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Research Paper, part of a special feature on **Quantifying Human-related Mortality of Birds in Canada**

A Synthesis of Human-related Avian Mortality in Canada

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ABSTRACT

Many human activities in Canada kill wild birds, yet the relative magnitude of mortality from different sources and the consequent effects on bird populations have not been systematically evaluated. We synthesize recent estimates of avian mortality in Canada from a range of industrial and other human activities, to provide context for the estimates from individual sources presented in this special feature. We assessed the geographic, seasonal, and taxonomic variation in the magnitude of national-scale mortality and in population-level effects on species or groups across Canada, by combining these estimates into a stochastic model of stage-specific mortality. The range of estimates of avian mortality from each source covers several orders of magnitude, and, numerically, landbirds were the most affected group. In total, we estimate that approximately 269 million birds and 2 million nests are destroyed annually in Canada, the equivalent of over 186 million breeding individuals. Combined, cat predation and collisions with windows, vehicles, and transmission lines caused > 95% of all mortality; the highest industrial causes of mortality were the electrical power and agriculture sectors. Other mortality sources such as fisheries bycatch can have important local or species-specific impacts, but are relatively small at a national scale. Mortality rates differed across species and families within major bird groups, highlighting that mortality is not simply proportional to abundance. We also found that mortality is not evenly spread across the country; the largest mortality sources are coincident with human population distribution, while industrial sources are concentrated in southern Ontario, Alberta, and southwestern British Columbia. Many species are therefore likely to be vulnerable to cumulative effects of multiple human-related impacts. This assessment also confirms the high uncertainty in estimating human-related avian mortality in terms of species involved, potential for population-level effects, and the cumulative effects of mortality across the landscape. Effort is still required to improve these estimates, and to guide conservation efforts to minimize direct mortality caused by human activities on Canada’s wild bird populations. As avian mortality represents only a portion of the overall impact to avifauna, indirect effects such as habitat fragmentation and alteration, site avoidance, disturbance, and related issues must also be carefully considered.

Key words: bird mortality; cats; collisions; human impacts; incidental take; industry; population effects

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INTRODUCTION

Several billion birds from over 400 species breed each year in Canada (Blancher 2002), in a wide variety of habitats. Landbirds, i.e., songbirds, raptors, upland gamebirds, represent most of the birds in Canada and tend to have large and widespread populations. Aquatic birds, such as waterfowl, seabirds, shorebirds, and inland waterbirds, occupy freshwater and marine habitats across the country. Birds occupy diverse niches across Canada that overlap substantially with human activities, and so are vulnerable to a large range of human-related stressors. The recent *State of Canada's Birds* report (NABCI-Canada 2012) highlighted conservation efforts that have contributed to increases in waterfowl and raptor populations, but shorebirds, grassland birds, and aerial insectivores have experienced rapid declines, some of which are attributed to human-driven habitat change and mortality across North America over the past 40 years (NABCI-Canada 2012).

Direct mortality resulting from human activities may have important consequences, particularly when it is additive to natural mortality, i.e. if individuals killed would have otherwise survived (Anderson and Burnham 1976). Agricultural practices, for example, have been identified as a factor in declines of Northern Pintail (*Anas acuta*; Miller and Duncan 1999, Prairie Habitat Joint Venture 2008) and Bobolink (*Dolichonyx oryzivorus*; COSEWIC 2010) as well as U.S. grassland birds (Mineau and Whiteside 2013), while reduced juvenile survivorship and population declines of urban songbirds have been linked to predation by cats (Crooks and Soulé 1999, Balogh et al. 2011). Quantification of the magnitude of human-related avian mortality, and its population-level effects on Canada's birds, is essential for directing management and conservation actions and for prioritizing future research directions (Loss et al. 2012); especially when considered in conjunction with indirect stressors such as habitat alteration and climate change.

Preventing and minimizing human-related mortality to birds, their nests, and eggs is widely supported by environmental legislation in Canada. Federal and provincial governments are responsible for the protection, conservation, and management of birds under the federal Migratory Birds Convention Act (S.C. 1994, c. 22), the federal Species at Risk Act (S.C. 2002, c. 29) and various provincial wildlife Acts. These laws generally prohibit the destruction of nests and eggs, and the "take" or killing of individual birds. Permitting systems exist to manage direct mortality due to hunting or while preventing damage and danger to the public, but provisions or systems to authorize inadvertent destruction of nests or birds as a consequence of anthropogenic activities, often called 'incidental take,' are applicable only to limited species or circumstances. Activities that may destroy nests or birds are currently managed through compliance promotion and by providing relevant information, e.g., timing of breeding seasons, key migration periods and pathways, to industrial sectors. This information allows the development and adoption of measures that minimize the risk of inadvertent destruction of nests and eggs, or killing of individuals.

Some sources of human-related avian mortality are well-quantified, such as the regulated sport harvest of game birds, but the magnitudes of most sources are imprecise or unknown. In particular, those affecting a few birds at a time, e.g., cat predation or building collisions, may often be overlooked because their local effects are rarely extrapolated nationally. Therefore, the number of birds killed annually in Canada as a result of human activities is poorly known, as are any resulting effects on populations. Despite limitations imposed by small-scale studies, nonrandom sampling designs, and an absence of experimental controls (Loss et al. 2012), preliminary estimates of human-related bird mortality at national- or continental-level scales can be highly informative. For instance, mortality from collisions with communication towers results in a total annual kill across the U.S. and Canada of about 6.8 million birds (Longcore et al. 2012), include disproportionately large impacts on certain species, many of conservation concern (Longcore et al. 2013). These studies can further highlight the susceptibility of particular bird groups to certain mortality sources, such as the vulnerability of long-distance or nocturnal migrants to collisions with towers and buildings (Klem 2009, Manville 2009, Arnold and Zink 2011) or of auks to bycatch in gill nets (Piatt et al. 1984).

The papers presented in this special feature of *Avian Conservation and Ecology* reflect the current scientific understanding of the magnitude of human-related bird mortality in Canada, based on data collected from a variety of industrial and other activities. Each paper reports an estimate of the total annual loss of birds, nests, or eggs, and considers the likelihood of population-level effects on species in Canada. In this synthesis, we compare the relative contribution of each source of mortality, including several estimates that are unpublished or were published recently elsewhere, and consider the implications of the total kill from all sources. Specifically, this synthesis aims to (i) identify, quantify, and compare sources of human-related avian mortality in Canada, (ii) explicitly model the sources of uncertainty in the mortality estimates, (iii) identify the remaining gaps in the current knowledge of threats to Canadian bird populations, and (iv) thereby help to prioritize research, policy, management, and conservation actions aimed at understanding and reducing human-related bird mortality in Canada.

METHODS

Sources of mortality

We synthesized estimates of the magnitude of human-related avian mortality in Canada from major industrial sectors and nonindustrial or public activities that we believe kill substantial numbers of birds. Initial estimates were developed in a series of reports prepared for Environment Canada. Nine of these are found in this special feature, namely mortality caused by: collisions with vehicles (Bishop and Brogan 2013), cats (Blancher 2013), marine industries, i.e., offshore oil and gas, commercial fisheries (Ellis et al. 2013), commercial forestry (Hobson et al. 2013), collisions with windows in buildings (Machtans et al. 2013), collisions with power transmission lines (Rioux et al. 2013), mechanical agricultural activities such as haying or mowing, cultivation, and harvest (Tews et al. 2013), terrestrial oil and gas (Van Wilgenburg et al. 2013), and wind power (Zimmerling et al. 2013). Estimates from communication towers appear elsewhere (Longcore et al. 2012). Reports on several other anthropogenic activities with more limited data are cited here as unpublished works (roadside maintenance: D. Abraham, D. Pickard, and C. Wedeles, *unpublished manuscript*; agricultural pesticides: P. Mineau, *unpublished manuscript*; mining: J. Williams, *unpublished manuscript*; electrical and hydro power generation: J.-P. L. Savard and S. Rioux, *unpublished manuscript*; Appendix 1). Unless otherwise specified, the information for each source presented in this synthesis is drawn directly from these papers and reports.

Published mortality estimates for three other activities are also presented for comparison. Sport-hunting totals for migratory game birds in Canada from years 2000-2011 were obtained from the National Harvest Survey data base (http://www.cws-scf.ec.gc.ca/harvest-prises/def_e.cfm). Data on total annual harvest of nonmigratory game birds, mainly Galliformes, were obtained from provincial and territorial government web sites and representatives. We also include an estimate of seabird mortality from chronic ship-source oil pollution in the northwest Atlantic from the late 1990s (Wiese and Robertson 2004).

We were unable to include several additional sources of human-related mortality that may be important to Canadian bird populations. A recent assessment of livestock impacts (B. Bleho, N. Koper, and C. S. Machtans, *unpublished manuscript*) found both positive effects of vegetation management and negative effects of trampling on bird nests, estimating a loss of ~1.5% of nests at a local scale, but is not included here because it did not quantify total mortality. We also did not calculate mortality and nest destruction from forest harvesting on private lands. Canada’s National Forestry Database (http://nfdp.ccfm.org) indicates that private land harvest accounts for ~19% of the total annual volume of wood harvested from all lands in Canada, but we did not assess whether harvest timing or bird densities were similar to those calculated for commercial harvest. We found little published information on the magnitude of avian mortality in Canada from aircraft-strikes, and impacts from large-scale tailings ponds remain uncertain (Timoney and Ronconi 2010), although the number of birds killed annually by these sources is expected to be small. Recent evidence also indicates potentially important population-level effects of rodenticides on birds of prey (Thomas et al. 2011), but this source of mortality was not considered here. Effects of the aquaculture industry were initially assessed because entanglements with exclusion nets or nets associated with farms are potential sources of mortality (Price and Nickum 1995). However, this mortality source has not been documented in Canada, and the consensus was that aquaculture currently causes very limited direct bird mortality. Information on indirect impacts of aquaculture development on marine bird populations is also limited, and shellfish aquaculture may sometimes benefit certain waterfowl species (Zydelis et al. 2006, 2009). As a result, aquaculture is not considered further. Finally, we do not include estimates of bird bycatch in freshwater fisheries although the documentation of large kills suggests this is an important information gap (e.g., Ellarson 1956).

Comparing mortality estimates between sources

Human activities can affect birds at different stages of their annual cycles. Activities that alter habitat during the breeding season, such as forestry and agricultural mowing, tend to destroy nests, eggs and young. Many other sources cause direct mortality of breeding adults, subadults, and juvenile birds, such as fishing or collisions with cars or buildings. We present total mortality estimates by the life stage where it occurs, to highlight differences among sources.

We used the methodology of Hobson et al. (2013) and Van Wilgenburg et al. (2013) to develop a stochastic simulation model that expresses stage-specific losses as an equivalent loss of potential adult breeders. This enabled a comparison of the effects of mortality affecting species at different life stages. In addition to allowing comparison of mortality across sources, this model explicitly quantified and combined the various sources of uncertainty in current mortality estimates. An advantage of this modeling approach is that it allowed us to combine data with various measures of central tendency and spread (means, medians, min-max ranges, confidence limits). These modeled values were also used to assess population-level effects of mortality.

The stochastic model controlled both for effects at differing life stages and for variation in life history strategies by converting all individuals to the potential breeding adult stage. However, we were unable to control for variation in time needed to reach those stages because longer lived and low-fecundity species take longer to reach breeding age, making populations slower to recover from perturbations. Our analysis also did not assess the effects of activities reducing future productivity through habitat loss or alteration, e.g., unreclaimed oil and gas clearings in forest, which may be a significant consequence of some of the industrial activities considered here. Our analysis does enable direct comparisons of mortality across various sources, which should be most reliable when focused on comparisons of sources that affect groups of species with similar life history characteristics. Most importantly, these comparisons of numbers killed do not take into account differences in population sizes of species, or species groups.

Stochastic model to derive estimate of potential adult breeders killed

Converting estimates of stage-specific losses to potential adult breeders using the stochastic model involved the following steps. First, we compiled estimates of stage-specific mortality (nest, egg/nestling, or independent bird) for each mortality source, including any information on age-composition (for independent birds killed) and species-group composition of the kill (see Appendix 2 for details). Additional author feedback was sought for some sources, especially regarding estimates of approximate species-group or age composition of the kill.

Next, unless exact values were available, probability distributions were assigned to all values for stage-specific kill totals, age-ratios, and species-group composition (see Appendix 2, Table A2.1). Kill totals from individual papers generally included some measure of central tendency (mean, median, or midpoint) and data spread (confidence interval or min-max range) that were converted to values required to model a log-normal distribution (mean μ and standard deviation σ). We modeled kill estimates as log-normal distributions because these estimates were all based on some multiplicative extrapolation. Age-ratios were modeled in various ways; draws from a binomial distribution were used when proportions were reasonably well known, beta distributions were used when estimated variances in proportions were available, and uniform distributions were used when only minimum and maximum values were reported. Similar distributions were used for species-group proportions, except that multinomial distributions were used when more than two species-groups were affected. For sport harvest of migratory birds, detailed data on age-ratios of the kill were available for ducks, geese, and shorebirds (snipe and woodcock), and age-ratio data for snipe and woodcock were applied to other species (doves, pigeons, rails, and cranes). Age-ratios were not needed for the harvest for upland nonmigratory game birds (Galliformes), because juvenile and adult nonbreeding season survivorship probabilities are comparable for these birds. Age at first breeding was assumed to be the second year of life for all species groups except seabirds, which were assumed to breed in their fifth year.

Demographic rates, with associated measures of data spread where available, were collated for each species group; these included clutch size, nest success, hatchability (or hatch success), survival of young to fledging, overwinter survivorship of juveniles, and adult survivorship. Note that in some instances only the product of several parameters was available, e.g., a general productivity value that equaled clutch size × hatching success × survival of hatchlings to fledgling (see Appendix 2, Table A2.2). For landbirds, except nonmigratory game birds, we used the values already collated in Hobson et al. (2013), with adult survival rates obtained from Johnston et al. (1997). All other demographic rates were obtained from literature values for species considered representative of each species group (Appendix 2, Table A2.2). For shorebirds, we chose values from two larger bodied upland nesting species, as these species are more likely to be affected by the mortality sources considered, i.e., mowing and collisions, compared to smaller Arctic-breeding migrants. When a particular value was not available, notably overwinter survival of hatch-year birds (S_o), this value was estimated using the other vital rates available, assuming a stable population ($S_o = (1- S_a)/F$), where S_a is adult survival and F is fecundity (number of independent young produced). A variety of distributions was used to model these vital rates. For instance, beta distributions were used for well-estimated parameters, draws from uniform distributions were used when uncertainty was high and only minimum and maximum values were available, and random draws from a collection of rates were used for landbirds and shorebirds where a number of estimates were available. See Appendix 2 for additional details on vital rates used for each species group.

Finally, these values and distributions were used to estimate the equivalent number of potential adult breeders that would be removed from the population, based on the stage-specific kill estimates. For example, for an activity that kills eggs and nestlings at the start of the breeding season, draws from the distribution of total kill of eggs for a given species group were multiplied by draws for estimates of nest success, hatch success, survival of young to fledging, and overwinter survival for that species group. Models were run 100,000 times, and various descriptive statistics of the resulting distributions were extracted. We present medians with 90% intervals, to allow direct comparison of the numbers presented for forestry (Hobson et al. 2013) and terrestrial oil and gas (Van Wilgenburg et al. 2013). Note that no conversion was necessary for these two sectors because the authors directly converted their estimates of nest losses to the equivalent loss of potential adult breeders.

Extent, scale, and scope of mortality

We tabulated the season when most human-related mortality occurs (spring, breeding, fall, winter) in Canada for each of the main groups (landbirds, seabirds, shorebirds, waterbirds, waterfowl) to better understand the timing and extent of mortality across Canadian bird populations. We assigned a qualitative score of ‘no/little known effect,’ ‘some effect,’ or ‘large effect’ to each source/group/season combination, based on the information in each paper or report and feedback from their authors. Generally, a ‘large effect’ score was assigned when a particular species group was clearly identified as being frequently killed during a given season, whereas ‘some effect’ was assigned to species groups and seasons that were peripherally affected. Note that factors that kill birds while they are outside of Canada, including human-caused mortality to migrants, were not included in this assessment.

To quantify the relative population impact of differing sources of human-related mortality (hereafter ‘population-level impacts’), we compared the estimated mortality to the total abundance of individual populations, species, or families where data were available at that resolution; in some cases, mortality data were not available below the level of broad taxonomic group. For wind power, marine industries, oil and gas, agriculture, and roadside maintenance, we present population-level impacts that were directly calculated by the paper or report authors; for building collisions, we calculated family-level impacts by combining kill data provided by authors with current estimates of family-level abundance in Canada (Blancher 2002; P. Blancher *unpublished data*). For all these estimates, total kill of nests/eggs/nestlings was converted to the equivalent mortality of potential breeding adults, as described above, to enable comparability among sources of mortality; see Appendix 3 for full details on population-level kill and abundance. Note that although population-level impact estimates provide examples of the relative importance of particular mortality sources, these populations do not represent a random sample of all population-level impacts because they may have been highlighted by authors for different reasons, e.g., those considered particularly at risk, those representative of most birds affected, or those with the best available data on population size. We considered reference levels of 10%, 1%, and 0.1% to be informative. Individual sectors near or above 10% could likely translate to detectable negative population effects. Population proportions of 1% are considered nationally significant from the perspective of management of protected areas (e.g., RAMSAR criteria). We are not aware of documented population effects for rates of mortality below 0.1% from individual sources.

Spatial assessment of mortality risk

A spatial representation of cumulative human-related mortality in Canada was created for a subset of sectors. Applicable or proxy spatial information was available for the following eight sources of terrestrial-based mortality: cats, bird-window collisions, bird-vehicle collisions, bird-communication tower collisions, agriculture (haying and crops), commercial forestry, oil and gas, and wind turbines. All data were summarized and displayed on a 50 × 50 km tile grid covering Canada. This grid-level balanced the goal of providing interpretable images against the false precision of mapping data that usually had low spatial resolution or concordance with specific processes causing mortality, e.g., we know precisely where all paved roads are, but not where bird-vehicle collisions occur on those roads. All data sources and detailed procedures used to derive the maps are provided in Appendix 4.

We began by taking the proportion of activity in a 50 × 50 km tile grid across areas of resolution defined by the original research paper, e.g., provincially for forestry; by turbine for wind facilities; and by applicable portions of Bird Conservation Regions for agriculture. The total mortality estimate for each tile was then calculated by multiplying the proportion of activity in each tile by the original mortality estimate (number of wind turbines, km^2 of oil and gas activity, etc.). The completed tiles from the eight sources were overlaid and summed to compute the total mortality estimate per tile.

The final map was colored using 10 classes calculated by the Jenks classifier (Jenks 1967) in ArcGIS 10 and output in raster format. We applied a low-pass filter to the raster output using a 5 × 5 tile kernel size (Jensen 2005). We caution that the map represents an index of probable mortality across key sources, and is only an approximation. Accurately mapping mortality would require spatially explicit information on bird density, specific details on how and when each sector interacts with birds in each tile, and a variety of covariates that are not available nationally or may not be understood, e.g., why does mortality at tall buildings apparently differ appreciably among cities (Machtans et al. 2013)?

RESULTS

Total mortality estimates

Mortality estimates from each human-related source ranged from a few thousand to tens or hundreds of millions of birds. In Canada, all combined sources of human-related mortality destroyed an average of ~2 million nests and killed ~269 million birds per year, or the equivalent of ~186 million potential adult breeders each year (Fig. 1). Cats and collisions with structures were the largest causes of human-related bird mortality in Canada: cumulatively, the top five sources of mortality, i.e., predation by feral and pet cats, and collisions with road vehicles, houses, and transmission lines, represented more than 95% of the individuals killed across all human-related sources. Because each of these top-ranking mortality sources are widespread, they may represent relatively small numbers at the local scale, but sum to very high levels of mortality when extrapolated across Canada. In contrast, some other mortality sources do not occur uniformly across the country, e.g., terrestrial oil and gas, fisheries, or are from industries located at relatively few scattered locations, e.g. wind power, and thus have relatively modest national-level kill totals, despite measurable localized effects.

The nine largest sources of anthropogenic mortality all killed mobile individual birds, including adult, subadult, and juvenile birds, although over a million nests and eggs are destroyed annually by forestry and agriculture, respectively (Fig. 1A). Fig. 1A and Table 1 show the total number killed by each source, identifying the life stage at which most mortality occurs, i.e., nest destruction, mortality of eggs or nestlings, or loss of independent mobile individuals. Mortality occurring at two stages, i.e., loss of eggs and mobile individuals through road maintenance, is shown as two points for that source. Note that although most estimates were made at a national level, e.g., by extrapolating from local-scale estimates across the country, a few were only made at smaller scales (indicated as hollow symbols in Fig. 1): the agricultural haying and road maintenance estimates each represent impacts on just five and six focal species, respectively, and the hydro reservoir estimate was made for Quebec only. Total Canada-wide cross-taxa mortality caused by these activities is therefore likely to be appreciably higher than the values presented here.

The relative ranking of mortality sources was similar for the stage-specific and converted values (Figs. 1A, 1B), particularly for the largest sources of mortality. However, for human activities that destroy eggs and nests, the equivalent potential adult breeder total was considerably reduced, and thus the relative ranking of these sources somewhat altered, because many of the eggs or young killed by these sources would have not been expected to survive to adulthood otherwise (Fig 1B).

Converted estimates pooled across related activities provided broad estimates for the main sources of human-caused mortality (Fig 1C). These pooled sectors were cats (feral and pet), transportation (vehicle-collisions, road maintenance, and chronic ship-source oil), buildings (collisions with all three types), electrical power (transmission-line collisions, hydro reservoirs, electrocutions, transmission-line maintenance, and wind energy), harvest (migratory and nonmigratory game birds), agriculture (haying and pesticides), fisheries (all gear types), oil and gas (all terrestrial and marine sources), and mining (pits/quarries and metals/minerals); the original single-source values for forestry and communication towers are also shown. Nonindustrial activities (cats, transportation, and buildings) still represented the greatest overall sources of mortality, while electrical power and agriculture represented the largest industrial sources of mortality, with an annual kill of over 18 million and over 2 million potentially breeding birds, respectively. At the other end of the spectrum, the fisheries, oil and gas, and mining industries each killed the equivalent of fewer than 25,000 breeders annually (Fig. 1C). Note that within sectors, some sources of mortality were relatively low, e.g., electrocutions in the electrical power sector, while others dominated the overall sectoral kill, e.g., transmission line collisions.

Evaluating potential population effects: seasonal and taxonomic distribution of mortality

The distribution of anthropogenic mortality among bird groups and across seasons for each mortality source showed that landbirds as a group were affected by the widest range of human activities (Table 2). These impacts occurred primarily during the breeding seasons, as expected, because many species overwinter outside of Canada. Shorebirds and waterfowl also faced many potential threats at their nesting sites, and birds across all groups confronted a range of human-caused mortality during spring and fall migration, particularly from collisions with cars, buildings, power-lines, and transmission structures.

Landbirds make up the majority of all Canadian breeding birds, and they constituted most of the estimated total mortality among the five species groups when expressed in common units of potential adult breeders (Table 3). In total, we estimated that 89% of all birds killed annually by human activities are landbirds; 6% are waterfowl, and the remaining 5% includes waterbirds, shorebirds, and seabirds. The majority of mortality occurred through direct kill of mobile individuals (74%; mostly cats, but see Table 2 for categories of impact type), with 25% of mortality caused by collisions. The destruction of nests represented less than 1% of overall estimated impact when converted to potential adult breeders.

Although overall national-scale mortality estimates illustrated the magnitude of bird mortality across Canada, some human-related activities had disproportionately large effects on particular species or populations, with the potential for population-level impacts at a regional or national level (Fig. 2; see Appendix 3 for full details). For example, marine fisheries bycatch had one of the lowest total mortality estimates nation-wide, but may annually kill a relatively large proportion of Canadian populations of a few species, e.g., Black-footed Albatross *Phoebastria nigripes*: 4% of the entire Canadian population, or Common Eiders *Somateria mollissima*: 7% of the Nova Scotia breeding population (Fig. 2). Mortality from building collisions also nonrandomly impacted landbirds. Overall, tall buildings killed less than 0.01% of total abundance of any landbird family, whereas between 2-5% of nuthatches, chickadees, and pigeons may have been killed at houses (see Bayne et al. 2012 for proportions of house-collision kills by family, which we used in Appendix 3 and Fig. 2). Although this simple comparison does not capture the complexity of potential population effects, it confirms that national mortality totals alone do not reflect the ecological importance of human-related activities for most species and that mortality is not simply proportional to abundance (see also Longcore et al. 2013).

We did not directly assess the impacts of sport harvest on populations of game birds because ongoing assessments exist elsewhere (e.g. Williams and Johnson 1995, Nichols et al. 2007), and extensive programs are in place throughout North America that ensure that any population-level effects of regulated harvests are sustainable in the long term (e.g., Runge et al. 2009). These impacts would likely have dominated Fig. 2, because sport-harvest was clearly important as a human-related source of mortality in Canada for waterfowl and an important factor for some other bird groups (Table 3).

Spatial distribution of mortality risk and potential cumulative effects

Human-related mortality from terrestrial sources was not uniformly distributed across Canada (Fig. 3A) because areas of higher mortality corresponded with areas of high human population and high human activity. Peak mortality for all sources combined was highest in southern Ontario and Quebec, around the five major prairie cities, and in southwestern British Columbia. In addition to having high human populations, and correspondingly large numbers of cats, buildings, and roads, numerous industries overlap with these areas. Overall, very little avian mortality from the sources that we mapped currently occurs in the northern part of many provinces and in the territories.

The distribution of mortality when excluding the three largest sources (cats, buildings, roads) was spread more evenly across southern Canada (Fig. 3B), partly reflecting broad areas of forest harvesting and the diffuse distribution of communication towers across this area. Southern Alberta and southeastern Ontario appeared to be areas for potential additive effects of multiple industries. The high values in the Maritimes were partially attributable to forestry, whereas those in the lower mainland of British Columbia primarily reflect the high number of hay farms. Individual, unsmoothed maps for each mortality source are provided in Appendix 4.

In contrast to most impacts of clearing activities (Fig. 3B), collision-based sources of mortality impacted some species more than others, and thus potential cumulative effects were harder to assess spatially. Based on available data, we found indications that different types of collisions appeared to affect different groups of landbirds. At the family level, warblers dominated birds killed in communication tower collisions (15 of the most abundant 20 species recorded, Longcore et al. 2013) whereas a wider variety of species dominated tall building collisions (only 6 of the top 20 were warblers, Machtans et al. 2013). At the species level, the top five species killed in tall building collisions in southern Ontario (based on the Toronto Fatal Light Awareness Program, www.flap.org) were Golden-crowned Kinglet (*Regulus satrapa*), White-throated Sparrow (*Zonotrichia albicollis*), Ruby-crowned Kinglet (*Regulus calendula*), Dark-eyed Junco (*Junco hyemalis*), and Ovenbird (*Seiurus aurocapilla*), together comprising 42% of mortalities. In contrast, the top five species killed in communication tower collisions in the Bird Conservation Region, which includes Toronto (Longcore et al. 2013), were Ovenbird, Ruby-crowned Kinglet, Blackpoll Warbler (*Setophaga striata*), Red-eyed Vireo (*Vireo olivaceus*), and Common Yellowthroat (*Geothlypis trichas*), together comprising 44% of mortalities. Species reported killed most often at wind-turbines only showed some overlap with these other collision-sources, with the top five being Horned Lark (*Eremophila alpestris*), Golden-crowned Kinglet, Red-eyed Vireo, European Starling (*Sturnus vulgaris*), and Tree Swallow (*Tachycineta bicolor*; Zimmerling et al. 2013). Only 80% of birds killed at wind turbines were passerines, proportionately much lower than at communication towers (97% passerines, Longcore et al. 2013) or in collisions with windows of tall buildings (90% passerines, Machtans et al. 2013). Much better species-level data are required concerning cat kills and window collisions at homes, as well as from the range of other human activities for which population-level data are not yet available, to better understand the most significant population impacts and to identify additive or cumulative impacts. Even the species comparisons above should be taken with caution because the spatial scale of the data sources differ across each study.

DISCUSSION

Interpreting mortality estimates

Human-related activities inadvertently kill hundreds of millions of birds and destroy millions of nests in Canada every year, with landbirds most affected. Birds are primarily affected during the breeding season, although collisions occur year round. Landbirds were subject to the largest diversity of impacts, suggesting that they may be most vulnerable to additive effects across sources and seasons. Many of these human-related activities also pose a threat to migrants when outside of Canada, mortality that has not been quantified here, and thus the cumulative year-round population-level effects will be higher for species that migrate outside Canada. For instance, in the United States a median estimate of 2.4 billion birds are killed annually by cats (Loss et al. 2013), and a substantial proportion of these birds will have been produced in Canada. In the context of severe population declines already observed for many groups (e.g. long-distance migrants: BirdLife International 2008; grassland breeders, shorebirds, aerial insectivores: NABCI-Canada 2012), human-related activities create additional population pressures for many of Canada's birds.

The estimated number of potential breeders killed annually by specific sectors or sources differs by several orders of magnitude, ranging from fewer than one thousand for routine marine oil and gas activities, to tens of millions for collisions with vehicles, transmission lines, and houses, and over 140 million for cat kills. Most of these activities are known to effect birds at a local scale, although extrapolation to the national level has highlighted the magnitude and potential significance of several widespread impacts, such as cats and building collisions. For other activities, a national scale perspective may lead to important local-scale mortality being overlooked, e.g., regionally concentrated fisheries bycatch. Our geographical assessment revealed the highest cumulative risk to birds in regions of high human population density and related road networks. Southern Alberta and Ontario also stood out as areas with potentially high cumulative effects because of a convergence of several human activities in addition to the top three sources, whereas other high risk locations were generally attributable to single mortality sources.

Although these estimates provide new insight into the relative significance of different industrial and other human-related activities to wild birds in Canada, the precision of our review is limited by the availability of relevant information from Canada. The wide confidence ranges around the converted estimates explicitly indicate the considerable uncertainty in our present knowledge of the magnitude of source-specific mortality, so these should be viewed as preliminary estimates pending further refinement, additional research, and increased monitoring and assessment.

Uncertainties and caveats

Accurate estimation of the magnitude of bird mortality from industrial and other human-related activities is compromised by the need to estimate large-scale national impacts by extrapolating from small studies, often with limited data. Wherever possible, authors directly accounted for known sources of bias, such as variability in detection and scavenging of bird carcasses (e.g., road vehicles: Bishop and Brogan 2013; building collisions: Machtans et al. 2013; wind power: Zimmerman et al. 2013; transmission line collisions: Rioux et al. 2013). Some explicitly assessed the sensitivity of mortality estimates to key parameters such as the number of unowned cats in Canada (Blancher 2013), or the timing of agricultural or oil and gas activities in relation to breeding seasons (Tews et al. 2013, Van Wilgenburg et al. 2013). Overall, we consider that the estimates presented in this issue are likely to be precise to within an order of magnitude, particularly because actual levels of mortality from each source will likely vary significantly from one year to the next.

Some important sources of estimation bias still remain. For instance, the scale of available data may sometimes be mismatched to the scale of human-related activities. The harvest volume from commercial forestry activities is typically reported provincially and not by area cut, while the density of nesting birds is inferred from extrapolating local-scale point-counts to Bird Conservation Regions, which do not align with provincial boundaries (Hobson et al. 2013). Additionally, specific Canadian data for predation rates by cats, pesticide use, and mortality from power generation were also lacking (Blancher 2013; Appendix 1), so the estimates presented here are derived in part using data from other countries or continents. Extrapolations for marine oil and gas were based on untested assumptions, with few data available to inform these estimates (Ellis et al. 2013).

Estimates of effects from most sources could be improved by a better understanding of the seasonal distribution of mortality. For instance, the proportion of industrial activities that occur within the breeding season had to be approximated for several sources (e.g., forestry: Hobson et al. 2013; oil and gas: Van Wilgenburg et al. 2013). Species-composition of the kill is also poorly known for many human activities (e.g., vehicle collisions: Bishop and Brogan 2013; transmission line collisions: Rioux et al. 2013), limiting our ability to evaluate potential population-level impacts. Finally, most analyses presented here were designed to estimate direct annual kill of individual birds or destruction of nests. Estimates for most mortality sources that also involve significant clearing or alteration of habitat do not reflect the total long-term impact of the activity on bird populations because most analyses did not account for additional long-term impacts, e.g., via habitat change (Wells et al. 2008) or related one-time mortality events, e.g., destruction of nests during initial construction of transmission lines (Rioux et al. 2013).

The stochastic simulation model addressed some of these biases, so that the distributions of potential adult breeder mortality are more likely to reflect the actual impacts of estimated mortality. The confidence limits around median estimates reflect the remaining uncertainty in the input values; for instance, the magnitude of mortality caused by fisheries bycatch or wind power is known with greater precision than that caused by mining activities or terrestrial oil and gas. These estimates all assume that most mortality estimated here is additive to natural mortality, so density-dependence was not incorporated into these conversions. The stochastic simulation model did make some simplifying assumptions, such as assigning age of first breeding to the second year of life for all but the seabirds, which would overestimate the number of potential breeders when breeding begins later, and by using nest success estimates that assume that nests were destroyed at the beginning of nesting, which would underestimate the number of potential breeders if nest destruction occurred later in the season. An important potential bias of the modeling process was the use of representative vital rates from only a few species, except the landbirds. In the future, more detailed estimates of species-specific kills could be incorporated with models using their species-specific vital rates to properly assess the effects of any particular mortality source. Finally, there are some considerations that the conversion to potential adult breeders could not incorporate. Long-lived, low-fecundity species take longer to recover from population perturbations, and mortality for these species is more likely to be additive than for shorter lived high-fecundity species. Additionally, long-lived, low-fecundity species tend to have much smaller population sizes, so a greater portion of the population is removed with each potential adult killed.

The risk mapping also relied on some important assumptions, specifically that mortality from each source was spread across the landscape in proportion to its existing spatial intensity. This is certainly not the case; forestry companies do not harvest equally across their tenure area and not every communication tower or wind turbine kills the average number of birds. However, adopting this assumption was necessary to create a first order spatial representation of the distribution of avian mortality risk across Canada.

The values considered here represent the current best estimates of source-specific annual bird mortality for Canada across all species groups and age classes, although a few sectoral mortality estimates must be considered to be quite preliminary, and there is some inherent uncertainty in all estimates. Moreover, because the magnitude of the estimates is likely to be fairly accurate, with true mortality levels contained within the estimation range, the relative ranking of mortality sources is unlikely to change substantially with improved precision.

CONCLUSIONS AND IMPLICATIONS

From a conservation perspective, it is now important to develop a more complete understanding of the population level effects of human-related avian mortality within and across sectors, at relevant spatial scales. Sources such as window strikes at houses cause high levels of mortality nation-wide, but this mortality is not spread equally across different species or families. Longcore et al. (2013) found similarly variable population impacts of communication tower collisions. Marine fisheries bycatch was not among the highest-ranking sources of mortality nation-wide, yet it kills disproportionately high numbers of birds from particular regional populations. Our assessment did not consider the fact that certain populations or species may still manifest a population-level consequence through additive effects of several mortality sources, even though each source individually would not be expected to show such an effect. Understanding these cumulative effects will not be possible until species-specific kill rates are available for all sectors. In the interim, those habitats or areas of the country where many sectors operate together are places where these multiple stressors have the potential to combine and create such a cumulative impact.

This synthesis and accompanying papers focus primarily on direct mortality of birds and destruction of nests resulting from human activities, but do not consider the potential longer term effects on birds from habitat changes. Wind turbines, for example, cause mortality by nest-destruction during construction as well as through collision mortality during operation. Indeed, recent evidence suggests that initial construction may sometimes pose a greater overall threat to birds (Pearce-Higgins et al. 2012). Commercial forestry, terrestrial oil and gas, and mining are further examples of activities where there may be significant longer term or broader scale effects of habitat modification that are not addressed here. Furthermore, mortality rates may change in the future for industries undergoing rapid rates of development, such as wind facilities, which are predicted to expand ten-fold in Canada over the next 10-15 years (CanWEA 2013). Human activities currently contributing relatively little to total mortality may therefore present a greater risk in years to come.

The complex relationships among all ecological factors regulating avian populations, and particularly migratory birds, require consideration of factors operating at points throughout the entire life cycle (Faaborg et al. 2010). For example, if wintering habitat conditions are not limiting, human-related mortality may be additive. However, if wintering habitat becomes limiting, human-related mortality may shift to being compensatory and its influence on population regulation may change. Improved understanding of species composition of mortality events, the magnitude of mortality of migrants south of Canada, and survival estimates at each life stage will be required to effectively model the demography of affected populations, particularly if bird conservation objectives include maintaining source-specific mortality from human-related causes below certain levels (e.g., McGowan and Ryan 2009, Runge et al. 2009, Dillingham and Fletcher 2011).

Insight into the relative magnitude of different human-related sources of mortality provides a valuable tool for guiding management, and affords additional perspectives for prioritizing conservation and research initiatives for Canada’s birds. We propose four key areas for future research or management. First, to enable more precise analyses and impact modeling, we recommend additional Canadian research into the magnitude of bird effects for data-poor sectors, e.g., pesticides, and the species likely affected, and into particular aspects of mortality, e.g., species composition and seasonal timing of the kill. Second, our results highlight the value of increased efforts to minimize impacts of widespread and generalized low-intensity human-related activities that create nationally high levels of mortality but could be mitigated at local scales, e.g., cats and buildings. Such investments could include local approaches using outreach and other available conservation tools. Third, we recommend specifically targeting those mortality sources identified as having population-level effects at regional or national levels for priority conservation action. Finally, we encourage further assessments that integrate the effects on populations across multiple sectors to truly understand the impacts of all mortality sources on priority species. Such mitigation efforts can reduce human-related impacts on birds if appropriately directed (as shown by e.g., Nocera et al. 2005, 2007: changing the timing of agricultural activities to reduce impacts on grassland breeders; Gehring et al. 2009: changing lights on communication towers to reduce collision mortality; and Løkkeborg 2011: modifying fishing gear to reduce bycatch of seabirds.

Given that the relative ranking of mortality sources considered here is unlikely to change substantially even with increased precision, an immediate focus should consider mitigation of those mortality sources with the highest magnitudes at the national level, e.g., cats and collisions. At the same time, scientists should try to identify and better understand potential population-level impacts on populations or species, at appropriate geographical scales. Effective application of these findings to the conservation of Canadian birds will require constructive collaboration among the public and various levels of government, nongovernmental organizations, and industries within Canada. This assessment should help target these initiatives appropriately to improve the population and conservation status of birds within Canada, as well as the continental conservation status for migratory species.

RESPONSES TO THIS ARTICLE

Responses to this article are invited. If accepted for publication, your response will be hyperlinked to the article. To submit a response, follow this link. To read responses already accepted, follow this link.

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LITERATURE CITED

Anderson, D. R., and K. P. Burnham. 1976. *Population ecology of the mallard IV: the effect of exploitation on survival.* Publication 128. U.S. Department of the Interior, U.S. Geological Survey, Reston, Virginia, USA.

Arnold, T. W., and R. M. Zink. 2011. Collision mortality has no discernible effect on population trends of North American birds. *PLoS ONE* 6(9):e24708. http://dx.doi.org/10.1371/journal.pone.0024708

Balogh, A. L., T. B. Ryder, and P. P. Marra. 2011. Population demography of Gray Catbirds in the suburban matrix: sources, sinks and domestic cats. *Journal of Ornithology* 152:717-726. http://dx.doi.org/10.1007/s10336-011-0648-7

Bayne, E. M., C. A. Scobie, and M. Rawson-Clark. 2012. Factors influencing the annual risk of bird-window collisions at residential structures in Alberta, Canada. *Wildlife Research* 39(7):583-592.

BirdLife International. 2008. *State of the world's birds: indicators for our changing world*. BirdLife International, Cambridge, UK.

Bishop, C. A., and J. M. Brogan. 2013. Estimates of avian mortality due to vehicle collisions on the

Canadian road network. *Avian Conservation and Ecology* 8(1): ZZ. http://dx.doi.org/10.5751/ACE-0575-0801ZZ

Blancher, P. J. 2002. *Importance of breeding birds exported from Canada – information on landbirds and shorebirds.* Unpublished report to the North American Bird Conservation Initiative Canada National Council. Ottawa, Ontario, Canada.

Blancher, P. J. 2013. Estimated number of birds killed by house cats (*Felis catus*) in Canada. *Avian Conservation and Ecology* 8(1): ZZ. http://dx.doi.org/10.5751/ACE-0557-0801ZZ

Canadian Wind Energy Association (CanWEA). 2013. *Powering Canada' futre.* CanWEA, Ottawa, Ontario, Canada. [online] URL: http://www.canwea.ca/pdf/Canada%20Current%20Installed%20Capacity_e.pdf

Committee on the Status of Endangered Wildlife in Canada (COSEWIC). 2010. *COSEWIC assessment and status report on the Bobolink* Dolichonyx oryzivorus *in Canada*. COSEWIC, Ottawa, Ontario, Canada. [online] URL: http://registrelep-sararegistry.gc.ca/default.asp?lang=En&n=7019552A-1

Crooks, K. R., and M. E. Soulé. 1999. Mesopredator release and avifaunal extinctions in a fragmented system. *Nature* 400:563-566. http://dx.doi.org/10.1038/23028

Dillingham, P. W., and D. Fletcher. 2011. Potential biological removal of albatrosses and petrels with minimal demographic information. *Biological Conservation* 144:1885-1894. http://dx.doi.org/10.1016/j.biocon.2011.04.014

Ellarson, R. S. 1956. *A study of the Old-squaw Duck on Lake Michigan*. Dissertation. University of Wisconsin, Madison, Wisconsin, USA.

Ellis, J. I., S. I. Wilhelm, A. Hedd, G. S. Fraser, G. J. Robertson, J.-F. Rail, M. Fowler, and K. H. Morgan. 2013. Mortality of migratory birds from marine commercial fisheries and offshore oil and gas production in Canada. *Avian Conservation and Ecology* 8(1): ZZ. http://dx.doi.org/10.5751/ACE-0578-0801ZZ

Faaborg, J., R. T. Holmes, A. D. Anders, K. L. Bildstein, K. M. Dugger, S. A. Gauthreaux Jr., P. Heglund, K. A. Hobson, A. E. Jahn, D. H. Johnson, S. C. Latta, D. J. Levey, P. P. Marra, C. L. Merkord, E. Nol, S. I. Rothstein, T. W. Sherry, T. S. Sillett, F. R. Thomson III, and N. Warnock. 2010. Recent advances in understanding migration systems of New World land birds. *Ecological Monographs* 80:3-48. http://dx.doi.org/10.1890/09-0395.1

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

Hobson, K. A., A. G. Wilson, S. L. Van Wilgenburg, and E. M. Bayne. 2013. An estimate of nest loss in Canada due to industrial forestry operations. *Avian Conservation and Ecology* 8(1): ZZ. http://dx.doi.org/10.5751/ACE-0583-0801ZZ

Jenks, G. F. 1967. The data model concept in statistical mapping. *International Yearbook of Cartography* 7:186–190.

Jensen, J. R. 2005. *Introductory digital image processing: a remote sensing perspective*. Third edition.

Pearson Prentice Hall, Upper Saddle River, New Jersey, USA.

Johnston, J. P., W. J. Peach, R. D. Gregory, and S. A. White. 1997. Survival rates of tropical and temperate passerines: a Trinidadian perspective. *American Naturalist* 150:771-789. http://dx.doi.org/10.1086/286093

Klem, D., Jr. 2009. Preventing bird-window collisions. *Wilson Journal of Ornithology* 121:314-321. http://dx.doi.org/10.1676/08-118.1

Løkkeborg, S. 2011. Best practices to mitigate seabird bycatch in longline, trawl and gillnet fisheries-efficiency and practical applicability. *Marine Ecology Progress Series* 435:285-303. http://dx.doi.org/10.3354/meps09227

Longcore, T., C. Rich, P. Mineau, B. MacDonald, D. G. Bert, L. M. Sullivan, E. Mutrie, S. A. Gauthreaux Jr., M. L. Avery, R. L. Crawford, A. M. Manville II, E. R. Travis, and D. Drake. 2012. An estimate of avian mortality at communication towers in the United States and Canada. *PLoS ONE* 7(4): e34025. http://dx.doi.org/10.1371/journal.pone.0034025

Longcore, T., C. Rich, P. Mineau, B. MacDonald, D. G. Bert, L. M. Sullivan, E. Mutrie, S. A. Gauthreaux Jr., M. L. Avery, R. L. Crawford, A. M. Manville II, E. R. Travis, and D. Drake. 2013. Avian mortality at communication towers in the United States and Canada: which species, how many, and where? *Biological Conservation* 158:410-419. http://dx.doi.org/10.1016/j.biocon.2012.09.019

Loss, S. R., T. Will, and P. P. Marra. 2012. Direct human-caused mortality of birds: improving quantification of magnitude and assessment of population impact. *Frontiers in Ecology and the Environment* 10:357–364. http://dx.doi.org/10.1890/110251

Loss, S. R., T. Will, and P. P. Marra. 2013. The impact of free-ranging domestic cats on wildlife of the United States. *Nature Communications* 4:1396. http://dx.doi.org/10.1038/ncomms2380

Machtans, C. S., C. H. R. Wedeles, and E. M. Bayne. 2013. A first estimate for Canada of the number of birds killed by colliding with building windows. *Avian Conservation and Ecology* 8(1): ZZ. http://dx.doi.org/10.5751/ACE-0568-0801ZZ

Manville, A. M., II. 2009. Towers, turbines, power lines, and buildings – steps being taken by the U.S. Fish and Wildlife Service to avoid or minimize take of migratory birds at these structures. Pages 262-272 *in* T. D. Rich, C. Arizmendi, D. W. Demarest, and C. Thompson, editors. *Tundra to tropics: connecting birds, habitats, and people*. Proceedings of the 4th International Partners in Flight Conference, Partners in Flight, McAllen, Texas, USA.

McGowan, C. P., and M. R. Ryan. 2009. A quantitative framework to evaluate incidental take and endangered species population viability. *Biological Conservation* 142:3128-3136. http://dx.doi.org/10.1016/j.biocon.2009.08.012

Miller, M. R., and D. C. Duncan. 1999. The northern pintail in North America: status and conservation needs of a struggling population. *Wildlife Society Bulletin* 27:788-800.

Mineau, P., and M. Whiteside. 2013. Pesticide acute toxicity is a better correlate of U.S. grassland bird declines than agricultural intensification. *PLoS ONE* 8(2):e57457. http://dx.doi.org/10.1371/journal.pone.0057457

Nichols, J. D., M. C. Runge, F. A. Johnson, and B. K. Williams. 2007. Adaptive harvest management of North American waterfowl populations: a brief history and future prospects. *Journal of Ornithology* 148(Suppl. 2):S343-S349. http://dx.doi.org/10.1007/s10336-007-0256-8

Nocera, J. J., G. Forbes, and G. R. Milton. 2007. Habitat relationships of three grassland breeding bird species: broadscale comparisons and hayfield management implications. *Avian Conservation and Ecology* 2(1): 7. [online] URL: http://www.ace-eco.org/vol2/iss1/art7/

Nocera, J. J., G. J. Parsons, G. R. Milton, and A. H. Fredeen. 2005. Compatibility of delayed cutting regime with bird breeding and hay nutritional quality. *Agriculture, Ecosystems & Environment* 107:245-253. http://dx.doi.org/10.1016/j.agee.2004.11.001

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

Pearce-Higgins, J. W., L. Stephen, A. Douse, and R. H. W. Langston. 2012. Greater impacts of wind farms on bird populations during construction than subsequent operation: results of a multi-site and multi-species analysis. *Journal of Applied Ecology* 49:386-394. http://dx.doi.org/10.1111/j.1365-2664.2012.02110.x

Piatt, J. F., D. N. Nettleship, and W. T. Threlfall. 1984. Net mortality of Common Murres *Uria aalge* and Atlantic Puffins *Fratercula acrtica* in Newfoundland, 1951-1981. Pages 196-206 *in* D. N. Nettleship, G. Sanger, and P. F. Springer, editors. *Marine birds: their feeding ecology and commercial fisheries relationships*. Special publication. Canadian Wildlife Service, Ottawa, Ontario, Canada.

Price, I. M., and J. G. Nickum. 1995. Aquaculture and birds: the context for controversy. *Colonial Waterbirds* 18 (Special Publication):33-45. http://dx.doi.org/10.2307/1521522

Prairie Habitat Joint Venture. 2008. *Prairie Habitat Joint Venture Implementation Plan 2007 - 2012*. Report of the Prairie Habitat Joint Venture. Environment Canada, Edmonton, Alberta, Canada.

Rioux, S., J.-P. L. Savard, and A. A. Gerick. 2013. 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. *Avian Conservation and Ecology* 8(1): ZZ. http://dx.doi.org/10.5751/ACE-0591-0801ZZ

Runge, M. C., J. R. Sauer, M. L. Avery, B. F. Blackwell, and M. D. Koneff. 2009. Assessing allowable take of migratory birds. *Journal of Wildlife Management* 73:556-565. http://dx.doi.org/10.2193/2008-090

Tews, J., D. G. Bert, and P. Mineau. 2013. Estimated mortality of selected migratory bird species from mowing and other mechanical operations in Canadian agriculture. *Avian Conservation and Ecology* 8(1): ZZ. http://dx.doi.org/10.5751/ACE-0559-0801ZZ

Thomas, P. J., P. Mineau, R. F. Shore, L. Champoux, P. A. Martin, L. K. Wilson, G. Fitzgerald, and J. E. Elliott. 2011. Second generation anticoagulant rodenticides in predatory birds: probabilities characterisation of toxic liver concentrations and implications for predatory bird populations in Canada. *Environment International* 37:914-920. http://dx.doi.org/10.1016/j.envint.2011.03.010

Timoney, K. P, and R. A. Ronconi. 2010. Annual bird mortality in the bitumen tailings ponds in northeastern Alberta, Canada. *Wilson Journal of Ornithology* 122:569-576. http://dx.doi.org/10.1676/09-181.1

Van Wilgenburg, S. L., K. A. Hobson, E. M. Bayne, and N. Koper. 2013. Estimated avian nest loss associated with oil and gas exploration and extraction in the Western Canadian Sedimentary Basin. *Avian Conservation and Ecology* 8(1): ZZ. http://dx.doi.org/10.5751/ACE-0585-0801ZZ

Wells, J., S. Casey-Lefkowitz, G. Chavarria, and S. Dyer. 2008. *Danger in the nursery: impacts on birds of tar sands oil development in Canada's boreal forest.* Natural Resources Defense Council, New York, NY, USA.

Wiese, F. K., and G. J. Robertson. 2004. Assessing seabird mortality from chronic oil discharges at sea. *Journal of Wildlife Management* 68:627-638. http://dx.doi.org/10.2193/0022-541X(2004)068[0627:ASMFCO]2.0.CO;2

Williams, B. K., and F. A. Johnson. 1995. Adaptive management and the regulation of waterfowl harvests. *Wildlife Society Bulletin* 23:430-436.

Zimmerling, J. R., A. Pomeroy, M. d'Entremont, and C. M. Francis. 2013. Canadian estimate of bird mortality due to collisions and direct habitat loss associated with wind turbine developments. *Avian Conservation and Ecology* 8(1): ZZ. http://dx.doi.org/10.5751/ACE-0574-0801ZZ

Zydelis, R., D. Esler, M. Kirk, and W. S. Boyd. 2009. Effects of off-bottom shellfish aquaculture on winter habitat use by molluscivorous sea ducks. *Aquatic Conservation: Marine and Freshwater Ecosystems* 19:34-42. http://dx.doi.org/10.1002/aqc.977

Zydelis, R., D. Esler, W. S. Boyd, D. L. Lacroix, and M. Kirk. 2006. Habitat use by wintering Surf and White-winged Scoters: effects of environmental attributes and shellfish aquaculture. *Journal of Wildlife Management* 70:1754-1762. http://dx.doi.org/10.2193/0022-541X(2006)70[1754:HUBWSA]2.0.CO;2

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Table 1. Life stage-specific (nests, eggs/ nestlings, or independent individuals) mortality estimates of human-related avian mortality in Canada derived directly from published papers and unpublished reports. These values are illustrated in Fig. 1A, and served as the basis for the stochastic model conversion to an equivalent number of potential adult breeders; mortality sources are listed in descending order of converted kill totals. Characteristics of the estimate are indicated in the last column, i.e., whether central values were mean, median, or midpoint of a range, and whether lower/upper values represent a confidence interval (CI) or a range. Note that the estimates for forestry and terrestrial oil and gas shown here represent the estimated number of nests destroyed.

	Nests			**Eggs or Nestlings**			**Individuals**			**Values**
Source	**Lower**	**Central**	**Upper**	**Lower**	**Central**	**Upper**	**Lower**	**Central**	**Upper**	**Estimated**
Cats – Feral							49,000,000	116,000,000	232,000,000	median, 95%CI
Cats - Domestic							27,000,000	80,000,000	186,000,000	median, 95%CI
Power - Transmission line collisions							10,100,000	25,600,000	41,200,000	mean, 95% CI
Buildings - Houses							15,800,000	22,400,000	30,500,000	mean, range
Transportation - Road vehicle collisions							8,914,341	13,810,906	18,707,470	Mean, 95%CI
Agriculture - Pesticides							960,011	2,695,415	4,430,819	midpoint, range
Harvest - Migratory birds								2,279,655		mean
Buildings - Low- and midrise							300,000	2,400,000	11,400,000	mean, range
Harvest - Nonmigratory birds							1,076,810	2,389,124	3,701,438	mean, 95% CI
Forestry - Commercial	615,959	1,351,340	2,086,720							midpoint, range
Transportation - Chronic ship-source oil							217,800	321,900	458,600	mean, 95% CI
Power - Electrocutions							160,836	481,399	801,962	midpoint, range
Agriculture - Haying					2,209,400					mean
Power - Line maintenance	258,849	388,274	592,418							midpoint, range
Communication - Tower collisions								220,649		mean
Power - Hydro reservoirs		152,162								mean
Buildings - Tall							13,000	64,000	149,000	mean, range
Fisheries - Marine gill nets							2185	20,612	41,528	mean, range
Power - Wind energy							13,330	16,700	21,600	mean, 95% CI
Oil and Gas - Well sites	7688	13,182	20,249							median, 90%CI
Mining - Pits and quarries					125,529					mean
Oil and Gas - Pipelines	503	6314	30,234							median, 90%CI
Mining - Metals and minerals				18,653	69,211	119,768				midpoint, range
Oil and Gas - Oil sands	1281	2939	5236							median, 90%CI
Oil and Gas - Seismic exploration	374	2280	16,438							median, range
Fisheries - Marine longlines and trawls							494	1,999	4058	mean, range
Transportation - Road maintenance				13,086	25,149	50,294	84	149	270	median, range
Oil and Gas - Marine							188	2244	4494	median, range
TOTAL		**1,916,491**			**2,429,289**			**268,704,752**		

Table 2. Seasonal and species-group breakdown for each source of human-related avian mortality in Canada: o little or no known effect, + some effect, including effects anticipated but not quantified [highlighted yellow], ++ large effect [highlighted orange], na not applicable. Within the effect-type categories (collisions, direct kill, or nest destruction), mortality sources are ordered in descending order of converted kill totals, as presented in Fig. 1B. Comparisons should be made within source rows, rather than within columns because the level of effect was evaluated qualitatively among seasons and species-groups within each source, and is not intended to reflect differences in magnitude among sources. Note that 'winter' refers only to impacts on birds while wintering in Canada.

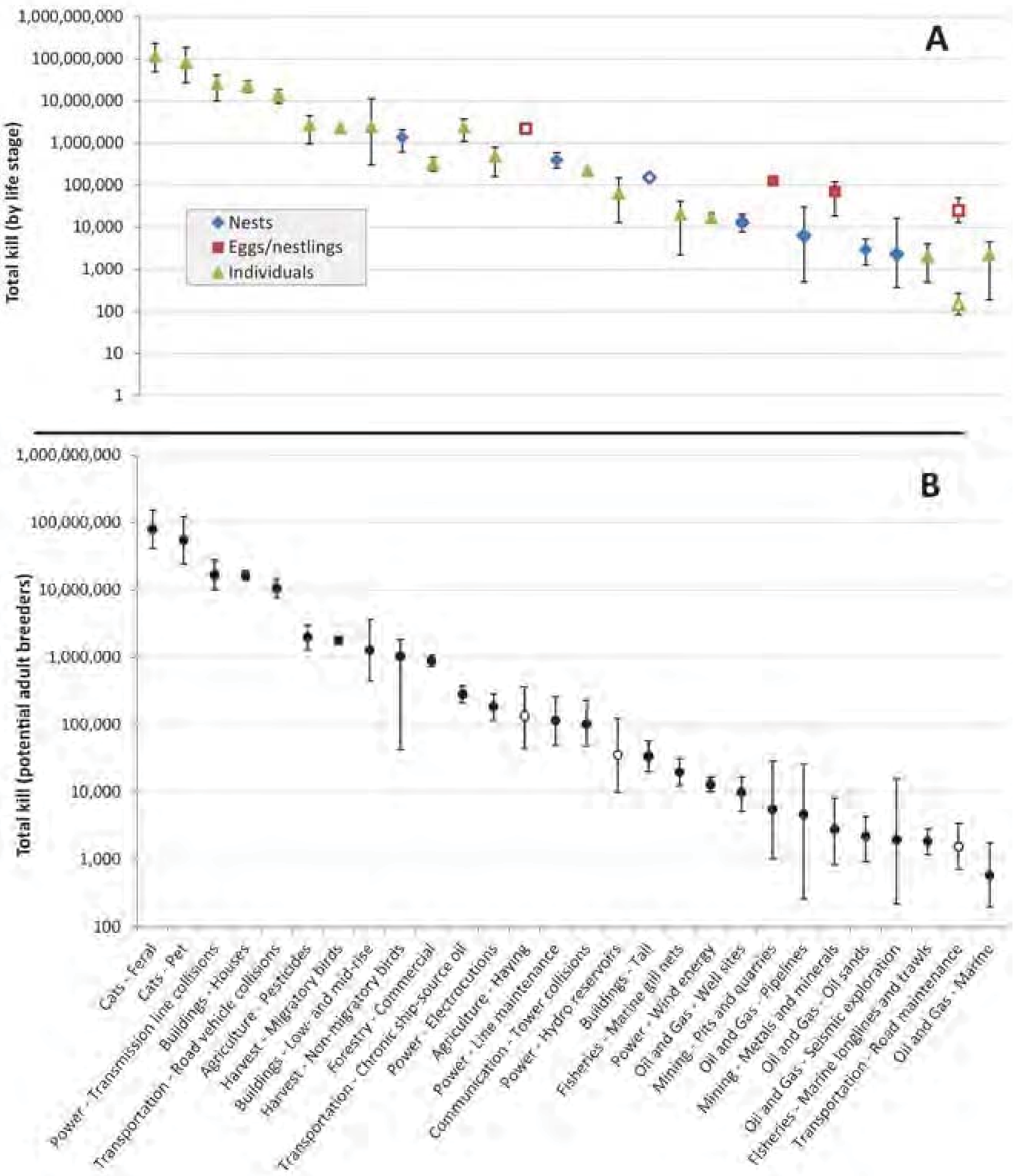
		LANDBIRDS				**SEABIRDS**				**SHOREBIRDS**				**WATERBIRDS**				**WATERFOWL**			
Primary type of impact	**Source**	**SPR**	**BRE**	**FALL**	**WIN**	**SPR**	**BRE**	**FALL**	**WIN**	**SPR**	**BRE**	**FALL**	**WIN**	**SPR**	**BRE**	**FALL**	**WIN**	**SPR**	**BRE**	**FALL**	**WIN**
Collisions	Transportation - Road vehicle collisions	+	++	+	+	o	o	o	o	+	+	+	o	+	+	+	o	+	+	+	o
	Buildings – Houses	++	++	++	+	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
	Power - Transmission line collisions	+	+	+	+	o	o	o	o	++	++	++	+	+	+	+	+	++	+	++	+
	Buildings - Low- and mid-rise	++	++	++	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
	Power – Electrocutions	+	+	+	+	o	o	o	o	+	o	+	o	+	o	+	o	o	o	o	o
	Communication - Tower collisions	++	+	++	+	o	o	o	o	+	o	+	o	+	o	+	o	+	o	+	o
	Buildings – Tall	++	o	++	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
	Power - Wind energy	+	++	+	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
Direct kill	Cats (feral and domestic)	++	++	++	++	o	o	o	o	o	+	o	o	o	+	o	o	o	+	o	o
	Agriculture – Pesticides	+	++	+	o	o	o	o	o	+	+	+	o	+	+	+	o	+	+	+	o
	Harvest - Migratory game birds	o	o	o	o	o	o	+	+	o	o	+	+	o	o	+	+	+	o	++	+
	Harvest - Non-migratory game birds	o	o	++	+	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
	Transportation - Chronic ship-source oil	o	o	o	o	o	o	o	++	o	o	o	o	o	o	o	o	o	o	o	o
	Fisheries - Marine gillnets	o	o	o	o	o	++	+	o	o	o	o	o	o	o	o	o	o	+	o	o
	Fisheries - Marine longlines and trawls	o	o	o	o	o	+	+	o	o	o	o	o	o	o	o	o	o	o	o	o
	Oil and Gas - Marine[†]	o	o	o	o	+	+	+	+	o	o	o	o	o	o	o	o	o	o	o	o
Nest destruction	Agriculture – Haying and mowing	na	++	na	na	na	o	na	na	na	o	na	na	na	o	na	na	na	++	na	na
	Forestry – Commercial	na	++	na	na	na	o	na	na	na	+	na	na	na	o	na	na	na	+	na	na
	Power - Line maintenance	na	++	na	na	na	o	na	na	na	++	na	na	na	++	na	na	na	++	na	na
	Power - Hydro reservoirs	na	++	na	na	na	o	na	na	na	++	na	na	na	++	na	na	na	++	na	na
	Oil and Gas - Terrestrial (all)	na	++	na	na	na	o	na	na	na	+	na	na	na	o	na	na	na	+	na	na
	Mining (all)	na	++	na	na	na	o	na	na	na	+	na	na	na	o	na	na	na	+	na	na
	Transportation - Road maintenance[‡]	na	++	na	na	na	o	na	na	na	+	na	na	na	o	na	na	na	++	na	na

[†] mortality from both direct kill and collisions;
[‡] mortality from both nest destruction and direct kill

Table 3. Median annual estimates of human-related mortality in Canada across the five major species groups, based on a stochastic model that converted stage-specific mortality to potential adult breeders, ranked in descending order according to total estimated mortality across all bird groups. Note that species-group totals do not sum exactly to the ‘all birds’ value because uncertainty in species composition was explicitly modeled and the “all birds” value was modeled independently of each species group’s total. See text and Appendix 2 for details of the stochastic model conversions. In cases where mortality was not fully extrapolated to all regions and taxa, e.g., where it was only estimated for a given region or set of focal species, the taxonomic or regional scope of the estimate is indicated; impacts estimated Canada-wide and across taxa are indicated as ‘all’ in the Scope column.

SOURCE	SCOPE	LANDBIRDS	SEABIRDS	SHOREBIRDS	WATERBIRDS	WATERFOWL	ALL BIRDS
Cats - Feral	All	78,600,000			293,400	380,500	79,600,000
Cats - Domestic	All	54,150,000			199,300	258,300	54,880,000
Power - Transmission line collisions	All	574,700		2,548,000	5,170,000	8,459,000	16,810,000
Buildings - Houses	All	16,390,000					16,390,000
Transportation - Road vehicle collisions	All	8,743,000		197,000	187,200	218,500	9,814,000
Agriculture - Pesticides	All	1,898,000		19,230	19,430	19,130	1,998,000
Harvest - Migratory game birds	All	235	55,520	24,770	8773	1,691,000	1,786,000
Buildings - Low- and mid-rise	All	1,132,000		26,310	23,870	32,190	1,283,000
Harvest - Non-migratory game birds	All	1,031,000					1,031,000
Forestry - Commercial	Landbirds	887,835					887,835
Transportation - Chronic ship-source oil	All		282,700				282,700
Power - Electrocutions	All	178,200		1715	1854	2275	184,300
Agriculture – Haying and mowing	5 species	135,400					135,400
Power - Line maintenance	All	70,140		4474		33,030	116,000
Communication - Tower collisions	All	101,500		965	1050	1278	101,500
Power - Hydro reservoirs	Québec	31,260		490	1571	158	35,770
Buildings - Tall	All	32,000		388	339	501	34,130
Fisheries - Marine gill nets	All		19,790				19,790
Power - Wind energy	All	13,060					13,060
Oil and Gas - Well sites	Landbirds	9815					9815
Mining - Pits and quarries	All	5169		39	168		5637
Oil and Gas - Pipelines	Landbirds	4687					4687
Mining - Metals and minerals	All	2798					2798
Oil and Gas - Oil sands	Landbirds	2193					2193
Oil and Gas - Seismic exploration	Landbirds	1966					1966
Fisheries - Marine longlines and trawls	All		1843				1843
Transportation - Road maintenance	6 species	1103		71		324	1545
Oil and Gas - Marine	All		584				584
TOTAL		**163,980,226**	**360,437**	**2,848,252**	**5,931,455**	**11,124,386**	**186,429,553**

Fig. 1. Annual mortality of Canadian birds due to human activities (log-scale). Panel A shows stage-specific estimates for each activity, according to whether entire nests, single eggs/nestlings, or mobile individuals were killed, as in original papers and reports. Values include both means and medians, and error bars represent both confidence limits (90% or 95%) and maximum/minimum ranges, as originally presented. Panel B shows converted mortality estimates for each activity (median with 90% confidence limits), where stage-specific kill totals have been converted to the equivalent number of potential adult breeders based on a stochastic model incorporating species-composition and demography. Hollow symbols indicate mortality only estimated for part of Canada or for a limited number of species, and thus where total Canada-wide cross-taxa mortality is likely much higher than these estimates. Panel C shows these same converted estimates (median with 90% confidence limits), pooled across related activities (cats: feral and pet; transportation: vehicle-collisions, road maintenance, and chronic ship-source oil; buildings: collisions with all 3 types; power: transmission-line collisions, hydro reservoirs, electrocutions, transmission-line maintenance, and wind energy; agriculture: haying and pesticides; harvest: migratory and nonmigratory birds; fisheries: all gear types; oil and gas: all terrestrial and marine sources; mining: both pits/quarries and metals/minerals), as well as the original single-source values for forestry and communication towers. Values in all panels are ranked in descending order according to the converted kill totals. See text and Appendix 2 for citations of papers and reports used as data sources.



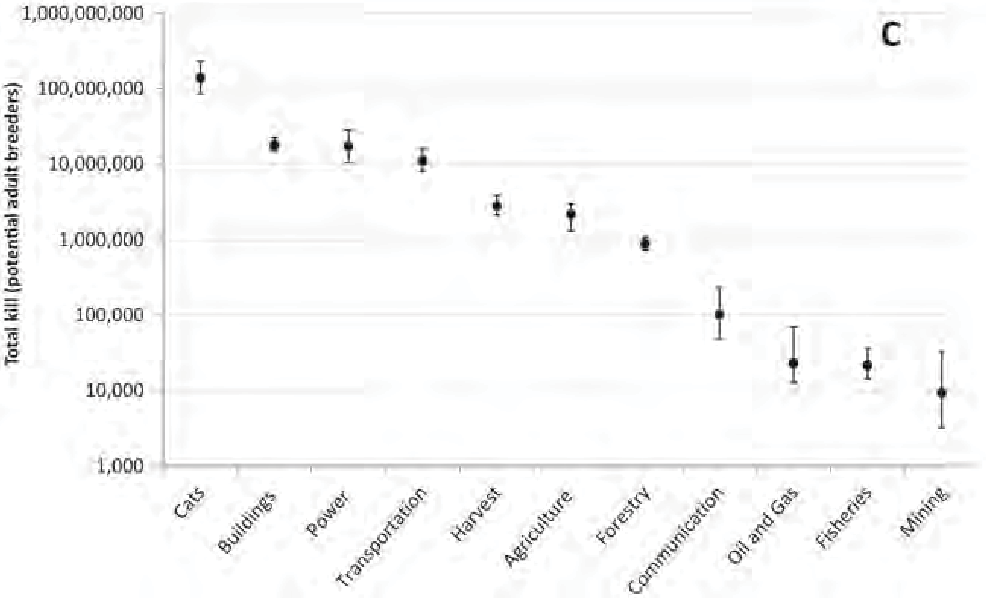

C
Total kill (potential adult breeders)
1,000,000,000
100,000,000
10,000,000
1,000,000
100,000
10,000
1,000
Cats
Buildings
Power
Transportation
Harvest
Agriculture
Forestry
Communication
Oil and Gas
Fisheries
Mining

Fig. 2. Proportion of population affected by anthropogenic mortality on Canadian birds, by species group (panel A) and by mortality source (panel B), for populations where data were available at sufficient resolution. Estimated annual kill for a given species, population, or family (converted to potential adult breeders) is plotted against the estimated Canadian abundance for that group, to show the estimated proportion of the total population killed by each activity. The three diagonal lines represent a mortality rate of 10%, 1%, and 0.1% for visual reference and are explained in more detail in the text. Details of mortality and abundance totals, as well as the identity of the species/population/family represented by each data point, are provided in Appendix 3. Game bird harvests are not included in this figure because they would dominate the figure and this source of mortality is regulated.

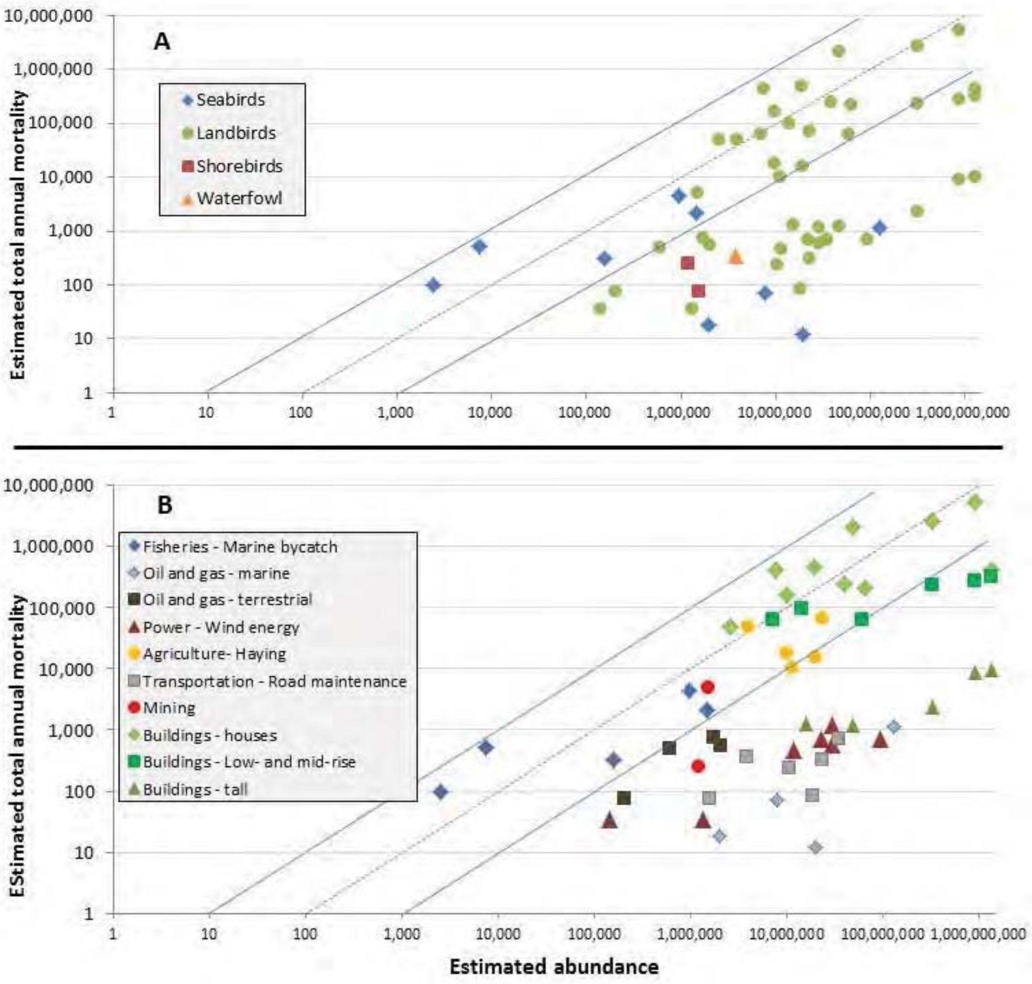


Fig. 3. Approximated distribution of total bird mortality estimates in Canada from eight terrestrial sources (cats, building collisions, vehicle collisions, agriculture, forestry, terrestrial oil and gas, communication towers, and wind turbines). Panel A is the sum of all eight sources, while panel B excludes the first three in the above list. These maps present the probability of mortality based on the distribution of each source in Canada. The hotspot on Montreal is because a single tile of our grid overlapped that city perfectly, while, for example, Toronto was centred at the intersection of 4 tiles. Unsmoothed maps for each mortality source and all mapping methods are provided in Appendix 4.