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Research Paper

Mortality of grassland birds increases with transmission lines

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ABSTRACT. Electrical transmission line development has been expanding globally by 5% per year, leading to increases in avian collisions with lines. Canadian estimates of transmission line collision mortalities range from 2.5 to 25.6 million birds per year, with the majority of mortalities attributed to collisions with overhead shield wires, and by susceptible birds that are young, large-bodied, with low maneuverability, or in open habitats. In this study, avian mortality was estimated for a ~4900 ha area in the mixed-grass prairie of southeastern Alberta following construction of two major transmission lines. We surveyed seven 500 m transects 7–10 times during both the breeding and migration seasons, where transects were categorized into road (n = 2), transmission line (n = 2), wetland (with transmission lines above; n = 1), or control (n = 2) areas. During the 2016 breeding season (5 May–24 June), we detected 23 mortalities under transmission lines, 7 mortalities beside roads, and no mortalities in controls. In the 2017 spring migration season (31 March–5 May), we detected 24 mortalities under transmission lines, 3 mortalities beside roads, and no mortalities in controls. Mortality rates were adjusted with biases estimated from detectability and scavenging trials. Scavenging rates were high (82% of carcasses were scavenged within 5 days) and detectability of deceased birds was positively related to body size. Overall, linear disturbances within the study area, including 37.7 km of highways and transmission lines, contributed to an estimated 75 deaths/km of linear disturbance during one migration and one breeding season (~50 deaths/km of transmission line and ~25 deaths/km of road; ~1904 bird mortalities total). These findings point to the need for mitigation to reduce bird mortality, thereby minimizing the long-term impact of linear disturbances, such as transmission lines and roads, on associated bird communities.

La mortalité d'oiseaux de prairies augmente avec les lignes de transport d'électricité

RÉSUMÉ. L'installation de lignes de transmission électrique s'est accrue de 5 % par an dans le monde, entraînant une augmentation des collisions d'oiseaux avec ces lignes. Les estimations canadiennes de la mortalité attribuable aux collisions avec les lignes de transmission se situent entre 2,5 et 25,6 millions d'oiseaux par an, la majorité des mortalités étant attribuées aux collisions avec les fils de blindage aériens et par des oiseaux sensibles, qui sont jeunes, de grande taille, peu manoeuvrables ou dans des habitats ouverts. Dans la présente étude, la mortalité d'oiseaux a été calculée pour une zone de ~4900 ha dans la prairie mixte du sud-est de l'Alberta suite à la construction de deux lignes de transmission majeures. Nous avons inventorié sept transects de 500 m de 7 à 10 fois pendant les saisons de nidification et de migration, les transects ayant été classés en zone de routes (n = 2), de lignes de transmission (n = 2), de milieux humides (avec des lignes de transmission au-dessus; n = 1) ou faisant office de témoin (n = 2). Au cours de la saison de nidification 2016 (5 mai-24 juin), nous avons détecté 23 mortalités sous des lignes de transmission, 7 mortalités à côté de routes et aucune mortalité dans les zones témoin. Au cours de la migration printanière 2017 (31 mars-5 mai), nous avons détecté 24 mortalités sous les lignes de transmission, 3 mortalités à côté de routes et aucune mortalité dans les zones témoin. Les taux de mortalité ont été ajustés au moyen de biais calculés à partir d'essais de détectabilité et de disparition des carcasses imputable aux charognards. Les taux de disparition étaient élevés (82 % des carcasses ont été éliminées dans les 5 jours) et la détectabilité des oiseaux morts était positivement liée à leur taille. Dans l'ensemble, les perturbations linéaires dans la zone d'étude, y compris 37,7 km d'autoroutes et de lignes de transmission, ont entraîné 75 mortalités/km de perturbation linéaire pendant une saison de migration et une saison de nidification (~50 mortalités/km de lignes de transmission et ~25 mortalités/km de routes; ~1904 mortalités d'oiseaux au total). Nos résultats soulignent la nécessité de mettre en place des mesures d'atténuation pour qu'on puisse réduire la mortalité d'oiseaux, minimisant ainsi l'impact à long terme des perturbations linéaires, telles que les lignes de transmission et les routes, sur les communautés d'oiseaux.

Key Words: *collisions; detectability trial; power line; road; scavenger trial; search bias*

INTRODUCTION

Collisions of birds into transmission lines have long been a source of conservation concern (Coues 1876, Quinn et al. 2011, Rioux et al. 2013, Loss et al. 2014). Yet, transmission line development is predicted to increase globally at a rate of 5% per year, with an associated increased mortality risk to avian species (Silva et al. 2010, Loss et al. 2014). Only ~2% of the world's bird species (~245 out of 10,824 global species; Cornell Lab of Ornithology 2021) have been documented colliding with transmission lines, particularly waterfowl, cranes, herons, grouse, and passerines (Brown et al. 1987, Bevanger 1995, 1998). Current estimates (from 2009) predict between 2.5 and 25.6 million birds are killed annually by transmission line collisions across a network of 231,966 km of lines in Canada (Rioux et al. 2013), but more

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studies are needed to enhance our understanding of this phenomenon.

Avian mortality along transmission lines is affected by infrastructural, biological, and environmental factors (Bevanger 1998, Loss et al. 2014). Structurally, overhead shield wires, i.e., the highest wire on transmission lines, pose a significant risk to birds because of their smaller diameter and limited visibility (Pandey et al. 2008, Murphy et al. 2009). Faanes (1987) reported that 91% of observed bird collisions were a result of hitting overhead shield wires and Pandey et al. (2008) reported that 68% of collisions involved the overhead shield wire. Biologically, the most susceptible birds tend to be large-bodied and weak fliers, with poor maneuverability, such as cranes and waterfowl (Ward and Anderson 1992, Bevanger 1998, Manville 2005, Shaw et al. 2010, Loss et al. 2014), as well as species that form flocks (Scott et al. 1972, Liguori 2009, Loss et al. 2014). Adult birds may be less likely to collide with transmission lines because of past learning, i.e., juvenile Sandhill Cranes (*Antigone canadensis*) were found to collide twice as often as others in the population (Ward and Anderson 1992), but may also be more likely to collide while moving between foraging and breeding sites (Anderson 1978). Environmentally, waterbirds and shorebirds are more likely to collide with transmission lines near wetlands, while raptors and passerines are more likely to collide in areas away from wetlands (Manville 2005). Collisions are also more likely during periods of poor visibility, such as during dusk, dawn, and at night (Scott et al. 1972, Avery et al. 1977, Hüppop et al. 2016). Although we know that mortality due to transmission lines varies with many factors, we still lack assessments in many regions of the world, which hinders our capacity for mitigation.

Canadian estimates of avian mortality from transmission line collisions vary widely (2.5 to 25.6 M per year; Rioux et al. 2013) and have been based on data collected in similar habitats in other countries because of limited data availability in Canada. Some of the variation in these estimates is caused by differences in correction factors that are applied to account for various forms of bias such as search, habitat, removal, and crippling bias (Beaulaurier 1981). Thus, there is a distinct need to estimate and compare these correction factors between studies. The number of birds killed by transmission line collisions in grasslands remains largely unknown, as are the factors that contribute to these collisions. Grassland birds may be at greater mortality risk because of the nature of transmission lines being a large flight obstacle in an otherwise open landscape. Previous studies of transmission lines suggest that avian mortalities are most common in flatter areas, including vineyards and open grasslands (Demerdzhiev 2014). Therefore, grassland bird species may be at greater risk in these flat, open habitats, including species that travel through the Central migratory flyway.

More than 200 bird species breed in Canada's grasslands, including approximately 25 grassland specialists (Partners in Flight 2021). Grassland bird populations have declined by 57% since 1970 (North American Bird Conservation Initiative Canada 2019), mainly because of loss of habitat, with only 25% of native Canadian prairie currently remaining (Weiler 2010, ABMI 2015). Bird populations could be further jeopardized by collisions with transmission lines, particularly species at risk whose populations are already of conservation concern, e.g., Sprague's Pipit (*Anthus spragueii*) and Baird's sparrow (*Centronyx bairdii*). Recently, a bird collision risk hotspot analysis in Alberta (Quinn et al. 2011) suggests that there are collision hotspots throughout the southern half of the province and that many populations in the grasslands may be at risk of collisions.

The construction of two major transmission lines in 2014 within the dry mixed-grass prairie of southeastern Alberta, Canada provided an opportunity to estimate mortality caused by collisions with transmission lines soon after construction in an understudied ecoregion. We surveyed seven 500-m transects during the breeding season and spring migration season of 2016 and 2017, respectively. Specifically, we compared transmission line, wetland (with transmission lines above), road, and control (undisturbed grassland) areas to one another. We estimated mortalities caused by transmission line collisions, as well as the adjacent highway to compare to the transmission line effect, and discuss the potential implications of these linear disturbances on the combined mortality effects of grassland birds.

METHODS

Study area

This study took place at the University of Alberta Mattheis Research Ranch, in southeastern Alberta (50.896736 N, -111.952711 W; Fig. 1; Appendix 1). The ranch encompasses ~4900 ha of native grassland bounded by the Red Deer River in the north and Matzhiwin Creek in the south. Most of the ranch is native, i.e., intact, non-cultivated, grassland with several constructed wetlands to provide waterfowl habitat. The ranch is divided into east and west blocks by Highway 36, a high-use transportation route. Three transmission lines are present along Highway 36; here we focus on one of two high-voltage transmission lines that were constructed in 2014–2015 (50–250 m from the highway; one 500 kV alternating current, one 500 kV direct current). Transmission line towers are spaced 300 to 400 m apart, and the three different lines are at least 50 m apart from each other, encompassing a disturbed area at least 100 m wide.

Study design

Transects

The study area was stratified into three treatments and a control (Fig. 1), with a total of seven transects divided among roads (n = 2), transmission lines (n = 2), wetlands (with a transmission line above; n = 1), and controls (n = 2). Each transect consists of a 500-m long and 30-m wide search area (i.e., 30 m adjacent to the primary paved road, Highway 36; 15 m on either side of the center line under the transmission line, including the water if a wetland was present underneath; and 30-m wide along transects in control locations). The wetland transect was only 400 m in length to target waterfowl mortalities, of which the length included the entire wetland and 50 m on either end. A second wetland transect was removed because of disturbance from telephone pole construction during sampling. We used a width of 30 m to minimize counting mortalities caused by the adjacent transmission and distribution lines, but was wide enough to encompass the entire area below the lines with a buffer of 5 m on either side.

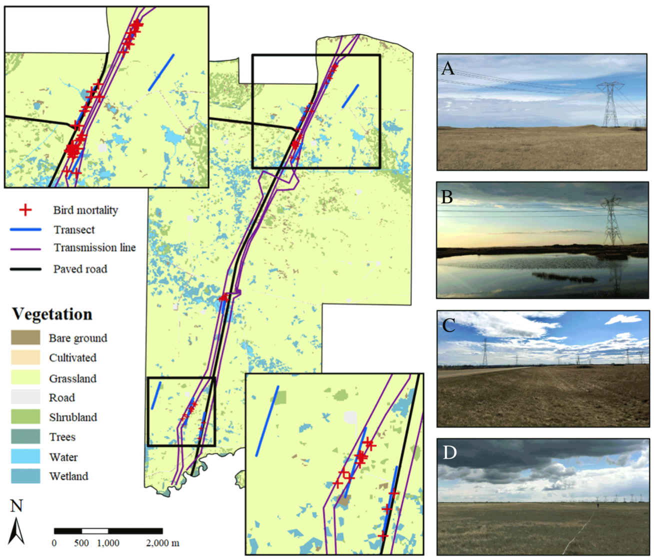


Fig. 1. Map of study area, the Mattheis Research Ranch in southeastern Alberta, Canada, with transects in blue where mortality surveys took place. Transects were divided into four treatments: (A) transmission line, (B) wetland (under transmission lines), (C) road, and (D) control.

Transmission line transects were at least 100 m from nearby roads, and control transects were at least 1000 m from both roads and transmission lines. The wetland transect was situated where transmission lines were strung above a body of water over 30 m in diameter and was sampled to facilitate the assessment of waterfowl mortalities.

Search effort

Searches for dead and injured birds were conducted during the breeding season (5 May–24 June) of 2016 (average 4.6 days between searches) and the spring migration season (31 March–5 May) of 2017 (average 3.6 days between searches). Observers systematically walked in a zig-zag pattern from the center of the transects with 1.5 hr of search effort per observer per 500 m distance (total search hours ~206 h). Each transect was searched 10 times during each search season, with the exception of the wetland transect, which was searched 7 times in 2016 because it was added later in the sampling season.

The location of all bird carcasses or partial remains was recorded and given a unique label, along with the date of discovery and species identified. Other notes, such as the condition of (or type of damage to) the carcass, were also recorded. Carcasses were photographed and removed upon discovery to eliminate repeat counts, and where necessary, frozen for later identification. Carcasses were included in the count when there were at least 5 feathers present, because feathers can fall out individually during molting or fights (Erickson et al. 2005). In addition to general transect surveys, detectability and scavenging trials were conducted to calculate bias and to adjust bird mortality rates.

Bias

Estimates of avian mortality from transmission line collisions are typically calculated by determining the number of mortalities per km of line, after adjusting for four main types of bias (Beaulaurier 1981): search, habitat, removal, and crippling bias. The detectability of carcasses is affected by terrain, bird species identity, vegetation, and searcher experience ("search bias"). Similarly, searches in some parts of the study area may be limited by habitat characteristics, such as unsearchable areas of water or dense vegetation ("habitat bias"). Alternatively, carcasses may be removed by scavengers before they are detected, especially if carcass searches occur many days apart ("removal bias"). Finally, some birds may collide with transmission lines but fall or perish outside the search area ("crippling bias").

We did not include any correction factor for habitat bias because all areas were searchable with safe terrain (wetlands were either waded or surveyed with binoculars and subsequent carcasses were removed to prevent double counting). We also did not assess crippling bias because of the difficulty of estimation and because crippling rates should not be borrowed from other studies on account of high variability between estimates (Rioux et al. 2013), but we discuss the implications on our mortality estimates and extrapolations.

Detectability (search-bias) experiment

Fourteen search-bias experiments (two per transect) were conducted in 2016 to determine adjustment factors for detectability of carcasses and to evaluate the search efficiency of observers conducting ground surveys for bird carcasses. The bird carcasses were obtained from hunters or were carcasses found during previous transect surveys, and represented a range of species and sizes, including Ring-necked Pheasant (*Phasianus colchicus*), Rock Dove (*Columba livia*), and sparrows (i.e., *Pooecetes gramineus*, *Passerculus sandwichensis*, *Spizella pallida*).

Before each trial, between 0 and 6 bird carcasses or remains with distinguishing factors (e.g., outer three wing primaries clipped, clumps of feathers placed in a bullseye pattern; n = 144) were randomly placed within the search area by another person. After placement, starting within 10 minutes, the observer, who was unaware of whether bird carcasses were placed in the area, examined the search area using the same sampling effort as that used in the main surveys, and recorded the number and location of carcasses found. The mean proportion of remains not found at each site was used to adjust for the detectability bias of undetected bird carcasses. This detectability bias was assumed to be constant between years because of only one observer conducting surveys in 2017.

Scavenging rate experiment

To quantify scavenger removal rates, bird carcasses (n = 28 in 2016, n = 23 in 2017) were placed near (< 300 m, but not within) the search areas of each transect at known locations and monitored until all carcasses were removed by scavengers. A carcass was considered "scavenged" when the carcass disappeared from the search area, or when bones and/or at least 5 feathers remained (Erickson et al. 2005). Sites were checked twice on a daily basis during the first 3 days after placement, and once daily thereafter until scavenging occurred. The surrounding areas (up to 50 m away) were also searched in case the carcasses had been moved by scavengers. During searches, the presence/absence of the carcass was recorded, as well as the stage of decomposition or scavenging activity (i.e., intact, > 50% present, 25–50% present, feathers and bone only, completely missing). Carcasses were either fresh or frozen birds and were a variety of sizes and species that are present in the region (carcasses included 9 Ring-necked Pheasants, some of which were cut into smaller pieces to mimic smaller passerines; 13 Rock Doves; 5 Black-billed Magpies [*Pica hudsonia*]; 2 American Crows [*Corvus brachyrhynchos*]; and 2 Brewer's Blackbirds [*Euphagus cyanocephalus*]), as surrogate species used to quantify carcass removal may result in inaccurate scavenging estimates (DeVault et al. 2017). Carcasses were thawed for at least 8 hr before deployment. The average length of time before a carcass was removed, as well as the proportion of carcasses not removed, were calculated at the end of each season and used to determine scavenging rate. We used Cox proportional hazard analyses to determine whether the rate of scavenging varied across sites, treatments, and time since placement.

Statistical analysis of mortalities

The number of bird mortalities associated with collisions either from vehicles along roads or transmission lines is based on the number of carcasses found, the detection rate of observers, and the carcass-removal rate from scavengers (Erickson et al. 2004). Bird mortalities caused by transmission lines were calculated using the equation from Erickson et al. (2004) of:

$$m_1 = \frac{\bar{c}}{\hat{\pi}} \qquad (1)$$

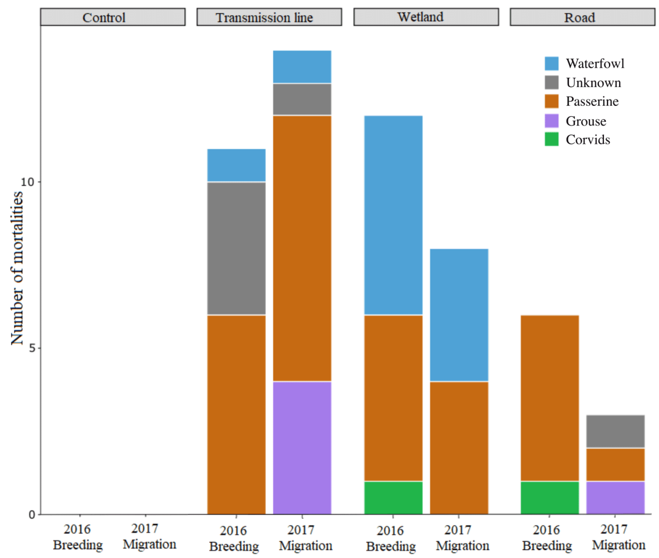
where m_1 is the estimated mortality rate $\bar{c}$ is the mean number of carcasses observed per kilometer of transmission line, and $\hat{\pi}$ is all bias (searcher efficiency and scavenging; Appendix 2). We calculated mortality estimates for transmission lines separately for each breeding and migration season, and calculated an average mortality estimate for roads across both seasons because of the limited number of carcasses found each season. Specifically, we calculated a mortality estimate of birds over the 27.5 km of high voltage transmission lines and 10.2 km of roads using data collected within our study area during the breeding season of 2016 and migration season of 2017.

RESULTS

During the 2016 breeding season, we found 23 dead birds underneath transmission lines, 6 next to or on roads, and none in the controls (Fig. 2, Table 1). There were 9 confirmed species found deceased in plots under transmission lines, with the Western Meadowlark (*Sturnella neglecta*), Vesper Sparrow (*Pooecetes gramineus*), Mallard (*Anas platyrhynchos*), and Northern Shoveler (*Spatula clypeata*) being the most common species in 2016 [13% each of mortalities; Western Meadowlark and Vesper Sparrow were the first and second most common species breeding in the study area, respectively (Martin 2018)]. The Western Meadowlark was the most common species found near roads (33% of mortalities; Table 1).

During the 2017 spring migration season, we found 22 dead birds underneath transmission lines, 3 next to or on roads, and none in the control (Fig. 2, Table 1). Most remains were clumps of feathers and bone, although some remains were entire bodies, and one was an injured Western Meadowlark that was unable to fly. Although 8 species were found deceased in transects under transmission lines, Western Meadowlarks were the most abundant at 31.8% of these mortalities (Table 1). Western Meadowlarks were also the most common species in the study area in 2016 (Martin 2018).

Fig. 2. Number of mortalities by type of bird (see Table 1 for species) and season. No mortalities were found in control transects. More species were found in transects with transmission lines (with or without wetlands). The greatest number of waterfowl mortalities were found in transects with wetlands under transmission lines. Perching birds represented the majority of mortalities.



Each dead bird found beside roads during the 2017 spring migration season was of a different species (Table 1).

Because there were no mortalities detected in control areas in either year, and the sample transects associated with transmission lines were at least 100 m from nearby roads, all carcasses found beneath transmission lines were attributed to collisions with overhead lines. In 2016, almost half of the carcasses found under transmission lines were situated where lines were above water, whereas only a third of carcasses were found under transmission lines with water during the migration period in 2017 (Fig. 2). Injuries to the leading portion of the head and chest appeared to be the cause of death for the majority of intact specimens. Many carcasses also had broken wings, which may have led to mortality due to shock or scavenging due to their inability to fly. Other mortalities found under the transmission lines that included only feather or bone remains were assumed to have been caused by transmission lines and subsequently scavenged, and notably were in similar condition to the carcasses used in the experimental scavenging trials.

Detectability rates were similar between observers during the breeding season of 2016 (two-way *t*-test, $t_{141} = 0.590$, $p = 0.556$). Absolute detection rates of the two observers in 2016 were 0.66 and 0.63 (proportion of carcasses detected by observers), with no differences detected between treatment areas or transects (ANOVA; $p_{treatment} = 0.169$; $p_{transect} = 0.235$). An average detection rate of 0.64 was therefore used in the derivation of estimates of total mortality. In 2017, the individual detectability rate was assumed to be the same as the previous year. Size of carcass had a marginally significant effect on detection, where large carcasses

Table 1. Number of bird mortalities found by transect and species during the 2016 breeding season (5 May to 24 June) and 2017 migration season (31 March to 5 May). Counts in brackets represent the number of mortalities found in transmission line transects with a wetland directly underneath the lines.

Transect	Species	Bird Group	2016 Count	2017 Count
Transmission Line	American Coot, *Fulica americana*	waterfowl	0	1
	American Robin, *Turdus migratorius*	passerine	0	2
	Brown Thrasher, *Toxostoma rufum*	passerine	1	0
	Clay-colored Sparrow, *Spizella pallida*	passerine	(1)	0
	Lapland Longspur, *Calcarius lapponicus*	passerine	0	1
	Mallard, *Anas platyrhynchos*	waterfowl	(3)	(1)
	Northern Shoveler, *Spatula clypeata*	waterfowl	(3)	(3)
	Orange-crowned Warbler, *Leiothlypis celata*	passerine	1	0
	Ring-billed Gull, *Larus delawarensis*	waterfowl	1	0
	Red-winged Blackbird, *Agelaius phoeniceus*	corvids	(1)	0
	Savannah Sparrow, *Passerculus sandwichensis*	passerine	0	(1)
	Unidentified Sparrow	passerine	(2)	(1)
	Sharp-tailed Grouse, *Tympanuchus phasianellus*	grouse	0	4
	Vesper Sparrow, *Pooecetes gramineus*	passerine	3	0
	Western Meadowlark, *Sturnella neglecta*	passerine	3(2)	7(2)
	Unknown	unknown	4	1
	Total		23(12)	22(8)
Road	American Robin	passerine	0	1
	Black-billed Magpie, *Pica hudsonia*	corvids	1	0
	Clay-colored Sparrow	passerine	1	0
	Eastern Kingbird, *Tyrannus tyrannus*	passerine	1	0
	Sharp-tailed Grouse	grouse	0	1
	Western Meadowlark	passerine	3	0
	Unknown	unknown	0	1
	Total		6	3
Control	Total		0	0
Combined Total			29	25

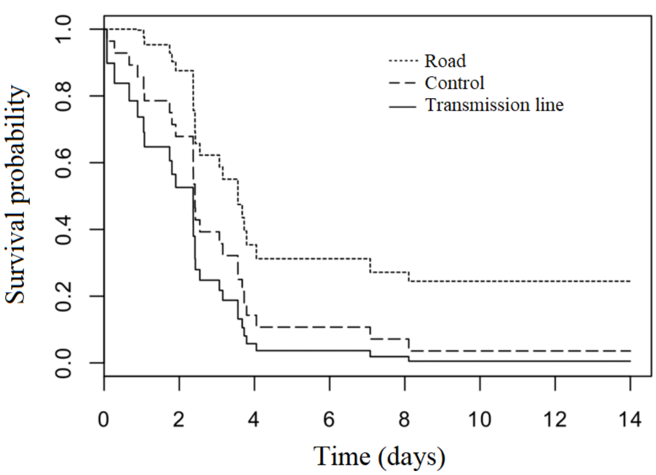
(wings or large birds) were detected more often than small carcasses (sparrows or feather clumps), with no effect of carcass color (ANOVA, p_{small} = 0.053, p_{brown} = 0.245, p_{grey} = 0.586; Table 2).

Table 2. Results from ANOVA evaluating the detectability of deceased birds based on the size and color of carcass across treatments (control, transmission line, and road).

Factor		Estimate	Standard Error	t-value	p-value
	Intercept	0.869	0.167	5.210	<0.001
Treatment (control as reference)	Transmission	-0.109	0.095	-1.138	0.257
	Road	-0.120	0.099	-1.207	0.230
Size (large as reference)	Small	-0.259	0.133	-1.956	0.053
Color (black as reference)	Brown	-0.130	0.112	-1.167	0.245
	Grey	0.089	0.163	0.547	0.586

Scavenging rates were similar among the three treatments (ANOVA; p_{power} = 0.404, p_{road} = 0.953; Table 3). Cox proportional hazard models demonstrated that there was a constant loss of bird carcasses over time through scavenging regardless of site (Fig. 3). An average scavenging rate was therefore used in the estimate of mortality, with 82% of carcasses scavenged within 5 days. Size and color of carcasses did not affect scavenging rate (Table 3). One carcass under a transmission line was never scavenged during the duration of the trial (n = 43 days).

Fig. 3. Cox hazard non-parametric test depicting the probability of carcass survival over time (days) (W = 4.82, df = 2, *p* = 0.090). Treatment did not affect carcass survival (ztransmission = -0.539, ptransmission = 0.590; zroad = 1.534, proad = 0.125).



After including biases for detection and scavenging (using equations from Erickson et al. 2004; Appendices 2 and 3), bird mortality rates were estimated at 49.7 (migration) to 50.6 (breeding) birds per linear kilometer of transmission line, while road mortality rates were approximately half of transmission lines at 25.6 birds per kilometer. Combined sources of mortality

Table 3. Results from the ANOVA evaluating the effect of scavenging time (days) based on treatment (control, transmission line, and road), carcass size, and carcass color.

Factor	Variable	Estimate	Standard Error	t-value	p-value
Treatment	Intercept	-9.687	32.087	-0.302	0.764
(control as reference)	Transmission	16.851	19.999	0.843	0.404
	Road	-1.242	20.840	-0.060	0.953
Size	Small	-6.583	32.436	-0.203	0.840
(large as reference)	Small-medium	10.875	34.364	0.316	0.753
	Medium	12.537	43.197	0.290	0.773
Color	Black and white	72.101	40.977	1.760	0.086
(black as reference)	Brown	13.874	42.233	0.329	0.744
	Grey	-7.507	29.618	-0.253	0.801

resulted in an estimated 1904 birds killed annually in the study area, based on data from two seasons (~72% of mortalities caused by transmission lines).

DISCUSSION

We observed high mortality rates, i.e., ~50 mortalities per linear kilometer, associated with the development of transmission lines compared to roads within Mattheis Ranch, a research center within the native semi-arid grasslands of Canada. Roads posed additional mortality risk, but were half as risky as transmission lines at ~26 mortalities per kilometer, contributing to ~28% of mortalities in the study area.

The average number of dead birds found per length of transmission line (49.7 to 50.6 mortalities per km) was similar to those estimated in other studies (42.3 ± 17.1 birds per km; reviewed by Rioux et al. 2013). Similarly, detection rates were comparable to those documented in other studies in open environments, e.g., in hay fields, cropland, dunes, and burned areas (an average detection probability of 65% for small-medium carcasses and up to 88% for large carcasses was found by Longcore et al. (2012), vs 64% from the current study), as well as studies that stratified data from open and forested environments (average 80% detection probability; Rioux et al. 2013). We used carcasses of a variety of sizes and colors in our detectability trials to represent the local bird community, while other studies focused on medium to large bird species. However, when estimating the total number of carcasses, we pooled large and small birds to correct for detection probability. Therefore, because detection of smaller carcasses was lower than that for larger carcasses, the number of passerine mortalities were underestimated, whereas large birds were overestimated. Scavenging rates were also greater in this study (82% after 5 days) than previous investigations (average of 39% after 7 days, Rioux et al. 2013), possibly because scavengers may detect carcasses more easily in open grasslands with favorable visibility.

Because of the difficulty in locating bird carcasses (e.g., here we found 54 dead birds in ~206 h of sampling), and thus the extensive time required to conduct each 500-m search transect, our results are based on a limited sample size (n = 7 transects). We also note that, even though we focused on the spring migration and breeding seasons, the inclusion of mortality estimates from fall migration could have substantially increased our estimates, especially because as much as 80% of bird mortalities may occur during fall (Faanes 1987). Still, we provide valuable information, particularly on the mortality of passerine birds, which are typically understudied regarding collision mortality in general (Rioux et al. 2013) and are of particular conservation concern in these grassland environments (Sauer et al. 2011). We also acknowledge a potential confounding effect of the nearby highway, located at least 100 m away from the transmission line along its length in the study area. However, because we found no mortalities in control transects and far fewer mortalities near roads than transmission lines, we suggest that transmission lines resulted in relatively greater mortality across our study area.

Crippling bias can be substantial given that an estimated average of 80% of birds that collide with transmission lines may continue in flight (Rioux et al. 2013). Because crippled birds can continue to fly for hundreds of meters after suffering from a collision (i.e., crippled birds have been found over 2 km from where they were injured; Bevanger 1995), there is indeed a possibility that some of the mortalities recorded under transmission lines were due to road mortalities and vice versa, but this is arguably a minor confounding effect in our results. Our data do not suggest that this was a determining factor underlying our results because control transects were placed at comparable distances from transmission lines but never showed mortalities. Another line of evidence supporting these results is provided by other transmission line mortality studies (see review by Rioux et al. 2013), which found similar mortality estimates to ours, and suggests that our estimates based on mortalities found directly under transmission lines are unlikely to suffer from severe effects of crippling bias. Ultimately, our results are based on the assumption that most birds affected by collisions with transmission lines and roads tended to land within 50 m from the collision event, and fewer at further distances, i.e., distance-decay relationship. This is an assumption that we deem acceptable in this system but should be evaluated further in future studies. Studies are also needed from randomized locations across the prairies that incorporate crippling bias to determine the specific accuracy of our mortality estimates, including the specific contribution of roads and transmission lines to bird mortality.

In contrast to previous investigations (i.e., Ward and Anderson 1992, Manville 2005, Shaw et al. 2010, Loss et al. 2014), small-bodied birds, particularly passerines, composed a substantial proportion (~53%) of mortalities compared to large-bodied birds in our study area. Moreover, this occurred despite their lower detectability, although the shorter (mixed-grass prairie) vegetation in our study area may have contributed to greater detection of smaller species (Longcore et al. 2012). Because passerines make up the majority of birds in grassland environments, with few large-bodied birds found away from wetlands, our sample may simply be representative of the typical bird community of this prairie grassland. Alternatively, it remains unclear if passerines are more likely to strike transmission structures and perish in open-grassland environments.

Collision rates may be higher immediately after transmission line construction because of the novelty of the obstacle in the environment, with collision rates possibly decreasing over time (Jones et al. 2007, Dornak 2010). If this is the case, mortality may decline as returning individuals learn to avoid lines in subsequent breeding seasons, particularly given that 5–30% of grassland bird species demonstrate breeding site fidelity (Small et al. 2012). Some birds may also change their behavior in response to transmission line construction, leading to reduced collision risk. For example, in a pre- and post-construction study of behavioral responses of raptors to transmission lines, Luzenski et al. (2016) found that a greater proportion of raptors flew at higher elevations immediately after the lines were constructed (72% pre-construction vs. > 90% post-construction), thereby avoiding collisions. More research is needed to determine if other taxa respond in the same way, especially those with different flight patterns, such as grouse and passerines.

Because transmission lines provide hunting perches for raptors (Steenhof et al. 1993, Coates et al. 2014), they also can have indirect effects on bird mortality. We typically detected carcasses along the entire length of transects under transmission lines, regardless of the presence of towers, with only two incidences of remains directly under a tower. As a result, our study suggests that predation was not the primary source of mortality near transmission lines, because a concentration of carcasses would be expected near towers where raptors hunt and consume prey. Electrocutions are also an issue for raptors specifically because they use transmission towers for hunting, resting, and nesting, and the level of risk can be affected by habitat, topography, climate, and transmission line structure (Kemper et al. 2013). Although we did not observe any raptor mortalities during transect searches, we only sampled a total of 1.4 km of transmission lines, which is a small area compared to raptors' home ranges (e.g., ~87–172 km² for Swainson's Hawks [*Buteo swainsoni*]; Fleishman et al. 2016).

Methods to mitigate bird mortality include line marking, managing surrounding lands to reduce attractiveness to birds, removing overhead shield wires, changing line configuration, rerouting existing lines, and burying lines (Alonso et al. 1994, Brown and Drewien 1995, Janss and Ferrer 1999, Crowder and Rhodes 2002, Quinn et al. 2011). Burying transmission lines is the only solution that completely eliminates bird collisions, a practice that is common in Belgium, Germany, Norway, Netherlands, and USA (Bernardino et al. 2018), but at a relatively high cost and disturbance to surrounding vegetation (Janss and Ferrer 1999, Jenkins et al. 2010). Rerouting existing lines and route planning for future lines can be effective in mitigating bird collisions by avoiding sensitive bird habitats and protected areas (D'Amico et al. 2018), but will not fully eliminate the risk of collision, especially during mass bird movement such as migrations. Removing overhead shield wires can lead to reductions in bird collision rates, but may leave the transmission lines vulnerable to lightning strikes and unreliable transmission (APLIC 2012). Line marking to increase the visibility of transmission lines is the most common method of mitigation but has had variable success (e.g., Alonso et al. 1994, Brown and Drewien 1995, Janss and Ferrer 1999, Ventana Wildlife Society 2009). A meta-analysis by Bernardino et al. (2019) suggests wire marking can reduce bird collisions by an average of ~50%, but this efficacy may be affected by habitat, marker type, and marker spacing. Flapper diverters appear to be more effective in reducing collisions than spiral diverters (~70% lower mean mortality rate; Ferrer et al. 2020), but studies that compare types of line markers are uncommon. By directly investigating bird flight responses to transmission lines using radar, Pavón-Jordán et al. (2020) determined that birds detect line markers and subsequently avoid flying in these areas in daytime when markers are most visible, highlighting the potential for line markers to reduce the risk of daytime bird collisions. Nocturnal bird collisions are also frequent, even in areas with glow-in-the-dark markers, but crane collisions were reduced by 98% using near-ultraviolet light to illuminate lines (Dwyer et al. 2019). These mitigation strategies designed to protect cranes and waterfowl may also inadvertently reduce passerine mortality, but this has not been thoroughly tested. Mitigation attempts of deterring passerines have not been examined elsewhere because they were not detected at levels considered to pose a significant risk. However, approximately 45% (21 deaths out of 47) of mortalities in this study were passerines, suggesting that mortality risk for passerines is under-studied, under-detected, or both.

The effect of mortality on bird populations caused by collisions with transmission lines is unknown. Although collisions with vehicles contributed to lower rates of mortality than transmission lines, the total length of highways within grasslands of the region far exceeds the length of transmission lines, and thus is likely to result in greater total mortalities and may have greater effects on bird populations. Several studies have concluded that collision mortality does not significantly impact select bird populations (e. g., Meyer 1978, Thompson 1978, James and Haak 1979, Beaulaurier 1981, Faanes 1987, Alonso and Alonso 1999), but more recent data suggests that collision mortality may in fact have population-level impacts (Schaub and Pradel 2004, Schaub et al. 2010, Loss et al. 2012), especially for bird species of conservation and economic concern (Hobbs 1987, Bevanger 1995, 1998, Janns 2000). Limited data in Canada restricts the confidence in impact estimates to populations, especially for migratory species that encounter collision risk across hundreds of kilometers of their migratory paths throughout the year (Rioux et al. 2013). More generally, mortalities caused by collisions with buildings in Canada are substantial but population effects are unknown (~24.9 million; Machtans et al. 2013), while mortalities caused by wind turbine collisions affecting less than 2% of populations are not thought to affect long-term populations (Zimmerling et al. 2013). Despite this, local populations of sensitive grassland species may have variable risks of local extinction because of wind turbine collision mortality (Erickson et al. 2015). Studies on transmission lines have been limited to date in Canada and the effects of mortality caused by collisions with buildings, communications towers, wind turbines, transmission lines, and cars, may all contribute to greater local population loss because of cumulative direct and indirect effects (Smith and Dwyer 2016).

CONCLUSION

We suggest that there is substantial risk of grassland bird mortality due to collisions with transmission lines and vehicles, with an estimated 50 birds per km of transmission line and 26 birds per km of road affected, totaling 1904 mortalities per year across ~4900 ha of grassland. Estimates of mortality due to transmission lines are still lacking in Canada (Rioux et al. 2013) and these results further point to a greater need for collision mitigation to protect declining grassland species.

Responses to this article can be read online at:
https://www.ace-eco.org/issues/responses.php/2096

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Appendix 1. Detailed description of study area, average precipitation and maximum temperatures.

The Mattheis Research Ranch is located in the dry mixedgrass prairie region of Alberta, Canada. These grasslands are characterized by a semi-arid climate, a typical growing season from late April through the end of October, annual rainfall averages of 354 mm, and approximately 120 days above 5°C (growing season) and an annual average temperature of 4.2°C (Table A.1, available online in Supporting Information). Dominant plant communities include needle-and-thread grass (*Hesperostipa comata*), blue grama (*Bouteloua gracilis*), western wheatgrass (*Pascopyrum smithii*), Junegrass (*Koeleria macrantha*) and sand grass (*Calamovilfa longifolia*). Common shrubs include thorny buffalo-berry (*Shepherdia argentea*), western snowberry (*Symphoricarpos occidentalis*), prairie rose (*Rosa arkansana*), and chokecherry (*Prunus virginiana*). Thorny buffalo-berry, an important shrub for the threatened Loggerhead Shrike (*Lanius ludovicianus*), increased following the creation of artificial wetlands (Dahl et al. 2020). Common forbs include pasture sage (*Artemisia frigida*), buffalobean (*Thermopsis rhombifolia*), and yellow sweet clover (*Melilotus officinalis*).

Table A1.1. Average precipitation and maximum temperature of the study area during the three years of surveys.

	Year	Average Precipitation (mm)	Average Maximum Temperature (°C)
September	2012	4.64	23.59
	2013	18.51	23.74
	2016	19.26	19.49
October	2012	34.39	8.69
	2013	10.93	12.95
	2016	19.26	9.46
November	2012	17.62	-1.44
	2013	21.10	-1.55
	2016	4.70	9.51
December	2012	15.07	-8.12
	2013	17.11	-8.61
	2016	-2.88	-6.58
January	2012	2.77	0.08
	2013	6.27	-3.90
	2016	15.32	-3.71
February	2012	8.89	1.96
	2013	1.49	0.43

	2016	9.83	4.56
March	2012	11.18	8.51
	2013	10.91	-0.65
	2016	4.05	9.80
April	2012	40.34	13.24
	2013	23.22	8.63
	2016	21.62	16.57
May	2012	52.97	17.98
	2013	51.23	20.70
	2016	68.96	18.86
June	2012	138.10	22.34
	2013	49.74	21.61
	2016	28.19	24.65
July	2012	26.33	27.30
	2013	49.74	24.77
	2016	120.53	25.02
August	2012	39.41	27.00
	2013	12.02	27.27
	2016	35.72	24.24

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Appendix 2. Mortality estimate equations from Erickson et al. (2004).

Observed Number of Carcasses

$\bar{c}$ mean number of carcasses observed per kilometer of transmission line (17.04/km in 2016, 17.78/km in 2017)

Search-Bias Rate

p proportion of trial carcasses detected by observers (0.642 in 2016, 0.655 in 2017)

Estimate of Carcass Removal Rates by Scavengers

$\bar{t}$ is the average length of time a carcass remains at the site before it is removed (2.66 in 2016, 2.21 in 2017)

$\bar{t} = \frac{\sum_{i=1}^{s} t_i}{s - s_c}$, where t_i is removal time of the *i*th carcass, *s* is number of carcasses used in trial, and s_c is number of carcasses remaining at day 40 of trial (1 carcass remaining after 40 days in 2016, 2 carcasses remaining after 40 days in 2017)

Average Interval Between Searches

I = average interval between searches in days (4.63 in 2016, 3.63 in 2017)

All Bias

$$\hat{\pi} = \frac{\bar{t} \cdot p}{I} \left[\frac{\exp\left(\frac{I}{\bar{t}}\right) - 1}{\exp\left(\frac{I}{\bar{t}}\right) - 1 + p} \right]$$

where *p* is estimated search-bias rate, $\bar{t}$ is the estimated carcass removal time, and *I* is the average interval between searches (approximately 4.63 days in 2016, 3.63 in 2017).

Estimated Mortality Rate

$$m_1 = \frac{\bar{c}}{\hat{\pi}}$$

Appendix 3. Additional values for calculating mortalities.

Table A3.1. Overview of values used in equation to estimate mortality caused by transmission lines during the breeding season and spring migration season.

	2016 Breeding	2017 Spring Migration
Length of transmission line in study area (km)	27.5	27.5
Annual mortality rate (deaths/km)	16.43	17.14
Average length of time for carcass scavenging (days)	2.67	2.21
Observer detection (proportion of carcasses detected)	0.64	0.66
Average interval between searches (days)	4.63	3.63
Adjusted annual mortality rate (deaths/km)	50.55	49.74
Annual mortality rate in study area (# deaths/year)	1,390	1,368

Table A3.2. Overview of values used to estimate mortality caused by collisions with cars on primary highways in the breeding and spring migration seasons in the study area.

	2016 and 2017 Average
Length of primary highway in study area (km)	10.24
Annual mortality rate (deaths/km)	10.00
Average length of time for carcass scavenging (days)	2.40
Observer detection (proportion of carcasses detected)	0.64
Average interval between searches (days)	3.22
Adjusted annual mortality rate (deaths/km)	25.64
Annual mortality rate in study area (# deaths/year)	525.11