, Smallwood 2007). For example, for small birds, up to 50% of carcasses can be scavenged in 24 hours (Flint et al. 2010). Depending on the extent of these detection biases, raw mortality numbers may be increased by several orders of magnitude. This generates significant challenges for accurately estimating the rates of avian mortality from power line collisions, and at present, estimates have been developed only for the United States and Norway (Bevanger 1995, Manville 2005). Adding to the complexity of detecting direct mortality, crippling rates of birds can be high and are very poorly quantified (Savereno et al. 1996, APLIC 2012). An additional challenge is the need to extrapolate from small-scale studies to regional or national assessments of power line collisions. Studies indicate that mortality rates are unevenly distributed in space and time, and are influenced by the orientation of power lines, local abundance of birds, meteorological conditions, and topographic features (Bevanger 1990, 1994).

Although mortality of birds due to collisions with transmission lines has been identified as a potential problem in Canada for more than 30 years (Blokpoel and Hatch 1976), the magnitude of this mortality has not been estimated at a national scale. Incidental mortality of migratory birds and species at risk, such as that caused by collisions, is prohibited by the *Migratory*

Bird Regulations under the *Migratory Birds Convention Act* and *Species at Risk Act* (APLIC 2012, Government of Canada 2013). Understanding the magnitude and relative vulnerability of species to collision mortality is thus required to develop effective conservation and management strategies. Transmission lines are a prevalent component of the Canadian landscape, and their siting and building are managed under the *Canadian Environmental Assessment Act* (CEAA 2013a). Since 1994, hundreds of environmental assessments involving transmission lines have been conducted across Canada (CEAA 2013b), and more than a dozen are currently in progress (CEAA 2013c). The global expansion of power lines at a rate of 5% per year (Jenkins et al. 2010), however, underscores the need to understand both the magnitude of the problem and the relative vulnerabilities of bird species. In sum, significant knowledge gaps coupled with increasing numbers of power lines and the responsibility to protect migratory and at-risk birds provide a strong rationale for this study to develop a first estimate of avian mortality due to collisions with transmission lines in Canada. This estimate will also allow for comparison with bird mortality due to other anthropogenic activities, such as roads, agriculture, and forestry. Using mortality rates from published literature and unpublished technical reports, we (1) develop estimates of avian mortality due to collisions with transmission lines, (2) quantify the variation and biases in these estimates, (3) estimate a plausible range of avian mortalities attributable to the electricity transmission sector in Canada, and (4) identify the conservation implications for species groups, and present recommendations for survey design and potential mitigations.

Line type

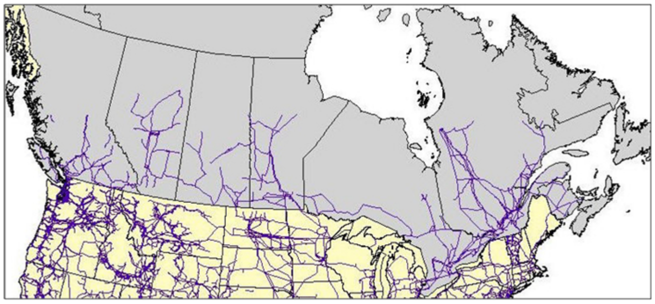
Transmission lines are generally defined as power lines that carry 115 kV or higher to load centers, while distribution lines (usually 1–69 kV) carry electricity to customers from these centers (APLIC 1994). We used a recent estimate of the total length of Canadian transmission lines of 231,966 km (Tecsult Inc. 2009, Association canadienne de l’électricité, 2010, *personal communication*) (Table 1). The distribution of transmission lines is not uniform across Canada. For example, the provinces of Quebec, Manitoba, and Alberta have the most high voltage transmission lines (> 230 kV) (Fig. 1). The total length of distribution lines in Canada (572,370 km) is about double that of transmission lines; however, Canadian data on collisions with this type of power line are lacking and sampling methodologies are weak. In fact, many studies indicate negligible collisions with distribution lines, often without presenting quantitative evidence (Janss and Ferrer 1998, APLIC 2012). Second, unlike transmission lines, most distribution lines do not have shield wires. Shield wires are the smallest and usually highest wire on transmission lines and are suspected to be the cause of most bird collisions (Bevanger and Brøseth 2001, APLIC 2012). Brown et al. (1987) found an 80% reduction in collision mortality of Sandhill Cranes and Whooping Cranes following removal of the earth (shield) wire from a span of 116-kV line. We focus primarily on transmission lines in this study but present preliminary estimates of mortality from distribution lines. We also focus only on direct collisions; we do not address mortalities due to electrocution, an additional source of mortality that is most prevalent on distribution lines and rarely occurs on transmission lines (Brown et al. 1987, Bevanger 1999, APLIC 2006). Given that the length of distribution lines in Canada is twice that of transmission lines in Canada, their impact should be evaluated when additional data are available.

Table 1. Length of transmission lines in Quebec and Canada.

Location	Length (km)	Source
Quebec	12,216	Tecsult 2009
Rest of Canada	219,750	ACE [†]
Total Canada	231,966	–
Lines > 230 kV in Canada	74,640	ACE [†]

[†] Association canadienne de l’électricité, 2010, *personal communication*

Fig. 1. Distribution of high voltage transmission lines across Canada. Note that lower voltage transmission lines are not mapped consistently across Canada; therefore, we present only the 74,640 km of lines > 230 kV. Statistical source: North American Reliability Council. Map Source: Global Energy Network Institute



Mortality estimates

We surveyed the literature to record avian losses incurred by transmission lines (APLIC 1994). To standardize across studies with differing methodologies, we included only studies that contained the following information: study length (of 200 days or greater), number of dead birds found, and total length of power line searched. Field protocols in these studies generally consisted of counting dead birds under a given stretch of power lines using line transect surveys (Meyer 1978, Beaulaurier 1981, Hartman et al. 1993, Hugie et al. 1993, Pearson 1993, Janss and Ferrer 1998) or by walking in zigzags along the right-of-way (Rusz et al. 1986, Crowder 2000, Heck 2007). We did not include studies that focused only on specific species unless data for all species encountered were presented. We excluded studies that did not remove accumulated dead birds during sampling, as well as those that used marked power lines (Beaulaurier 1981, Crowder 2000).

Because mortality rates vary throughout the year, we selected mortality estimates for studies conducted over most of the year (at least 200 days) and estimated a mean minimum mortality index (MMI; the number of birds found dead per kilometer of transmission line per year) for all values found in the studies selected, following Rubolini et al. (2005). Because few species remain in snow-covered areas of Canada in winter (78% winter outside of the country [NABCI 2012]), we standardized all our estimates in northern Canada by subtracting the winter period (1 December–28 February; 90 days) from the extrapolated estimates for localities that had at least 80% snow cover between 1 December and 28 February (Hall et al. 2006). This may have excluded some mortality; studies in Norway (Bevanger and Brøseth 2001) suggest high collision mortality of ptarmigan occurs in winter, but we assumed that this mortality represents a small fraction of the total. Studies of short duration typically overestimate mortality because they focus on the most active periods and do not include periods of low mortality. Therefore, to minimize this bias, we selected site-specific data and/or data that covered the whole annual period, and did not include studies based on shorter periods (see Appendix 1 for a complete list).

Correcting for survey biases

Estimates of detection biases were summarized from all studies regardless of whether they met our inclusion criteria for mortality estimates. We also expanded our review to include estimates of scavenger and search biases from studies conducted by the wind power industry.

METHODS

We expressed scavenger bias as the percentage of carcasses removed by scavengers after seven days because (1) one week corresponds to the most frequent sampling interval encountered in the literature (APLIC 1994), and (2) it reduces the magnitude of possible bias induced by scavenger swamping (i.e., providing more carcasses than scavengers can consume so that some of the carcasses become unattractive to scavengers) (Smallwood 2007). We standardized all scavenging rates to this interval by assuming constant daily scavenging rates over the interval presented, and extrapolating to seven days. Detection biases favor large birds over small birds (because small birds are less likely to be detected and are scavenged more rapidly), which contributes to a smaller fraction of estimated total bird fatalities (Bevanger 1998, Smallwood 2007). To avoid overestimating scavenging and underestimating detection rates, we selected values only from trials performed with medium-sized and/or large birds (i.e., from Rock Dove [*Columba livia*] to Canada Goose [*Branta canadensis*] sizes). Because of their greater flying abilities, small birds are thought to be less vulnerable to collision with the overhead wire of transmission lines. Using the higher scavenging and lower detection rates associated with smaller carcasses would have led to an overestimation of medium and large bird mortality. Also, relatively few studies have dealt with small birds, so those data are unreliable. Finally, we focused on larger birds because population effects are more likely for them than for smaller more numerous birds. However, clearly, studies are needed to quantify small bird collision casualties with transmission lines. To control for seasonal variation in scavenging rates (Smallwood 2007) and observer efficiency (Bevanger and Brøseth 2004), we selected trial values in a season-independent way (in any season), and estimated a mean yearly rate for both parameters.

We estimated losses due to crippling using the number of birds that collide with transmission lines but fall outside of a given search area, or the number of injured birds that move outside of the search area (Savereno et al. 1996, APLIC 2012). Estimates of crippling rates were rare in the literature, likely due to the logistical effort and challenges in detecting crippled birds (APLIC 2012). Many authors relied on previous assessments of crippling rates to calculate the total number of dead birds found at the scale of their study area (e.g., Beaulaurier 1981, Bevanger 1995). It is emphasized by many that crippling rates should not be borrowed from other studies without significant evaluation, partly because species sizes and other scenario-specific factors are important; larger birds are more likely to lose control after glancing power lines than are smaller birds (W. Brown, *personal communication*, *in* APLIC 2012). Crippling biases are particularly difficult to estimate because birds must be observed hitting the power lines and continuing their movement elsewhere, which is very difficult unless radio tracking or other techniques are employed (Bevanger 1995).

Estimates of Canadian losses

We calculated estimates for four different bias correction scenarios: one uncorrected for any biases, a second corrected for search bias, a third corrected for search and scavenging biases, and a fourth corrected for search, scavenging, and crippling biases. We calculated the lower 95% confidence interval (CI), the mean, and the upper 95% CI values of the arithmetic mean of mortality data (Appendix 1). Corrected estimates were obtained following Bevanger (1995) and then multiplied by the total length of transmission lines in Canada. Following this method, the total number of dead birds found (tdb) was divided by the product of search (pbf), scavenging (pnr), habitat (ps), and crippling (pbk) biases (Table A2.1) as follows: $tdb/pbf{\cdot}pnr{\cdot}ps{\cdot}pbk$. For corrected scenarios, we assumed that 100% of the area was efficiently searchable, and did not correct for habitat biases.

We calculated estimated annual bird losses for Canada in four ways: one using an average of all the data available on mortality rates, the next using the upper and lower 95% CI of the average MMI, another using a geographically similar area (Michigan) as a proxy for Canada, and a fourth using a geographically stratified approach. Although there were no estimates from Canada, we stratified in the following ways: (1) transmission lines located in low risk areas (e.g., boreal Canada; ~60% of lines) incur low collision rates because they are in forested areas and are for the most part oriented north–south in the general direction of bird migration (we used the average of the five lowest rates found in the literature; Appendix 1, mean = 0.7 ± 0.3, coefficient of variation = 38%); (2) transmission lines in southern Canada (~30% of lines) incur higher collision rates, geographically similar to those measured in Michigan; and (3) in a few areas (~10% of lines) mortality is assumed to be high ("hot spots") and incurs higher losses similar to values for North Dakota (Appendix 1; mean = 41.0 ± 55.9, *n* = 7, CV = 136). We calculated a cumulative estimate based on the relative proportion of the three strata.

To identify potentially vulnerable species, we surveyed the literature for studies that recorded transmission line mortalities for species in Canada and the northern U.S. (Fig. 2). In order to combine data across studies, we assumed that the counts of dead birds represented continuous survey effort over the entire study period and reflected the relative proportion of different species detected (e.g., two different studies over two months would be treated the same whether the surveys were conducted every three days or once per week).

RESULTS

Rates of collision mortality

The sampling design for seven of the nine studies selected was based on "convenience sampling" (sampling at irregular intervals) (Anderson 2001); one was systematic (sampling at regular intervals) (Alonso and Alonso 1999), and one was unknown (Rubolini et al. 2005). Among the studies reviewed, none mentioned the sampling effort invested per site, and only one study provided an approximate value of total sampling effort (EPRI 2003). The average number of dead birds per kilometer of transmission line per year (MMI) for the nine studies selected was 42.3 ± 17.1 (± CI 95%; *n* = 32, CV = 119%) (Appendix 1). Our results show that MMI values are less variable between years (mean CV = 38%) than between sites (mean CV = 102%) (Table A2.2). However, Rusz et al. (1986) monitored a site for five years and obtained a CV of 70% in their estimate of collision rates between years, which suggests that interannual variation can be high. The frequency distribution of the number of carcasses found per kilometer of transmission line per year (MMI; Fig. 3) shows that our sample does not seem to be biased by data from sites with unusually high mortality rates. However, the sites included are diverse and from a variety of countries, and the studies were not conducted in Canada.

Fig. 2. Relative frequency of avian mortalities due to collisions with transmission lines in Canada (Anderson 1978, Meyer 1978, Cassel et al. 1979, James and Haak 1979, Beaulaurier 1981, Malcolm 1982, Rusz et al. 1986, Faanes 1987, Anderson and Murphy 1988, Savereno et al. 1996, McKenna and Allard 1976). Data were standardized to control for differences in search effort. Mortalities are grouped by avian Order. *Mortalities for these Orders may be underrepresented due to their frequent appearance in single-species studies (e.g., for endangered populations); therefore, numbers for these groups should be interpreted with caution. N/A: bird remains that could not be identified or categorized.

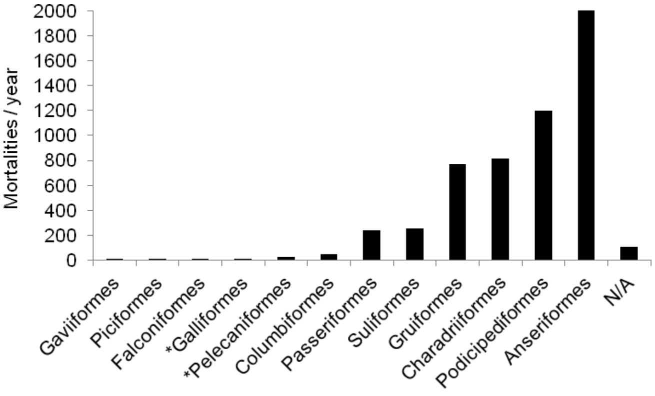
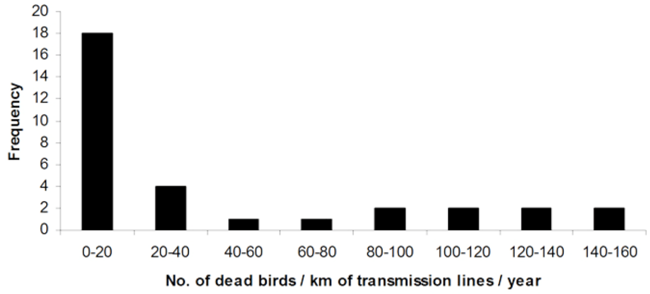


Fig. 3. Frequency distribution of the number of bird carcasses found per kilometer of transmission line per year from nine studies conducted between 1972 and 2005 (*n* = 32).



Estimating detection and crippling biases

Investigator efficiency at finding medium-sized to large birds averaged 80% among the 12 studies we examined, which suggests a high degree of consistency (*n* = 38, 95% CI= ± 5%, CV = 18%) (Table A2.3). Removal rates of medium-sized to large birds by scavengers after seven days was highly variable

Table 2. Estimates of annual bird mortality (in millions) from collisions with transmission lines in Canada. We applied four different estimates of the minimum mortality index (MMI = # dead birds per kilometer of transmission line per year) multiplied by the total length of transmission lines in Canada: (a) an average estimate across all suitable studies (*n* = 32 study sites, "average MMI estimates"), (b) an estimate using the maximum and minimum values across all studies (*n* = 32 study sites, "Minimum and maximum estimates"), (c) an estimate using MMI from geographically similar regions (data from Michigan, "MMI from geographically similar estimates," and (d) an estimate stratified into high, average, and low rates to reflect regional variation ("geographically stratified estimates"). Stratified estimates use the average of the five lowest values in the literature ("low risk" values: 60% of transmission lines), the average of the geographically similar values to Canada (30%), and the hot spot values (10%). For each estimate, we applied a sequence of more refined correction factors: (i) MMI alone ("uncorr"), (ii) MMI plus a search correction, (iii) MMI plus search and scavenging rate ("search"), MMI plus scavenging and search rates ("scav"), (iv) MMI plus search, scavenging, and crippling rates ("cripp").

Type of Mortality Estimate	MMI Value Used (Mean ± CI)	Correction Applied			
		Uncorr	Search	Search + Scav	Search + Scav + Cripp
a) Average estimates (millions)					
Lower 95% CI		5.8	7.3	11.9	59.7
Average	(42.3 ± 17.2)	9.8	12.3	20.1	100.4
Upper 95% CI		13.8	17.2	28.2	141.1
b) Minimum and maximum estimates (millions)					
Min.	(25.1)	5.8	6.9	9.5	39.7
Max.	(59.5)	13.8	18.4	36.7	229.5
c) MMI from geographically similar estimates (millions)					
Lower 95% CI		1.4	1.8	2.3	7.1
Average	(16.4 ± 10.4)	3.8	4.8	6.2	19.0
Upper 95% CI		6.2	7.7	10.1	30.9
d) Geographically stratified estimates (millions)					
Lower 95% CI	(0.7 ± 0.2)†	1.0	1.2	2.0	10.1
Average	(16.4 ± 10.3)‡	2.5	3.1	5.1	25.6
Upper 95% CI	(54.5 ± 33.1)§	4.0	5.0	8.2	41.2

† Low risk strata (60%)
‡ Medium risk strata (30%)
§ High risk strata (10%)

and averaged 39% for the 16 studies selected (*n* = 37, 95% CI = ± 11%, CV = 84%; Table A2.3). Only four studies that appropriately measured crippling rates were found. Reported values averaged 80% and showed low variability (*n* = 4, 95% CI = ± 4%, CV = 17%; Table A2.4). Because of the strong effect of crippling rates on estimates, we present our results both with this bias incorporated and without it. Additional studies that estimate crippling rates are needed to further refine overall mortality estimates.

Canadian collision mortality

We calculated Canadian collision mortality in three ways: first, using an average detection estimate based on data from all countries of origin (*n* = 32 sites), another using a geographical area similar to that of Canada, as a proxy, and a third using estimates stratified by location and habitat. Using data from the literature, independent of geographical origin, as well as the average values for search efficiency, scavenging, and crippling rates, we estimated that between 5.8 and 141.1 million birds are killed annually due to collisions with transmission lines in Canada (Table 2). The addition of estimated scavenging and search efficiency rates increased the estimated collision mortality by a factor of 2, while the cumulative addition of the crippling bias increased estimates by a factor of 10. Because there was uncertainty in the estimates of search, scavenging, and crippling rates, we also derived a minimum estimate using the lower 95% CI MMI and a maximum estimate using the upper 95% CI MMI. Overall, the number of birds estimated to be killed in Canada due to collisions ranged between 5.8 and 229.5 million, respectively (Table 2).

If mortality rates vary geographically, we may over- or underestimate the true collision mortality in Canada. To explore the effect of the geographical origin of mortality rates on the estimated total, we restricted mortality rates to the values derived from studies located close to Canada (i.e., Michigan; geographically similar mean MMI = 16.4 ± 10.3, *n* = 5, CV = 71%). These estimates ranged from 1.4 million birds (uncorrected) to 30.9 million birds (corrected for search, scavenger, and crippling bias) colliding with transmission lines, slightly lower than the estimate obtained using the range-wide data (Table 2).

To account for the variation in collision risk across Canada, stratified estimates were calculated by summing the product of each representative location's MMI (i.e., low risk, geographically similar, or hot spot areas' MMI) and associated proportional length of transmission lines covered by each stratum. The stratified scenario, considering these representative areas (60%, 30%, and 10% of lines, respectively), yielded average estimates of 2.5 (uncorrected) to 25.6 million (fully corrected) birds (Table 2).

We also assessed the relative vulnerability of different bird groups to collision mortality by tallying the rates of detection of different species groups (Fig. 2). Overall, Anseriformes (waterfowl) were most commonly detected, followed by Podicipediformes (grebes) and Charadriiformes (shorebirds). As expected, cranes (Gruiformes) also commonly collided with transmission lines.

Distribution line mortality in Canada

Because there were so few data on the impact of distribution lines on Canadian birds, we used the average of the five lowest casualty estimates for transmission lines (MMI = 0.66) and multiplied it by the total length of distribution lines in the country (572,370 km) to derive a conservative estimate of 377,764 birds killed per year. If we assume similar scavenging and crippling rates, the estimate increases to 774,107 and 3.9 million birds per year, respectively. This is likely a conservative estimate.

DISCUSSION

The length of transmission lines in Canada is currently 231,966 km, based on data from 2009, although globally, power line expansion is predicted to increase by ca. 5% per year (Jenkins et al. 2010). Although there are approximately four times more roads than transmission lines in Canada (Transport Canada 2013), avian mortality due to transmission lines is of a similar magnitude to road-related mortalities (Calvert et al. 2013), which suggests that mortality due to collisions with transmission lines is one of the top five highest sources of human-related avian mortality. The existing estimates of transmission line MMIs were highly variable, ranging from 0.3 to 154.07 birds killed per kilometer of transmission line per year (Appendix 1). Rates varied partly due to sampling biases in the distribution of the data among sites and years. Investigator efficiency at finding medium-sized to large birds was high, averaging 80%. However, scavenging rates were extremely variable and their incorporation contributed to a wide range of mortality estimates. We were unable to estimate detection and scavenging rates for small birds. Detection rates for small birds are likely to be lower, which would increase mortality estimates for this group. Crippling rates are estimated to be high; however, data are very limited. The incorporation of scavenging and efficiency rates increases the estimated collision rate by a factor of 2, while addition of the crippling bias increases estimates by a factor of 10. Consequently, understanding the magnitude of these three biases is essential to obtaining accurate mortality estimates.

Factors contributing to avian collisions

The factors that contribute to a species' vulnerability to power line collisions are generally well known. Species that flock, have rapid flight, and are large with slow maneuverability (high wing loading and low wing aspect ratio) are especially vulnerable, with younger individuals and nocturnal migrants exhibiting further vulnerability (Crivelli et al. 1988, Bevanger 1998, Erickson et al. 2001, Crowder and Rhodes 2002, Manville 2005, Jenkins et al. 2010). In addition, species such as cranes have poor vision directly ahead during flight, which partly contributes to their greater vulnerability to power line collisions (Martin and Shaw 2010). Similarly, high rates of collision by waterfowl may be due to adaptations for underwater vision; that is, many waterfowl are emmetropic, which causes nearsightedness above water (Jones et al. 2007, APLIC 2012). These characteristics should assist managers in assessing relative collision vulnerabilities of species prior to power line construction, which would allow more effective mitigations to be identified at the species level during environmental assessments.

The probability of collision is also influenced by the environmental and site attributes of transmission lines. Line placement, weather conditions, lighting, topography, and exposure to human disturbances have all been implicated in avian collisions (APLIC 1994, Pandey et al. 2008). Specifically, the height of power lines with respect to flight paths can be extremely important. Transmission lines (18.3–58 m) may be a greater threat to birds while flying at higher altitudes (e.g., migratory flights), while distribution lines (6.4–14.6 m) may become dangerous during lower altitude local flights (APLIC 2012). Pandey et al. (2008) found that the middle span of power lines was the most common place for collisions, which suggests that birds might aim for the point equidistant from the more visible poles. Human disturbance can cause flushing of flocks into power lines (Krapu 1974), in some cases causing dozens of mortalities at once (Blokpoel and Hatch 1976). Distracting lights can also disorient birds (some power lines crossing water bodies are lighted for aircraft safety), although the color and intensity of lights appear to have very different effects; steady burning lights appear to be the most detrimental (Longcore et al. 2008), while blinking red lights have been shown to significantly reduce collisions (Gehring et al. 2009, APLIC 2012). Time of day also appears to be important, with most collisions typically occurring at dusk and dawn (Pandey et al. 2008), although some studies have found little diurnal pattern (Martin and Shaw 2010). Tailwinds can also play an important role, which suggests that many collisions may be due to a lack of control in the flight path as opposed to poor visibility alone (Savereno et al. 1996). Unsurprisingly, weather associated with poor visibility, such as fog, cloud, and precipitation, is also associated with higher collision rates (APLIC 2012). Landscape features will affect the flight path of birds, potentially funneling them towards power lines (Bevanger 1990, APLIC 1994, Janss and Ferrer 2000, Martin and Shaw 2010), which makes line orientation an important feature in design planning (APLIC 2012).

Assessing impacts on bird populations

Several studies have concluded that collision mortality does not significantly impact selected bird populations (Meyer 1978, Thompson 1978, James and Haak 1979, Beaulaurier 1981, Faanes 1987, Alonso and Alonso 1999). Given the paucity of data on Canadian collision rates and mortalities, especially at the species level, we cannot evaluate impacts at a population level with confidence. Estimating impacts for migratory birds is further complicated because mortality rates are cumulative across the annual cycle, and migratory birds are exposed to different threats during migration and on their wintering and breeding grounds (i.e., Krapu 1979). For example, Whooping Cranes are highly vulnerable to collisions with transmission lines. The entire Whooping Crane population winters in the United States (COSEWIC 2010), where electrical structures are far more numerous than in Canada, which suggests that impacts during winter may be detrimental to recovery. Collisions are thought to be more common during migratory movements (Morkill and Anderson 1991), which suggests that a better understanding of impacts during migration is needed.

In addition, these impacts can be cumulative across the annual cycle. However, migration routes vary both within and across species, which leads to variation in the cumulative risk of collision. Estimating cumulative mortality for collision risks for species that breed in Canada is consequently very challenging and requires both a better understanding of, and improved methodologies for, integrating impact across the annual cycle.

The existing studies that have assessed collisions with transmission lines all use a nonrandom sampling design. This is not uncommon in the avian collision literature (Lehman et al. 2007) because the geographical scale of studies is usually restricted to problematic hot spots. Studies that assess collision probabilities over landscapes where selection is random or at least systematic and stratified by habitat composition would allow the sources of variation to be identified, and would greatly improve our ability to develop estimates that could be extrapolated over entire management units. We do not know if our national estimates are based on a representative sample of mortality rates, although our sample does not appear to be biased toward higher counts. The definition of a hot spot has yet to be quantified in Canada, but most studies report MMI rates between 0 and 20 dead birds per kilometer of transmission line per year (Fig. 3). Consequently, rates above this indicate areas of increased collision vulnerability.

The use of collision rates from southern locations and other countries may not reflect collision rates across Canada. For example, most major transmission lines in Canada are located in the boreal forest and are oriented north–south, parallel to the general direction of bird migration. We believe that collision rates associated with transmission lines in the boreal forest are likely to be lower than those associated with lines in more southern biomes, but to an unknown degree. Therefore, we consider our estimate, stratified by habitat, of 25.6 ± 15.5 million birds to be the most robust estimate currently available. However, we caution that these estimates should be compared to similar studies since most studies do not incorporate crippling losses. Without incorporating crippling losses, at least 5.1 ± 3.1 million birds are killed each year due to collisions with transmission lines.

Relative species vulnerability

Vulnerability to collisions with transmission lines varies across bird groups. Bevanger (1998) found that mortality by shorebirds (40%), waterfowl (24%), cranes and herons (14%), and Passeriformes (12%) was most frequently reported. Falconiformes, Anseriformes, and Charadriiformes accounted for half of collision fatalities reported across 100 studies (Hunting 2002). A compilation of more than 50 studies worldwide lists grebes, ducks, wading birds, shorebirds, raptors, and upland game birds as most vulnerable to collision mortality (SAIC 2000). The relative vulnerability of groups in Canada appears to be similar. Our compilation of avian mortality records from multiple transmission line studies carried out in Canada and the northern U.S. (Fig. 2) indicates that waterfowl (Anseriformes), grebes (Podicipediformes), shorebirds (Charadriiformes), and cranes (Gruiformes) are the top four most commonly killed bird groups. The absence of Pelecaniformes and Galliformes from the top of this list is likely due to our exclusion of studies that focused on particular species (i.e., endangered species).

While identifying the relative collision vulnerability of different bird groups can help prioritize future work, it is clear that some species are particularly susceptible and may require species-specific mitigations. Of the 74 avian species listed under the *Species at Risk Act* (Government of Canada 2013), 59% belong to categories identified by Bevanger (1998) as the most vulnerable to collisions. One species of particular concern is the endangered Whooping Crane, for which power line strikes have been identified as a threat to recovery (COSEWIC 2010). The threatened Least Bittern (*Ixobrychus exilis*) in southeastern Canada, and Alberta’s at risk Trumpeter

Swan also appear to be susceptible to collisions with human-built structures (Alberta Trumpeter Swan Recovery Team 2006, COSEWIC 2009). The Great Blue Heron (*Ardea herodias fannii*), currently of special concern (COSEWIC 2008), is distributed within the densely populated area surrounding the Georgia Strait, where human populations are expected to double in the next 30 years, which could exacerbate the identified threat of power line collisions (COSEWIC 2008). At the national level in Canada, waterfowl and raptor populations are increasing (NABCI 2012), which suggests that (at current levels) collisions are not impacting populations. On the other hand, a marked decrease in aerial insectivores (e.g., Barn Swallows [*Hirundo rustica*], Chimney Swifts [*Chaetura pelagica*], Common Nighthawks [*Chordeiles minor*], and shorebirds [NABCI 2012]) suggests that power line mortality may be contributing to their declines.

Mitigation measures

Our estimates of avian mortality due to collisions with transmission lines, and the predicted increases in transmission lines, highlight the need to identify and evaluate potential measures to reduce mortality. To date, the most cost-effective mitigation, line marking, has consistently shown reductions in avian mortalities from collisions; however, the effectiveness of various types of marking varies widely (9.6%–80%) (Beaulaurier 1981, Morkill and Anderson 1991, Crowder 2000, APLIC 2012). In addition, line marking reduces mortality mainly for less vulnerable bird species (Janss and Ferrer 1998, 2000), thereby necessitating additional measures for highly susceptible species. Line burial or complete removal of static wires in areas of low-lightning strike risk is of course the ultimate measure to reduce avian mortalities, but is also generally the most expensive approach (APLIC 2012). A better understanding of the relationship between bird densities, collision risk, and habitat type would help identify high-risk areas and allow better allocation of resources. Use of a geographic information systems (GIS) approach to this knowledge gap is recommended.

New technology such as Bird Strike Indicators (line-mounted vibration sensing/recording devices) are a promising tool in estimating avian power line collision rates, and they significantly reduce detection biases. The device, developed by the California Energy Commission, has operated successfully in extreme weather conditions, and is not biased by traffic vibrations (Pandey et al. 2008). In addition, this device can transmit data remotely (with possible applications to monitoring Canada’s boreal forest), and eliminates the need for estimating scavenger and search biases (Pandey et al. 2008). Identification to the species level is still difficult, and Bird Strike Indicators are likely to be deployed only at hot spots, so additional problems still remain. A potential mitigation for this problem is the development of Bird Activity Monitors, an image-recording detection system based on a trigger mechanism; however, this system is still in the early stages of development (EPRI 2003). GIS studies linking bird density, migration corridors, and habitat type would greatly help in quantifying collision risks.

CONCLUSION

Overall estimates of collision mortality are strongly influenced by the magnitude of detection biases. Additional work is needed to understand the factors influencing rates of bird collisions with transmission lines. Estimates of search, scavenging, and crippling biases are highly variable across sites and seasons, which makes extrapolations difficult. Crippling rates, in particular, appear to be high and frequently are not measured or incorporated into estimates. A better understanding of crippling rates is a critical need. Not surprisingly, scavenging rates were highly variable between years and sites, which suggests that some assessment of scavenging rates should be considered in each study. Pandey et al. (2008) used trapping to eliminate scavengers completely from their study area for a short period of time, which not only reduced scavenging bias to zero but also identified species composition of scavengers. This may allow estimates to be calculated based on the numbers and diet of identified scavengers in a given area/habitat. For a more detailed review of scavenging and crippling biases, see Bishop et al. (2013).

We were limited in our ability to stratify transmission lines into major biomes, habitats, and line types. Such stratification would improve our estimates. Also, most collision estimates in the literature were based on studies done in areas that are highly susceptible to collisions; therefore, they are likely unrepresentative of most transmission lines and they likely overestimate casualties. However, the lack of Canadian data on mortalities in most biomes, provinces, and habitats precludes any detailed analysis. It is clear that any study on collision mortalities must take into consideration scavenging, detection, and crippling biases. Our estimates are crude but provide a first estimate of the range of bird mortality due to collisions with transmission lines in Canada.

Responses to this article can be read online at:
http://www.ace-eco.org/issues/responses.php/614

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LITERATURE CITED

Alberta Trumpeter Swan Recovery Team. 2006. *Alberta Trumpeter Swan Recovery Plan, 2005–2010*. Alberta Sustainable Resource Development, Fish and Wildlife Division, Alberta Species at Risk Recovery Plan No. 12. Edmonton, Alberta, Canada.

Alonso, J. A., and J. C. Alonso. 1999. Collision of birds with overhead transmission lines in Spain. Pages 57–82 *in* M. Ferrer, and G. F. Janns, editors. *Birds and power lines: collision, electrocution, and breeding*. Quercus, Madrid, Spain.

Anderson, D. R. 2001. The need to get the basics right in wildlife field studies. *Wildlife Society Bulletin* 29:1294–1297.

Anderson, W. L. 1978. Waterfowl collisions with power lines at a coal-fired power plant. *Wildlife Society Bulletin* 6:77–83.

Anderson, B. A., and S. M. Murphy. 1988. *Lisburne terrestrial monitoring program, 1986 and 1987: the effects of the Lisburne powerline on birds: final report.* Alaska Biological Research Inc., Fairbanks, Alaska, USA.

Avian Power Line Interaction Committee (APLIC). 1994. *Mitigating bird collisions with power lines: the state of the art in 1994*. Edison Electric Institute, Washington, D.C., USA.

Avian Power Line Interaction Committee (APLIC). 2006. *Suggested practices for avian protection on power lines: the state of the art in 2006*. Edison Electric Institute, APLIC, and the California Energy Commission, Washington, D.C., USA.

Avian Power Line Interaction Committee (APLIC). 2012. *Reducing avian collisions with power lines: the state of the art in 1994*. Edison Electric Institute and APLIC, Washington, D.C., USA.

Beaulaurier, D. L. 1981. *Mitigation of bird collisions with transmission lines*. Bonneville Power Administration, Portland, Oregon, USA.

Bevanger, K. 1990. Topographic aspects of transmission wire collision hazards to game birds in the Central Norwegian coniferous forest. *Fauna Norvegica, Series C. Cinclus* 13:11–18.

Bevanger, K. 1994. Bird interactions with utility structures: collision and electrocution, causes and mitigating measures. *Ibis* 136:412–425. http://dx.doi.org/10.1111/j.1474-919X.1994.tb01116.x

Bevanger, K. 1995. Estimates and population consequences of tetraonid mortality caused by collisions with high tension power lines in Norway. *Journal of Applied Ecology* 32:745–753. http://dx.doi.org/10.2307/2404814

Bevanger, K. 1998. Biological and conservation aspects of bird mortality caused by electric power lines: a review. *Biological Conservation* 86:67–76. http://dx.doi.org/10.1016/S0006-3207(97)00176-6

Bevanger, K. 1999. Estimating bird mortality caused by collision and electrocution with power lines: a review of methodology. Pages 29–56 *in* M. Ferrer, and G. F. Janns, editors. *Birds and power lines: collision, electrocution, and breeding*. Quercus, Madrid, Spain.

Bevanger, K., and H. Brøseth. 2001. Bird collisions with power lines—an experiment with ptarmigan (*Lagopus* spp.). *Biological Conservation* 99:341–346. http://dx.doi.org/10.1016/S0006-3207(00)00217-2

Bevanger, K., and H. Brøseth. 2004. Impact of power lines on bird mortality in a subalpine area. *Animal Biodiversity and Conservation* 27:67–77.

Bishop, C. A., and J. M. Brogan. 2013. Estimates of avian mortality attributed to vehicle collisions in Canada . *Avian Conservation and Ecology* 8(2): 2. http://dx.doi.org/10.5751/ACE-00604-080202

Blokpoel, H., and D. R. M. Hatch. 1976. Snow geese, disturbed by aircraft, crash into power lines. *Canadian Field-Naturalist* 90:195.

Brown, W. M., C. Roderick, and E. G. Bizeau. 1987. Mortality of cranes and waterfowl from powerline collisions in the San Luis Valley, Colorado. Pages 128–136 *in Proceedings of the 1985 Crane Workshop* (Grand Island, 1985). Platte River Whooping Crane Maintenance Trust, Grand Island, Nebraska, USA.

Calvert, A. M., C. A. Bishop, R. D. Elliot, E. A. Krebs, T. M. Kydd, C. S. Machtans, and G. J. Robertson. 2013. A synthesis of human-related avian mortality in Canada. *Avian Conservation and Ecology* 8(2):11. http://dx.doi.org/10.5751/ACE-00581-080211

Canadian Environmental Assessment Agency (CEAA). 2013a. *Overview: Canadian Environmental Assessment Act*, 2012. [online] URL: http://www.ceaa.gc.ca/default.asp?lang=En&n=16254939-1

Canadian Environmental Assessment Agency (CEAA). 2013b. *Canadian Environmental Assessment Archives*. [online] URL: http://www.ceaa.gc.ca/052/index-eng.cfm

Canadian Environmental Assessment Agency (CEAA). 2013c. *Canadian Environmental Assessment Registry*. [online] URL: http://www.ceaa.gc.ca/050/index-eng.cfm

Cassel, J. F, D. W. Kiel, J. J. Knodel, and J. M. Wiehe. 1979. *Relations of birds to certain power transmission lines in central North Dakota*. North Dakota State University, Fargo, North Dakota, USA. Prepared for United Power Association.

Committee on the Status of Endangered Wildlife in Canada (COSEWIC). 2008. *COSEWIC assessment and update status report on the Great Blue Heron* fannini *subspecies* Ardea herodias fannini *in Canada*. Committee on the Status of Endangered Wildlife in Canada, Ottawa, Ontario, Canada. [online] URL: http://www.sararegistry.gc.ca/document/default_e.cfm?documentID=1615

Committee on the Status of Endangered Wildlife in Canada (COSEWIC). 2009. *COSEWIC assessment and update status report on the Least Bittern* Ixobrychus exilis *in Canada*. Committee on the Status of Endangered Wildlife in Canada, Ottawa, Ontario, Canada. [online] URL: http://www.sararegistry.gc.ca/document/default_e.cfm?documentID=1807

Committee on the Status of Endangered Wildlife in Canada (COSEWIC). 2010. *COSEWIC assessment and update status report on the Whooping Crane* Grus americana *in Canada*. Committee on the Status of Endangered Wildlife in Canada, Ottawa, Ontario, Canada. [online] URL: http://www.sararegistry.gc.ca/document/default_e.cfm?documentID=2095

Coues, E. 1876. The destruction of birds by telegraph wire. *American Naturalist* 10:734–736. http://dx.doi.org/10.1086/271788

Crivelli, A. J., H. Jerrentrup, and T. Mitchev. 1988. Electric power lines: a cause of mortality in *Pelecanus crispus* Bruch, a world endangered species, in Porto-Lago, Greece. *Colonial Waterbirds* 11:301–305. http://dx.doi.org/10.2307/1521012

Crowder, M. R. 2000. *Assessment of devices designed to lower the incidence of avian power line strikes*. Thesis. Purdue University, West Lafayette, Indiana, USA.

Crowder, M. R., and O. E. Rhodes, Jr. 2002. Relationships between wing morphology and behavioural responses to unmarked power transmission lines. Pages 403–410 in J. W. Goodrich-Mahoney, D. F. Mutrie, and C. A. Guild, editors. *The Seventh International Symposium on Environmental Concerns in Rights-of-Way Management*. Elsevier, Boston, Massachusetts, USA.

Electric Power Research Institute (EPRI). 2003. *Bird strike indicator/bird activity monitor and field assessment of avian fatalities*. EPRI, Palo Alto, California, Audubon National Wildlife Refuge, Coleharbor, North Dakota, Edison Electric Institute, Washington, D.C., Bonneville Power Administration, Portland, Oregon, California Energy Commission, Sacramento, California, NorthWestern Energy, Butte, Montana, Otter Tail Power Company, Fergus Falls, Minnesota, Southern California Edison, Rosemead, California, Western Area Power Administration, Lakewood, Colorado. 1005385.

Erickson, W. P., G. D. Johnson, M. D. Strickland, K. J. Sernka, and R. E. Good. 2001. *Avian collisions with wind turbines: a summary of existing studies and comparisons to other sources of avian collision mortality in the United States*. Western Ecosystems Technology, Inc., Cheyenne, Wyoming, USA.

Faanes, C. A. 1983. *Assessment of power lines sitting in relation to bird strikes in the northern Great Plains*. 1980 Annual Report. U.S. Fish and Wildlife Service, Northern Prairie Wildlife Research Center, Jamestown, North Dakota, USA.

Faanes, C. A. 1987. *Bird behavior and mortality in relation to power lines in prairie habitats*. Fish and Wildlife Technical Report 7. United States Department of the Interior, Jamestown, North Dakota, USA.

Flint, P. L., E. W. Lance, K. M. Sowl, and T. F. Donnelly. 2010. Estimating carcass persistence and scavenging bias in a human-influenced landscape in western Alaska. *Journal of Field Ornithology* 81:206–214. http://dx.doi.org/10.1111/j.1557-9263.2009.00262.x

Gehring, J., P. Kerlinger, and A. M. Manville, II. 2009. Communication towers, lights, and birds: successful methods of reducing the frequency of avian collisions. *Ecological Applications* 19:505–514. http://dx.doi.org/10.1890/07-1708.1

Government of Canada. 2013. *Species at Risk Act* (S.C. 2002, c. 29). [online] URL: http://laws-lois.justice.gc.ca/eng/acts/S-15.3/page-1.html

Hall, D. K, G. A. Riggs, and V. V. Salomonson. 2006. *MODIS/Terra Snow Cover Monthly L3 Global 0.05 Deg CMG V005, 2009*. National Snow and Ice Data Center, Boulder, Colorado, USA.

Hartman, P. A., S. Byrne, and M. F. Dedon. 1993. *Bird mortality in relation to the Mare Island 115-kV transmission line: final report 1988–1991*. Report 443-91.3. Department of the Navy, Western Division, California, USA.

Heck, N. 2007. *A landscape-scale model to predict the risk of bird collisions with electric power transmission lines in Alberta*. Thesis. University of Calgary, Calgary, Alberta, Canada.

Hugie, R. D., J. M. Bridges, B. S. Chanson, and M. Skougard. 1993. Results of a post-construction bird monitoring study on the Great Falls-Conrad 230-kV transmission line. *In Proceedings: Avian Interactions with Utility Structures International Workshop (Miami, 1992)*. Electric Power Research Institute, Palo Alto, California, USA. TR-103268 (Project 3041).

Hunting, K. 2002. *Assessing and mitigation avian mortality from collisions with power lines* [abstract only]. Western Section, The Wildlife Society 2002 Annual Conference Paper. Visalia, California, USA.

James, B. W., and B. A. Haak. 1979. *Factors affecting avian flight behaviour and collision mortality at transmission lines*.

Western Instate Commission for Higher Education-Bonneville Power Administration, Boulder, Colorado, USA.

Janss, G. F. E., and M. Ferrer. 1998. Rate of bird collision with power lines: effects of conductor-marking and static wire-marking. *Journal of Field Ornithology* 69:8–17.

Janss, G. F. E., and M. Ferrer. 2000. Common Crane and Great Bustard collision with power lines: collision rate and risk exposure. *Wildlife Society Bulletin* 28:675–680.

Jenkins, A. R., J. J. Smallie, and M. Diamond. 2010. Avian collisions with power lines: a global review of causes and mitigation with a South African perspective. *Biological Conservation* 10:1–16.

Jones, M. P., K. E. Pierce, Jr., and D. Ward. 2007. Avian vision: a review of form and function with special consideration to birds of prey. *Journal of Exotic Pet Medicine* 16:69–87. http://dx.doi.org/10.1053/j.jepm.2007.03.012

Krapu, G. L. 1974. Avian mortality from collisions with overhead wires in North Dakota. *Prairie Naturalist* 6:1–6.

Krapu, G. L. 1979. Sandhill Crane use of staging areas in Nebraska. Pages 1–5 *in* J. C. Lewis, editor. *Proceedings of the 1978 Crane Workshop (Rockport, 1978)*. Colorado State University and National Audubon Society, Rockport, Texas, USA.

Lehman, R. N., P. L. Kennedy, and J. A. Savidge. 2007. The state of the art in raptor electrocution research: a global review. *Biological Conservation* 136:159–174. http://dx.doi.org/10.1016/j.biocon.2006.09.015

Longcore, T., C. Rich, and S. A. Gauthreaux, Jr. 2008. Height, guy wires, and steady-burning lights increase hazard of communication towers to nocturnal migrants: a review and meta-analysis. *Auk* 125:485–492. http://dx.doi.org/10.1525/auk.2008.06253

Malcolm, J. M. 1982. Bird collisions with a power transmission line and their relation to botulism at a Montana wetland. *Wildlife Society Bulletin* 10:297–304.

Manville, A. M., II. 2005. *Bird strikes and electrocution at power lines, communication towers, and wind turbines: state of the art and state of the science—next step toward mitigation*. U.S. Forest Service General Technical Report PSW-GTR-191, Washington, D.C., USA.

Martin, G. R., and J. M. Shaw. 2010. Bird collisions with power lines: failing to see the way ahead? *Biological Conservation* 143:2695–2702. http://dx.doi.org/http://dx.doi.org/10.1016/j.biocon.2010.07.014

McKenna, M. G., and G. E. Allard. 1976. Avian mortality from wire collisions. *North Dakota Outdoors* 39:16–18.

Meyer, J. R. 1978. *Effects of transmission lines on bird flight behaviour and collision mortality*. Western Interstate Commission for Higher Education-Bonneville Power Administration, Portland, Oregon, USA.

Morkill, A. E., and S. H. Anderson. 1991. Effectiveness of marking powerlines to reduce Sandhill Crane collisions. *Wildlife Society Bulletin* 19:442–449.

North American Bird Conservation Initiative Canada (NABCI). 2012. *The state of Canada's birds, 2012*. Environment Canada, Ottawa, Ontario, Canada.

Pandey, A., R. Harness, and M. K. Schriner. 2008. *Bird strike indicator field deployment at the Audubon National Wildlife Refuge in North Dakota: phase two*. California Energy Commission, PIER Energy Related Environmental Research Program. CEC-500-2008-020.

Pearson, D. C. 1993. Avifauna collision study in the San Jacinto Valley of southern California. *In Proceedings: Avian Interactions with Utility Structures International Workshop (Miami, 1992)*. Electric Power Research Institute, Palo Alto, California, USA. TR-103268 (Project 3041).

Rubolini, D., M. Gustin, G. Bogliani, and R. Garavaglia. 2005. Birds and power lines in Italy: an assessment. *Bird Conservation International* 15:131–145. http://dx.doi.org/10.1017/S0959270905000109

Rusz, P. J., H. H. Prince, R. D. Rusz, and G. A. Dawson. 1986. Bird collisions with transmission lines near a power plant cooling pond. *Wildlife Society Bulletin* 14:441–444.

Savereno, A. J., L. A. Savereno, R. Boettcher, and S. M. Haig. 1996. Avian behaviour and mortality at power lines in coastal South Carolina. *Wildlife Society Bulletin* 24:636–648.

Science Applications International Corporation (SAIC). 2000. *Avian collision at transmission lines associated with the Hells Canyon complex*. Technical Report Appendix E.3.2-20. Science Applications International Corporation, Boise, Idaho, USA.

Smallwood, S. K. 2007. Estimating wind turbine-caused bird mortality. *Journal of Wildlife Management* 71:2781–2791. http://dx.doi.org/10.2193/2007-006

Tecsult Inc. 2009. *Portrait détaillé de l'occupation humaine du territoire et des activités reliées aux divers secteurs de l'industrie des six régions de conservation des oiseaux du Québec*. Tecsult Inc. for the Canadian Wildlife Service, Quebec Region, Québec, Canada.

Thompson, L. S. 1978. Transmission line wire strikes: mitigation through engineering design and habitat modification. Pages 27–52 *in* M. L. Avery, editor. *Impacts of transmission lines on migratory birds*. U.S. Fish and Wildlife Service, Washington, D.C., USA.

Transport Canada. 2013. Road transportation. [online] URL: http://www.tc.gc.ca/eng/road-menu.htm

APPENDIX 1. MMI (dead birds/km wire/year) values used to calculate standardized mortality rates.

Locality	Dead birds/km wire	Study length (days)	MMI	Source
California	14.2	281	18.45	Hartman *et al.* 1993
California	10.2	317	11.72	Hartman *et al.* 1993
California	5.9	315	6.88	Hartman *et al.* 1993
California	107.4	281	139.46	Hartman *et al.* 1993
California	108.4	317	124.84	Hartman *et al.* 1993
California	96.8	315	112.21	Hartman *et al.* 1993
Italy	152.5	640	86.97	Rubolini *et al.* 2005
Italy	39.1	730	19.57	Rubolini *et al.* 2005
Italy	36.0	365	36.03	Rubolini *et al.* 2005
Michigan†	19.1	238	22.10	Rusz *et al.* 1986
Michigan†	5.2	238	6.03	Rusz *et al.* 1986
Michigan†	7.8	266	8.09	Rusz *et al.* 1986
Michigan†	11.3	266	11.69	Rusz *et al.* 1986
Michigan†	31.3	252	34.16	Rusz *et al.* 1986
North Carolina	67.8	1461	16.94	Savareno *et al.* 1996
North Dakota†	112.6	201	154.07	EPRI 2003
North Dakota†	106.6	201	145.90	EPRI 2003
North Dakota†	113.9	397	78.89	Faanes 1987
North Dakota†	67.9	397	47.03	Faanes 1987
North Dakota†	149.1	397	103.27	Faanes 1987
North Dakota†	54.4	397	37.71	Faanes 1987
North Dakota†	8.3	397	5.77	Faanes 1987
Spain	0.5	365	0.50	Alonso et Alonso 1999
Spain	0.8	365	0.80	Alonso et Alonso 1999
Spain	0.8	365	0.80	Alonso et Alonso 1999
Spain	14.1	365	14.10	Alonso et Alonso 1999
Spain	0.9	365	0.90	Alonso et Alonso 1999
Spain	2.7	365	2.70	Alonso et Alonso 1999
Spain	2.0	365	2.00	Alonso et Alonso 1999
Spain	0.3	365	0.30	Alonso et Alonso 1999
Spain	2.9	366	2.88	Janss et Ferrer 1998
U.K.	594.9	2192	99.06	Scott *et al.* 1972

† Localities where MMI values were calculated for 275 days. MMI was calculated for 365 days in the remaining localities.

APPENDIX 2. Biases associated with estimating bird mortalities.

Table A2.1. Definition of bias sources and associated acronyms from Bevanger (1995).

Bias source	Acronym	Definition
Search	*pbf*	Percentage of dead birds found based on dead bird plant study.
Scavenging	*pnr*	Percentage of dead birds not removed by scavengers.
Habitat	*ps*	Proportion of line section which is searchable.
Crippling	*pbk*	Proportion of birds colliding that were killed and fell outside the search area.

Table A2.2. Yearly and site variation of MMI (No. of dead birds/km of transmission lines/year) values for studies that sampled at least two sites over a minimum of two years and for which site specific data were available. MMI values for Hartman *et al.* 1993 were calculated for 375 days (study conducted in California) whereas values for Hugie *et al.* 1993 were calculated for 275 days (study conducted in Montana).

Site	Year	MMI	Site	MMI	Source
Hayfield Transect	1988-1989	18.45	Saltpond Transect	139.46	Hartman *et al.* 1993
Hayfield Transect	1989-1990	11.72	Saltpond Transect	124.84	Hartman *et al.* 1993
Hayfield Transect	1990-1991	6.88	Saltpond Transect	112.21	Hartman *et al.* 1993
Bole Bench	Spring 1988	1.93	Lake Creek	6.82	Hugie *et al.* 1993†
Bole Bench	Spring 1989	3.87	Lake Creek	13.78	Hugie *et al.* 1993†

† The study length per site is less than 200 days in Hugie *et al.* 1993. The results of this study were not used elsewhere than in this table.

Table A2.3. Crippling bias values used to calculate standardized mortality rates. Values represent the number of birds colliding with wires that fall outside the search area.

Country	Value	Source
USA	0.75	Meyer 1978
USA	0.75	Savereno *et al.* 1996
USA	0.73	Savereno *et al.* 1996
USA	0.82	Crowder 2000

Table A2.4. Search and scavenger bias values used to calculate standardized mortality rates. Search bias is referred as the percentage of planted birds founds by observers. Scavenger bias rates are expressed as the percentage of carcasses remaining after 7 days.

Search bias			Scavenger Bias		
Country	Rate	Source	Country	Rate	Source
USA	0.82	Beaulaurier 1981	Norway	0.21†	Bevanger and Brøseth 2004
USA	0.78	Beaulaurier 1981	USA	0.47†	Beaulaurier 1981
USA	0.72	Brown and Drewien 1995	USA	0.63†	Beaulaurier 1981
USA	0.88	Erickson *et al.* 2000	USA	0.20	Brown and Drewien 1995
USA	0.78	Erickson *et al.* 2003	USA	0.18†	Erickson *et al.* 2000
USA	0.92	Erickson *et al.* 2004	USA	0.08†	Erickson *et al.* 2000
USA	1.00	Erickson *et al.* 2004	USA	0.15†	Erickson *et al.* 2000
USA	0.60	Erickson *et al.* 2004	USA	0.05†	Erickson *et al.* 2000
USA	1.00	Erickson *et al.* 2004	USA	0.13†	Erickson *et al.* 2003
USA	0.80	Erickson *et al.* 2004	USA	0.30†	Erickson *et al.* 2004
USA	0.80	Erickson *et al.* 2004	USA	0.18†	Erickson *et al.* 2004
USA	0.67	Erickson *et al.* 2004	USA	0.20†	Erickson *et al.* 2004
USA	0.60	Erickson *et al.* 2004	USA	0.25†	Erickson *et al.* 2004
USA	0.91	Erickson *et al.* 2004	USA	0.20†	Erickson *et al.* 2004
USA	0.60	Erickson *et al.* 2004	USA	0.23†	Erickson *et al.* 2004
USA	0.75	Erickson *et al.* 2004	USA	0.15†	Erickson *et al.* 2004
USA	1.00	Erickson *et al.* 2004	USA	0.16†	Erickson *et al.* 2004
USA	0.89	Erickson *et al.* 2004	USA	0.17†	Erickson *et al.* 2004
USA	0.67	Erickson *et al.* 2004	USA	0.14†	Erickson *et al.* 2004
USA	0.44	Erickson *et al.* 2004	USA	1.00†	Flint *et al.* 2010
USA	0.75	Erickson *et al.* 2004	USA	0.19	Johnson *et al.* 2003
USA	1.00	Johnson *et al.* 2003	USA	0.33	Jones and Stokes inc. 2008
USA	0.75	Johnson *et al.* 2003	USA	0.30	Kerlinger *et al.* 2006
USA	1.00	Johnson *et al.* 2003	USA	0.57	Kerlinger *et al.* 2006
USA	1.00	Johnson *et al.* 2003	USA	0.91†	Kostecke and Linz 2001
USA	1.00	Kerlinger *et al.* 2006	USA	0.99†	Kostecke and Linz 2001
USA	1.00	Kerlinger *et al.* 2006	USA	0.91†	Kostecke and Linz 2001
USA	0.87	Meyer 1978	USA	1.00†	Kostecke and Linz 2001
USA	0.63	Meyer 1978	USA	1.00†	Meyer 1978
USA	0.80	Meyer 1978	USA	1.00†	Meyer 1978
USA	0.73	Meyer 1978	USA	0.00	Orloff and Flanery 1992
USA	0.82	Higgins *et al.* 1995	USA	0.64†	Savareno *et al.* 1996
USA	0.63	Higgins *et al.* 1995	USA	0.35†	Savareno *et al.* 1996
USA	0.88	Strickland (unpub. data)	USA	0.31	Smallwood *et al.* 2010
USA	0.78	Osborn *et al.* 2000	USA	0.00	Smallwood *et al.* 2010
USA	0.92	Osborn *et al.* 2000	S. Africa	0.49†	Shaw 2009
USA	0.66	Savareno *et al.* 1996			
USA	0.73	Savareno *et al.* 1996			

† Extrapolated or inferred values

APPENDIX 3. Literature cited in Appendices 1 – 2.

Alonso, J. A. and J. C. Alonso. 1999. Collision of birds with overhead transmission lines in Spain. Pages 57-82 *in in* M. Ferrer, G. F. Janns, editors. *Birds and power lines: collision, electrocution, and breeding*. Quercus, Madrid, Spain.

Beaulaurier, D. L. 1981. *Mitigation of bird collisions with transmission lines.* Bonneville Power Administration, Portland, Oregon, USA.

Bevanger, K. 1995. Estimates and population consequences of tetraonid mortality caused by collisions with high tension power lines in Norway. *Journal of Applied Ecology* 32:745-753.

Bevanger, K., and H. Brøseth. 2004. Impact of power lines on bird mortality in a subalpine area. *Animal Biodiversity and Conservation* 27:67-77.

Brown, W. M., and R. C. Drewien. 1995. Evaluation of two power line markers to reduce crane and waterfowl collision mortality. *Wildlife Society Bulletin* 23:217-227.

Crowder, M. R. 2000. *Assessment of devices designed to lower the incidence of avian powerline strikes.* Thesis, Purdue University, West Lafayette, Indiana, USA.

EPRI [Electric Power Research Institute]. 2003. *Bird strike indicator/bird activity monitor and field assessment of avian fatalities.* Palo Alto, California, USA.

Erickson, W. P., G. D. Johnson, M. D. Strickland, and K. Kroner. 2000. *Final report: avian and bat* mortal*ity associated with the Vancycle Wind Project, Umatilla County, Oregon: 1999 study year*. Umatilla County Department of Resources Services and Development, Pendleton, Oregon, USA.

Erickson, W. P., K. Kronner, and B. Gritski. 2003. Nine Canyon Wind Power Project avian and bat monitoring report. Report to Nine Canyon Technical Advisory Committee, Energy Northwest, WEST, Cheyenne, Wyoming, USA.

Erickson, W. P., J. Jeffrey, K. Kronner, and K. Bay. 2004. Stateline wind project wildlife monitoring final report, July 2001-December 2003. Technical Report submitted to FPL Energy, the Oregon Energy Facility Siting Council and the Stateline Technical Advisory Committee. WEST, Cheyenne, Wyoming, USA.

Faanes, C. A. 1987. Bird behavior and mortality in relation to power lines in prairie habitats. Fish and Wildlife Technical Report 7. United States Department of the Interior, Jamestown, North Dakota, USA.

Flint, P. L., E. W. Lance, K. M. Sowl, and T. F. Donnelly. 2010. Estimating carcass persistence and scavenging bias in a human-influenced landscape in western Alaska. *Journal of Field Ornithology* 81:206-214.

Hartman, P. A., S. Byrne, and M. F. Dedon. 1993. Bird mortality in relation to the Mare Island 115-kV transmission line: final report 1988–1991 *in: Proceedings: Avian Interactions with Utility Structures. 1993.* Electric Power Research Institute, Palo Alto, California, USA.

Higgins, K. F.; C. D. Dieter, and R. E. Usgaard. 1995. *Monitoring of seasonal bird activity and* mortal*ity on Unit 2 at the Buffalo Ridge Windplant, Minnesota.* Kenetech, Inc., San Francisco, California, USA.

Hugie, R. D., J. M. Bridges, B. S. Chanson, and M. Skougard. 1993. Results of a post-construction bird monitoring study on the Great Falls-Conrad 230-kV transmission line *in: Proceedings: Avian Interactions with Utility Structures. 1993.* Electric Power Research Institute, Palo Alto, California, USA.

Janss, G. F. E., and M. Ferrer. 1998. Rate of bird collision with power lines: effects of conductor-marking and static wire-marking. *Journal of Field Ornithology* 69:8-17.

Johnson, G.D., W.P. Erickson, J. White, and R. McKinney. 2003. Avian and bat mortality during the first year of operation at the Klondike Phase I Wind Project, Sherman County, Oregon. Northwestern Wind Power, Goldendale, Washington, USA.

Jones and Stokes, Inc. 2008. Altamont pass carcass removal/scavenging trial. Technical Memorandum. ICF Jones and Stokes Inc., Sacramento, California, USA.

Kerlinger, P., R. Curry, L. Culp, A. Jain, C. Wilkerson, B. Fisher, and A. Hasch. 2006. Post-construction avian and bat fatality monitoring study for the High Winds Wind Power Project, Solano County, California: two-year report. High Winds, LLC and FPL Energy, Juno Beach, Florida, USA.

Kostecke, R. M., G. M. Linz, and W. J. Bleier. 2001. Survival of avian carcasses and photographic evidence of predators and scavengers. *Journal of Field Ornithology* 72:439-447.

Meyer, J. R. 1978. Effects of transmission lines on bird flight behavior and collision mortality. Bonneville Power Administration, Portland, Oregon, USA.

Orloff, S., A. Flannery. 1992. Wind turbine effects on avian activity, habitat use, and mortality in Altamont Pass and Solano County Wind Resource Areas. California Energy Commission, Sacramento, California, USA.

Osborn, R. G., K. F. Higgins, R. E. Usgaard, C. D. Dieter, and R. D. Neiger. 2000. Bird mortality associated with wind turbines at the Buffalo Ridge Wind Resource Area, Minnesota. *American Midland Naturalist* 143:41-52.

Rubolini, D., M. Gustin, G. Bogliani, and R. Garavaglia. 2005. Birds and power lines in Italy: an assessment. *Bird Conservation International* 15:131-145.

Rusz, P. J., H. H. Price, R. D. Rusz, and G. A. Dawson. 1986. Bird collisions with transmission lines near a power plant cooling pond. *Wildlife Society Bulletin* 14:441-444.

Savereno, A. J., L. A. Savereno, R. Boettcher, and S. M. Haig. 1996. Avian behaviour and mortality at power lines in coastal South Carolina. *Wildlife Society Bulletin* 24:636-648.

Scott, R. E., L. J. Roberts, and C. J. Cadbury. 1972. Bird deaths from power lines at Dungeness. *British Birds* 65:273–286.

Shaw, J. M. 2009. *The end of the line for South Africa's national bird? Modeling power line collision risk for the Blue Crane.* M.Sc. Thesis, University of Cape Town, Rondebosch, South Africa.

Smallwood, K. S. 2007. Estimating wind turbine-caused bird mortality. Journal of Wildlife Management 71: 2781-2791.

Smallwood, K. S., D.A. Bell, S.A. Snyder, and J. E. Didonato. 2010. Novel scavenger removal trials increase wind turbine-caused avian fatality estimates. *Journal of Wildlife Management* 74:1089-1097.