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Original Article

Marking Power Lines to Reduce Avian Collisions Near the Audubon National Wildlife Refuge, North Dakota

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ABSTRACT Overhead power lines can pose collision risks to birds. Risks may be mitigated through marking lines with high-visibility devices, but the effectiveness of line marking remains unclear. Effectiveness is particularly poorly described for lines bisecting open water, where detection of carcasses can be difficult. We marked 3 of 9 spans (lines between adjacent structures) along a causeway crossing open water and 2 adjacent spans over lake shores between Lake Sakakawea and Lake Audubon near Audubon National Wildlife Refuge, North Dakota, USA. Over 3 years, we found 1,186 avian carcasses, including 276 attributed to power-line collision. American coots (*Fulica americana*; $n = 83$) and double-crested cormorants (*Phalacrocorax auritus*; $n = 27$) were the species most commonly associated with power-line collision, but we also found carcasses of 51 other species, including a piping plover (*Charadrius melodus*; $n = 1$). Multivariable modeling indicated line marking over open water reduced predicted collisions per span per season (mid-April through mid-October, 2006–2008) from 10.3 to 5.8. Birds with high-aspect-ratio wings benefitted most from line marking (e.g., shorebirds and gulls). If the 9 open-water spans we studied were unmarked for 30 years, we predicted 2,775 collisions. We predicted only 1,560 collisions if all of these spans were marked. Our data demonstrate that a wide variety of avian species are at risk of collision with lines bisecting open water, marking lines can reduce collision risk, and because collisions persisted and some line markers fell off power lines, improvements to effectively mark lines are needed.

KEY WORDS American coot, avian, *Charadrius melodus*, collision, double-crested cormorant, *Fulica americana*, line marking, *Phalacrocorax auritus*, piping plover, power line.

Overhead power lines can pose collision risks to birds. These risks are not uniform, but vary with habitat, local avian populations, and line design (Bevanger and Brøseth 2004, Rollan et al. 2010, Avian Power Line Interaction Committee [APLIC] 2012). Collision risks have typically been identified where aquatic habitats and species with high wing loading, high flight speeds, and poor maneuverability co-occur (Shaw et al. 2010, Quinn et al. 2011, Barrientos et al. 2012). Large, heavy-bodied birds such as herons, cranes, swans, and pelicans are thought to be more susceptible to power-line collisions than are smaller, more maneuverable species (APLIC 2012). However, relatively small duck and grouse species are also vulnerable to collision because of their high flight speed and low altitude (Bevanger and Brøseth 2004, APLIC 2012). Birds flying in flocks can be at increased collision risk because the intended flight path can be obscured for some individuals (APLIC 2012). Power lines bisecting daily movement corridors (such as those located between roosting and foraging sites) can be particularly problematic (Bevanger and Brøseth 2004, Stehn and Wassenich 2008, APLIC 2012). Collision risks also are exacerbated during low light, fog, or inclement weather (Savereno et al. 1996, APLIC 2012). Based on field observations, birds generally avoid large-diameter energized wires (i.e., conductors) by adjusting flight altitudes upward, but subsequently collide with smaller, less visible overhead static wires frequently located above the energized conductors on transmission lines (Murphy et al. 2009, Ventana Wildlife Society 2009, Martin and Shaw 2010). Overhead static wires are critical to the reliability of transmission lines because they shield the line, preventing damage caused by lightning strikes to energized conductors.

Line markers are used to mitigate or reduce avian collision risk by increasing the visibility of overhead lines to birds. The effect of marking lines has varied widely across studies, primarily with habitat, species, and season (Bevanger and Brøseth 2004, Mojica et al. 2009, Wright et al. 2009). Though widely divergent field and statistical methods preclude direct comparison of effect sizes among studies,

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individual studies (Morkill and Anderson 1991, Brown and Drewien 1995, Murphy et al. 2009) and meta-analysis (Barrientos et al. 2012) consistently indicate that line marking reduces avian collisions with power lines.

Most studies of avian collisions with power lines have examined the effects of marking non-energized overhead static wires or low-voltage distribution wires. Marking high-voltage (i.e., ≥230 kilovolt [kV]) transmission wires is not feasible because attaching materials to high-voltage lines can result in conductor damage (Hurst 2004). Also, most studies of avian collisions with power lines have occurred over land where carcass detection rates should be higher than in water bodies. To our knowledge, only Wright et al. (2009) reporting sandhill crane (*Grus canadensis*) collisions with power lines crossing the Platte River in South-central Nebraska, USA, and Pandey et al. (2007) reporting collisions of >90 species on the causeway studied here, have previously documented collision risk over water.

To investigate the effect of power-line markers on reducing avian collisions over water, we marked and monitored overhead static wires, transmission wires (≥60 kV), and sub-transmission wires (<60 kV) paralleling a causeway bisecting 2 water bodies. We expected line marking to reduce avian collision, and we evaluated our expectations by comparing avian mortalities under marked spans to avian mortalities under unmarked spans. We also expected some line markers to be more durable than others, so we quantified persistence of line markers on the power line we studied.

STUDY AREA

Our study was conducted adjacent to U.S. Highway 83 approximately 2 miles north of Coleharbor, North Dakota, USA, near the Audubon National Wildlife Refuge (Universal Trans Mercator coordinates Zone 14 30160 E, 5274300 N). At this site, U.S. Highway 83 (4 lanes), a railway line (one set of tracks), and a multi-circuit electrical transmission power line were situated parallel to one another along a causeway bisecting Lake Sakakawea to the west and Lake Audubon to the east (Fig. 1). The power-line segment along the causeway was approximately 4 km long and consisted of 2 overhead static wires, 2 115-kV circuits, and 1 41.6-kV circuit (each circuit included 3 separate wires) supported by steel-lattice towers approximately 40 m tall (Fig. 2).

Lake Audubon and Lake Sakakawea attracted breeding waterfowl, pelicans, gulls, terns, grebes, cormorants, and

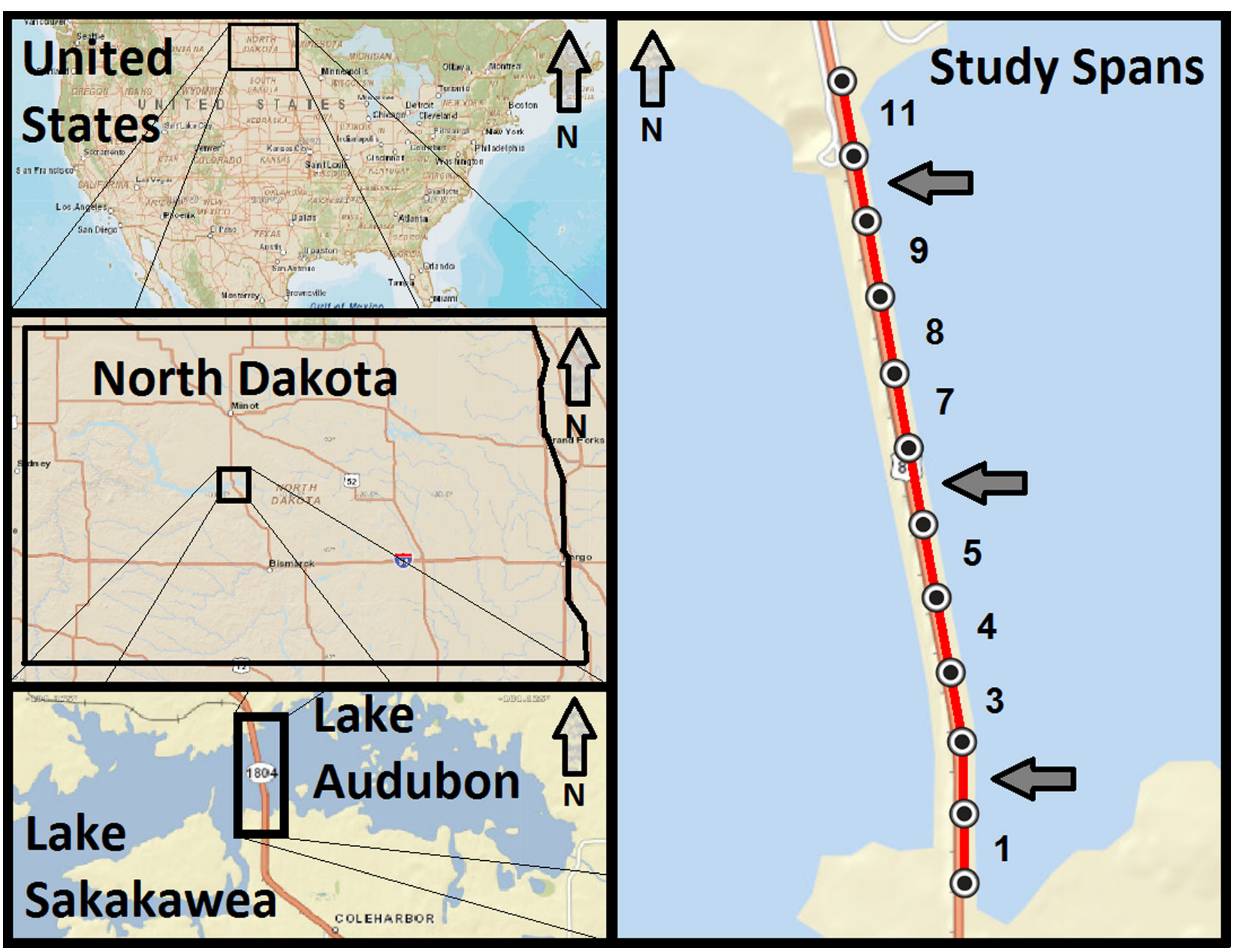

Figure 1. Location of study site (left) in central North Dakota, USA, where from 2006 to 2008 we studied effects of installing high-visibility markers on overhead power lines on rates of avian collision. Location of study spans (right) are numbered 1–11 and indicated with dark lines linking circles. Circles indicate tower locations. Horizontal arrows indicate spans where we applied various markers.

Figure 2. Line marking on non-energized overhead static lines (top 2 wires), energized transmission lines (center 6 wires), and energized sub-transmission lines (bottom 3 wires) during study of avian collision with power lines conducted from 2006 to 2008 in central North Dakota, USA.

numerous shorebirds and passerines; and thousands of additional birds moved through the area during spring and autumn migrations (McKenna and Allard 1976). The region was known to be occupied by 2 endangered species: the whooping crane (*Grus americana*) and the piping plover (*Charadrius melodus*; USFWS 2009, American Bird Conservancy 2012).

METHODS

From 2006 through 2008, we studied avian collisions at 11 spans. To evaluate the effectiveness of marking, we marked and monitored 3 spans; and we did not mark, but also monitored, 8 spans on the same line. A span is defined as the power lines strung between 2 adjacent steel-lattice towers. We predicted line marking would reduce avian collisions with power lines but not reduce the overall collisions associated with the causeway because many collisions were with vehicles, and we expected some line markers would be more durable than others. Prior to line marking we searched the areas below all 11 spans 6 days/week from 4 April through 9 October in 2006. In 2007, line marking was installed and we continued monitoring for evidence of collisions at all 11 spans 6 days/week from 20 April through 11 October in 2007, and from 21 April through 7 October in 2008. We installed line markers approximately every 10 m on all wires except the center phase of the sub-transmission line, which was shielded by marked lines on either side in the same horizontal plane (see lowest 3 wires in Fig. 2). Our installation of line-marking devices began 9 April 2007 and was completed 13 April 2007. Each marked span remained marked throughout the duration of our study, we replaced broken line markers between the 2007 and 2008 monitoring seasons, and we switched line-marker types among spans between seasons.

To evaluate the durability of line markers, we used 3 different commercially available line markers, and evaluated both short-term (8 months) and long-term (64 months) durability. We included line markers with moving parts (i.e., active devices) and line markers without moving parts (i.e., passive devices). Specifically, in 2007, we marked span 3 with BirdMark Flappers (P&R Tech, Beaverton, OR; active devices), span 7 with Swan Flight Diverters (Preformed Line Products, Cleveland, OH; passive devices), and Span 11 with Firefly Flappers (P&R Tech; active devices). In 2008, we marked span 3 with Swan Flight Diverters, Span 7 with Firefly Flappers, and Span 11 with BirdMark Flappers (Fig. 3). We used different line markers on each treatment span so the durability of competing products could be evaluated, though because of small sample sizes of marked spans, we pooled all marked spans for collision analyses. We evaluated durability in November 2007 after 8 months of use, and again in July 2012 after 64 months of use, so that short- and long-term differences in durability could be quantified. In response to findings in November 2007, we switched from an active Firefly Flapper model in 2007 to a passive Firefly Flapper model in 2008 (the latter is illustrated in Fig. 3). We quantified durability by identifying the proportion of devices retained over each time period, and 95% confidence intervals on those proportions.

U.S. Highway 83 and an adjacent railway bisected the 2 lakes. Both the highway and the railway were protected from wave action by riprap (an assemblage of boulders installed to prevent erosion). U.S. Highway 83 consisted of a smooth paved surface where carcasses were easily detected, so we searched U.S. Highway 83 below all 11 spans at the beginning and end of each survey day (daily) via a vehicle traveling ≤19 km/hr (≤10 miles/hr). Gaps between riprap

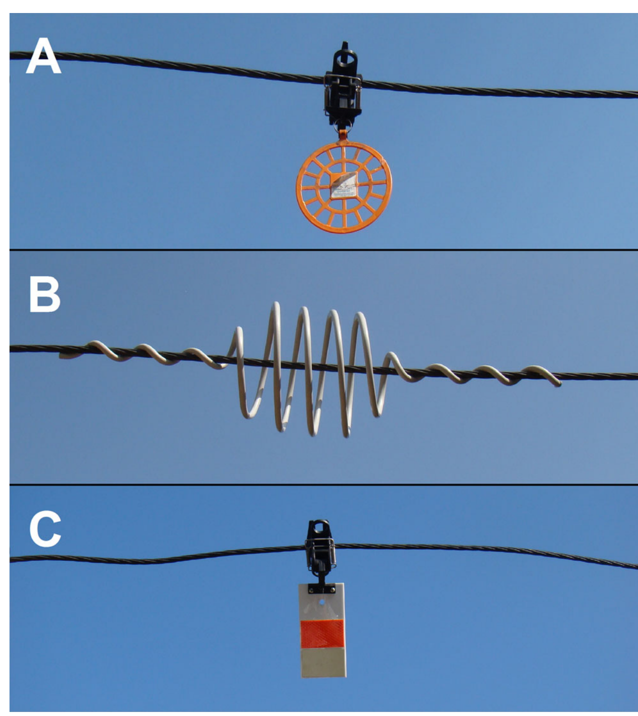

Figure 3. Power-line markers used to reduce avian collision in a study in central North Dakota, USA, from 2006 to 2008: (A) BirdMark Flapper (P&R Tech), (B) Swan Flight Diverter (Preformed Line Products), (C) Firefly Flapper (P&R Tech) without moving parts. The scale of all 3 photos is 1 m from left edge to right edge.

boulders and railroad ties required careful scrutiny to identify carcasses, so we searched these areas on foot beneath 3–4 spans daily. Over the course of 3 days, all areas beneath all spans were searched with equal effort. Each carcass was attributed to the span above it, and all carcasses were removed as they were discovered to prevent double counting.

Not all carcasses were necessarily the result of collision with overhead power lines, so we conducted necropsies to evaluate injuries and identify likely causes of death. We conducted necropsies on each intact carcass by palpating carcasses to identify broken bones, skinning the breast and neck to view any bruising, and completely opening the body cavity to view internal injuries. We did not necropsy carcasses flattened by highway vehicle traffic. Following previous studies (Work 2000, Veltri and Klem 2005), we assumed carcasses occurring as a result of collision with overhead power lines would have injuries only on the leading edges of the head, neck, wings, breast, and anterior portion of the back (Cousins et al. 2012). We assumed carcasses occurring as a result of collisions with a vehicle or train would have crushing injuries to leading surfaces, as well as to lateral and posterior areas. Bird mortality also might have occurred as a result of disease or other factors unrelated to our study (Mojica et al. 2009), and carcasses without diagnostic injuries were categorized as having an undetermined cause of death. To differentiate the effects of line marking on all mortalities found in the area versus power-line collision mortality, we analyzed all mortality data together and also conducted separate analyses including only mortalities attributed to power-line collision.

Modeling

We compared avian collisions on marked spans with avian collisions on unmarked spans. We used generalized linear models with log-links to estimate the mean count of carcasses and to evaluate whether line marking reduced avian mortality caused by power-line collisions in our study area. We included 3 fixed effects in our candidate models: 1) line marking, 2) habitat type, and 3) year. Using these 3 variables, we constructed biologically meaningful *a priori* additive-only models because sample sizes were insufficient to explore interactive models.

We distinguished 2 types of habitat. The terminal spans at each end of the studied line segment were immediately adjacent to the lake shore where trees might shield the line from avian collision (Mojica et al. 2009, Rollan et al. 2010, APLIC 2012). These 2 spans were defined as lake shore. All other spans were unshielded by vegetation, bisected Lake Sakakawea and Lake Audubon, and were defined as bisecting open water. We included year (2006, 2007, and 2008) as a candidate variable to account for the possibility that annual differences in bird use might influence collision rates.

The Poisson distribution and the negative binomial distribution are 2 distributions commonly used to model count data (Wackerly et al. 2008). The Poisson distribution has a strong assumption of no overdispersion, such that the mean equals the variance. The negative binomial distribution allows the variance to exceed the mean by incorporating an overdispersion parameter. We evaluated the fit of both distributions to our data. Using our global model (count of carcasses = line marking + habitat type + yr) in each set of analyses (all carcasses vs. power-line collision only), we compared model fit of the Poisson and negative-binomial distributions using a likelihood-ratio test available in the R package pscl (Jackman 2012). Our null hypothesis in these tests was that the data were Poisson-distributed unless a large χ^2 critical value indicated evidence of over-dispersion. If over-dispersion occurred, the negative binomial distribution would better fit the data and be more appropriate in modeling. We also graphically evaluated the global models for all carcasses and for only power-line collisions by examining patterns in the deviance versus fitted, leverage, and Cook statistics plots. We used the R package stats (R Development Core Team 2011) to conduct Poisson modeling of our data and the R package MASS (Venables and Ripley 2002) to conduct negative binomial modeling. We evaluated model parsimony using Akaike's information criterion with a small-sample-size bias correction (AIC_c; Burnham et al. 2011). We model-averaged parameter

Table 1. Species with >5 carcasses attributed to power-line collision and species of special concern in central North Dakota, USA, where from 2006 to 2008 we studied effects of installing high-visibility markers on overhead power lines on rates of avian collision. A table describing all carcasses of all species is included in online Appendix S1. Wing type from Scott and McFarland (2010). A "—" indicates no carcasses were observed.

Species			Cause of death			
Common name	Scientific name	Wing type	Power-line collision	Vehicle collision	Undetermined	Total
American coot	*Fulica americana*	Other	83	59	76	218
Double-crested cormorant	*Phalacrocorax auritus*	Other	27	1	9	37
Ring-billed gull	*Larus delawarensis*	High aspect ratio	17	11	21	49
Gadwall	*Anas strepera*	Medium aspect ratio	10	1	4	15
Sora	*Porzana carolina*	Other	9	22	22	53
Eared grebe	*Podiceps nigricollis*	Other	8	4	3	15
Mallard	*Anas platyrhynchos*	Medium aspect ratio	8	—	3	11
Yellow-headed blackbird	*Xanthocephalus xanthocephalus*	Elliptical	8	15	5	28
Blue-winged teal	*Anas discors*	Medium aspect ratio	7	1	5	13
Franklin's gull	*Leucophaeus pipixcan*	High aspect ratio	7	2	2	11
Western grebe	*Aechmophorus occidentalis*	Other	7	2	3	12
Bank swallow	*Riparia riparia*	Medium aspect ratio	6	72	30	108
Savannah sparrow	*Passerculus sandwichensis*	Elliptical	6	29	5	40
Piping plover	*Charadrius melodus*	Medium aspect ratio	1	1	—	2

Table 2. Model-averaged parameter estimates ($\hat{\beta}$) and standard errors (SE) for variables considered in modeling avian carcasses per span in central North Dakota, USA, where from 2006 to 2008 we studied effects of installing high-visibility markers on overhead power lines on rates of avian collision. 95% confidence intervals overlapping zero indicate variables that were not statistically different from zero.

	Avian carcasses attributed to all mortality sources			Avian carcasses attributed to power-line collision only		
Parameter	$\hat{\beta}$	SE	95% CI overlaps zero	$\hat{\beta}$	SE	95% CI overlaps zero
Intercept	3.636	0.077	No	1.888	0.188	No
Line marking	−0.235	0.117	Yes	0.458	0.176	No
Habitat type	−0.060	0.114	Yes	0.568	0.159	No
Yr averaged	−0.106	0.110	Yes	0.095	0.149	Yes

estimates to incorporate model selection uncertainty (Burnham and Anderson 2002). We used model weights (ω_i) to compute evidence ratios that assess parsimony of best models relative to each of our other candidate models (Burnham et al. 2011). We interpreted variable effects on counts by examining model-averaged coefficients, relative importance of main effects, and fitted values.

Wing Types

The effectiveness of line marking is believed to be higher for some avian species or groups than for others (Jenkins et al. 2010, Quinn et al. 2011, APLIC 2012). Because avian collision risk with power lines is influenced by a bird's ability to maneuver away from power lines detected immediately prior to a pending collision, the wing shape and wing loading of a bird may influence the effectiveness of line marking (APLIC 2012). Consequently, for each carcass found, we identified the wing type to 1 of 6 categories (Scott and McFarland 2010): 1) elliptical (typical of passerines), 2) game bird, 3) high aspect ratio, 4) medium aspect ratio (typical of high-speed flyers), 5) slotted–high lift (typical of hawks), and 6) other. The carcasses of 3 birds not identified to species were excluded from this analysis because a wing type could not be assigned. Because line marking is designed to increase the distance at which lines are visible, we predicted that line marking would be most beneficial to birds with relatively low maneuverability based on wing shape, (i.e., those with game bird and high-aspect-ratio wings). We used a χ^2 test of whether the count of bird carcasses by span (marked or unmarked) was independent of wing shape. This approach assumed equal exposure of birds to each span, but did not require knowledge of the number birds in the area. We considered results significant at $\alpha = 0.05$.

RESULTS

We identified 1,186 carcasses of 95 avian species (Table 1; Appendix S1), including 276 carcasses of 53 species attributed to power-line collision. Considering only carcasses attributed to power-line collision, we found 40 carcasses below marked spans bisecting open water ($\bar{x} = 6.67$ carcass/span/season), 197 carcasses below unmarked spans bisecting open water ($\bar{x} = 9.38$ carcasses/span/season), and 39 carcasses below unmarked lake shore spans ($\bar{x} = 6.50$ carcass/span/season). American coots ($n = 83$), double-crested cormorants ($n = 27$), ring-billed gulls ($n = 17$), gadwalls ($n = 10$), and soras ($n = 9$) were most commonly associated with power-line collision, but we also found 48 additional species including one piping plover and numerous wading birds and passerines attributed to collision (see Table 1 and Appendix S1 for scientific names).

There was no difference in line marking when all sources of avian mortality were considered together. The negative binomial distribution best fit our entire data set ($\chi^2 = 59.72$, df = 28, $P < 0.001$), and the Poisson distribution best fit our subset of power-line collision data only ($\chi^2 = 32.59$, df = 28, $P = 0.251$). When considering all carcasses, we found no difference in the number of carcasses by span, regardless of the presence of line marking, whether spans were adjacent to shore or over open water, or the year data were collected (Table 2; all $\hat{\beta}_i$ 95% CIs included zero). Thus, model-averaged predictions of the number of carcasses per span were not different for marked versus unmarked spans regardless of proximity to lake shore or year of data collection (Fig. 4).

When considering carcasses attributed to power-line collision only, model-averaging $\hat{\beta}_i$s and 95% confidence intervals on $\hat{\beta}_i$s were consistent with the most parsimonious (best) model, indicating the presence of line marking and the type of habitat traversed by the line were important predictors of collision risk (Table 2). The best model fit our data 4.7 times better than the next best model, which also included year effects (Table 3). A model including only line marking was the only other model within 7 AIC_c of the best of the models we fitted, but our best model fit the data 12.3 times better than the model with only line marking. Thus,

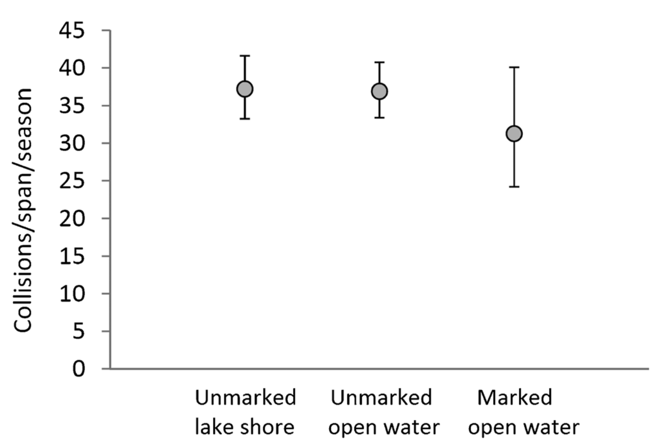

Figure 4. Model-averaged predicted carcasses per span per season (mean and 95% CI) based on avian carcasses that were attributed to power-line collision, vehicle collision, and unidentified cause of death during study of avian collision with power lines conducted from 2006 to 2008 in central North Dakota, USA.

Table 3. Models predicting counts of carcasses attributed only to power-line collisions in central North Dakota, USA, where from 2006 to 2008 we studied effects of installing high-visibility markers on overhead power lines on rates of avian collision. Number of parameters (K), log likelihoods ($-\ln(L)$), difference in Akaike's Information Criterion value corrected for small sample size (ΔAIC_c), and Akaike weights (w_i) are indicated.

Model	K	$-\ln(L)$	ΔAIC_c	ω_i	Evidence ratio
Line marking + habitat type	3	85.692	0.000	0.758	1.000
Line marking + habitat type + yr	5	84.541	3.093	0.161	4.695
Line marking	2	89.415	5.018	0.062	12.291
Line marking + yr	4	88.264	7.745	0.016	48.059
Habitat type	2	93.131	12.451	0.001	505.394
Null	1	94.754	13.425	0.001	822.628
Habitat type + yr	4	91.980	15.178	0.000	1,976.105
Yr	3	93.603	15.822	0.000	2,727.224

habitat and line marking were influential in collision risk. Year was far less important than the other 2 factors considered (Fig. 5), and averaging across years, our model predicted spans over open water with line marking averaged significantly fewer collisions (5.8 collisions/span/yr) than spans over open water without line marking (10.3 collisions/span/yr; Fig. 6).

Line marking influenced power-line collisions differently depending on wing type ($\chi^2 = 9.45$, df $= 4$, $P = 0.051$; Table 4). Given the frequencies of carcasses with each wing type under marked versus unmarked spans, species with high-aspect-ratio wings were found below marked spans less than expected (i.e., species with high-aspect-ratio wings benefitted most from marking), and species with medium-aspect-ratio (high-speed) wings were found below marked spans more than expected (i.e., benefitted least from marking).

Line markers differed in durability. In November 2007 after 8 months of use 4.9% (11 of 225) of the active Firefly Flappers, 100% (161 of 161) passive Swan Flight Diverters, and 98.8% (160 of 162) active BirdMark Flappers remained in place. In July 2012, after 64 months of use, 100% (230 of 230) of the passive Firefly flappers, 100% (165 of 165) Swan Flight Diverters, and 42.1% (67 of 159) BirdMark Flappers remained in place. In the short term, Firefly Flappers were less likely to remain in place prior to our switching from active to passive devices; and in the long term, BirdMark Flappers were less likely to remain in place though these active devices did outlast active Firefly Flappers (Fig. 7).

DISCUSSION

Marking power lines bisecting open water enabled a 28.9% reduction (from 10.3 to 5.8. carcasses/span/yr) in the number of carcasses attributed to collision per span per season. This improvement met the goal of reducing avian power-line collisions, but because collisions persisted, long-term concerns persist (Bech et al. 2012). Assuming a 30-year service life of the power lines, extrapolating our modeled estimate of annual mortality to 30 years, an estimated total number of avian collisions would be 2,775 birds (95% CI = 2,403–3,205) for the 9 spans bisecting open water if all spans remained unmarked. If these same spans were marked, our model indicated an estimated total of 1,560 bird collisions (95% CI = 1,189–2,047) would be likely.

Because line marking does not eliminate all avian collision risk (Wright et al. 2009, APLIC 2012, Barrientos et al. 2012), and some line markers were not as durable as hoped, additional improvements will be important to maximize the effectiveness of line marking. A critical area where improvements are warranted is to increase detectability of line markers from greater distances so that birds, particularly those that fly at greater speeds, have more

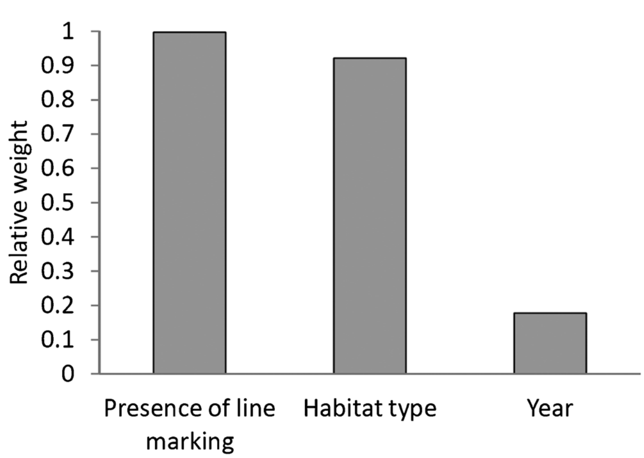

Figure 5. Relative importance weight of variables predicting avian carcasses attributed only to power-line collision during study of avian collision with power lines conducted from 2006 to 2008 in central North Dakota, USA.

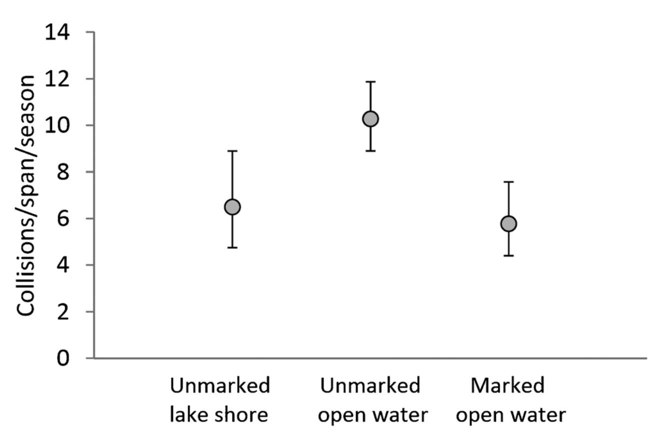

Figure 6. Model-averaged predicted carcasses per span per season (mean and 95% CI) attributed only to power-line collision, averaged across years during study of avian collision with power lines conducted from 2006 to 2008 in central North Dakota, USA.

Table 4. Count of carcasses attributed to power-line collision versus wing type, and percent each cell contributes to overall χ^2 value. Study was conducted in central North Dakota, USA, where from 2006 to 2008 we studied effects of installing high-visibility markers on overhead power lines on rates of avian collision.

	Wing type						
Line marking	Elliptical	Game bird	High aspect	High speed	High lift	Other	Total
Count of carcasses							
Absent	28	0	29	49	8	124	238
Present	4	0	0	9	4	17	34
Sum	32	0	29	58	12	142	273
Percent of partial χ^2 values							
Absent	0.00	0.00	5.38	6.28	0.67	0.09	12.4
Present	0.00	0.00	38.07[a]	44.59[b]	4.63	0.29	87.6

[a] Percent of partial χ^2 values substantially higher than expected.
[b] Percent of partial χ^2 values substantially lower than expected.

maneuvering space to avoid power lines (Jenkins et al. 2010, De La Zerda 2012); this is consistent with our finding that line marking was least beneficial to birds with medium-aspect-ratio wings.

Alternative strategies to increase device detectability include high-contrast combinations of dark- and light-colored reflective materials and glow-in-the-dark highlights mounted on dark background materials (e.g., recently developed devices manufactured by P&R Tech; Power Line Sentry, Fort Collins, CO; and TE Connectivity, Wilmington, DE). To our knowledge no studies have investigated or compared the effectiveness of glow-in-the-dark line markers, despite the possibility that these devices may be more effective during low-light periods (i.e., dawn, dusk, inclement weather) when many collisions are believed to occur (Savereno et al. 1996, APLIC 2012). Consequently, though line marking is increasing worldwide at considerable cost to electric utilities, the comparative effectiveness of recently available improvements in line markers is unresolved (Barrientos et al. 2011).

Our sample size was insufficient for statistical analyses of the relative effect size of the 3 line markers we used, but did allow evaluation of their relative durability. We found that active markers tended to fall off power lines more quickly than did passive markers. If active line markers are used, their durability should be quantified. The ideal spacing of line markers also is unexplored. We hypothesize that it is likely that inflection points exist below which adding more line markers improves mitigation, and above which little additional benefit is gained, although we acknowledge that environmental conditions and the types of birds at the site will influence among-site variability in inflection points. Research to identify these inflection points would greatly benefit both birds and electric utilities.

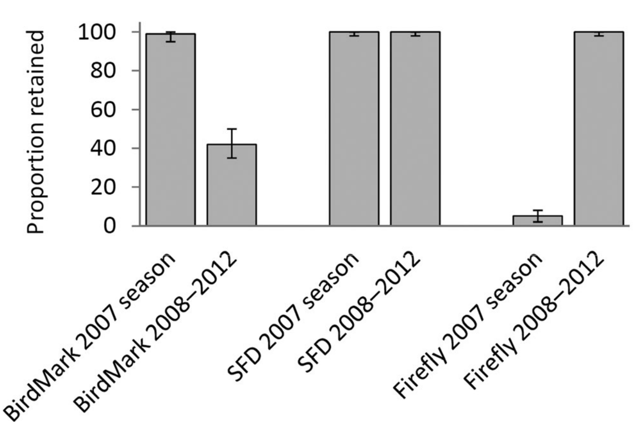

Figure 7. Proportion of devices retained on marked power-line spans during the periods indicated during study of avian collision with power lines, as conducted from 2006 to 2008 in central North Dakota, USA. SFD indicates Swan Flight Diverter.

Consistent with the only other studies we know of to evaluate power-line collisions over water (Pandey et al. 2007, Wright et al. 2009), we emphasize the importance of marking spans bisecting or crossing open water. Our data suggest unmarked shoreline spans may have had lower collision rates than spans bisecting open water. Mojica et al. (2009) found higher rates of shore line collisions when compared with inland spans. We did not study inland spans, so we are unable to draw similar comparisons; however, findings of habitat effects are consistent with previous studies where the landscape surrounding a span influenced the likelihood of avian collision (Garrido and Fernández-Cruz 2003, Rollan et al. 2010, Shaw et al. 2010) and also are consistent with studies indicating high risks primarily for large or aquatic birds, particularly Anatidae species (Yee 2008, Barrientos et al. 2012). Our findings, together with those of Wright et al. (2009), suggest that avian collisions with power lines over water may be more prevalent than previously documented.

For several reasons, our data on collisions at over-water power lines likely represent a conservative estimate of the actual avian mortality at our study site. First, we did not conduct surveys year-round. Thus, any avian collision that occurred outside our survey period would not be included in our findings (e.g., Wright et al. 2009). Second, any birds that collided with the lines but continued to fly, only to die elsewhere (i.e., crippling effect; Pandey et al. 2007, Ventana Wildlife Society 2009, Simmons 2011), or any that fell into open water would not have been detected by our search effort. Third, some carcasses flattened by vehicles and that were not attributed to power-line collision could have collided with power lines and then fallen onto the roadway and sustained additional damage leading to incorrect categorization. Finally, scavengers may have removed some carcasses before we were able to recover or document them.

MANAGEMENT IMPLICATIONS

Most of the carcasses we found (77%) were attributed to vehicle collision, not power-line collision, and there was no difference in the number of carcasses relative to line marking when we included all carcasses in our analyses. Thus, we found no evidence that marking power lines influenced numbers of bird fatalities attributed to vehicle collisions. This is consistent with prior studies reporting that birds tend to move upward when they perceive large-diameter lines and subsequently hit smaller diameter overhead static wires (Pandey et al. 2007, Murphy et al. 2009, Martin and Shaw 2010). Consequently, we suggest that in addition to marking all spans along the causeway we studied, managers should consider separate mitigation measures to minimize the risk of vehicle collisions (e.g., reduced speeds, signage) in areas with high avian populations or species of concern.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article at the publisher's web-site.

Appendix S1. Carcasses identified found along the Audubon Causeway between Lake Sakakawea and Lake Audubon, North Dakota, USA, April–October, 2006–2008.

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