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Research Paper

Mitigating avian collisions with power lines through illumination with ultraviolet light

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ABSTRACT. Collisions with anthropogenic structures by long-distance migrants and threatened and endangered species are a growing global conservation concern. Increasing the visibility of these structures may reduce collisions but may only be accepted by local residents if it does not create a visual disturbance. Recent research has shown the potential for ultraviolet (UV) light, which is nearly imperceptible to humans, to mitigate avian collisions with anthropogenic structures. We tested the effectiveness of two UV (390–400 nm) Avian Collision Avoidance Systems (ACASs) at reducing collisions at two 260-m spans of marked power lines at the Iain Nicolson Audubon Center at Rowe Sanctuary, an important migratory bird stopover location in Nebraska. We used a randomized design and a tiered model selection approach employing generalized linear models and the Akaike Information Criterion to assess the effectiveness of ACASs considering environmental (e.g., precipitation) and detection probability (e.g., migration chronology) variables. We found focal (assessed power line) and distal (neighboring power line) ACAS status and environmental variables were important predictors of avian collisions. Our top model suggests that the focal ACAS illumination reduced collisions by 88%, collisions were more likely at moderate (10–16 km/h) compared to lower or higher wind speeds, and collision frequency decreased with precipitation occurrence. Our top model also indicates that the distal ACAS illumination reduced collisions by 39.4% at the focal power line when that ACAS was off, suggesting a positive “neighbor effect” of power line illumination. Although future applications of ACASs would benefit from additional study to check for potential negative effects (for example, collisions involving nocturnal foragers such as bats or caprimulgiform birds drawn to insects), we suggest that illuminating power lines, guy wires, towers, wind turbines, and other anthropogenic structures with UV illumination will likely lower collision risks for birds while increasing human acceptance of mitigation measures in urban areas.

Atténuation des collisions aviaires avec des lignes à haute tension grâce à un éclairage ultraviolet

RÉSUMÉ. Les collisions entre les structures anthropiques et les oiseaux migrateurs de longue distance et les espèces menacées et en danger sont une préoccupation croissante en termes de conservation mondiale. L’amélioration de la visibilité de ces structures pourrait réduire les collisions, mais cette mesure n’est acceptable par les résidents locaux que si elle ne génère pas de perturbation visuelle. Des recherches récentes ont démontré le potentiel de la lumière ultraviolette (UV), laquelle est presque imperceptible pour les humains, pour atténuer les collisions aviaires avec des structures anthtopiques. Nous avons testé l’efficacité de deux systèmes d’évitement des collisions aviaires (ACAS) utilisant des UV (390 à 400 nm) pour réduire les collisions sur deux portées de 260 m de lignes à haute tension marquées au Centre Audubon Iain Nicolson dans le sanctuaire de Rowe, une halte importante pour les oiseaux migrateurs au Nebraska. Nous avons utilisé une conception randomisée et une approche de sélection de modèle à plusieurs niveaux employant des modèles linéaires généralisés et le critère d'information Akaike pour évaluer l’efficacité des ACAS en tenant compte des variables environnementales (par ex. précipitations) et de probabilité de détection (par ex. chronologie des migrations). Nous avons constaté que les variables de statut ACAS et d’environnement focales (ligne électrique évaluée) et distales (ligne électrique voisine) permettaient de prédire assez précisément les collisions aviaires. Notre principal modèle suggère que l’illumination ACAS focale réduit les collisions de 88 %, que les collisions se font plus probablement à une vitesse de vent modérée (10 à 16 km/h) plutôt qu’à des vitesses de vent plus faibles ou plus fortes, et que la fréquence des collisions diminue en cas de précipitations. Notre principal modèle indique que l’illumination ACAS distale réduisait les collisions de 39,4 % sur la ligne d’électricité focale lorsque l’ACAS était éteint, ce qui suggère un « effet de voisinage » positif de l’illumination des lignes électriques. Les applications futures de systèmes ACAS bénéficieraient d’études plus poussées pour vérifier les effets négatifs potentiels (par exemple, collisions impliquant des prédateurs nocturnes comme les chauves-souris ou les oiseaux caprimulgiformes attirés par les insectes). Nous pensons cependant que l’illumination aux ultraviolets des lignes électriques, des haubans, des tours, des turbines éoliennes et autres structures anthropiques serait susceptibles d’atténuer les risques de collision pour les oiseaux tout en améliorant l’acceptation humaine des mesures d’atténuation en zone urbaine.

Key Words: *Antigone canadensis; ACAS; Avian Collision Avoidance System; Branta canadensis; Canada Goose; power line marking; Nebraska; Platte River; Sandhill Crane, UV technology*

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INTRODUCTION

Avian collisions with anthropogenic infrastructure are an increasing global conservation concern (Loss et al. 2015, Garcês et al. 2020). Collisions involve buildings (Hager et al. 2017), communication towers (Longcore et al. 2012), and energy infrastructure (Loss 2016), including solar facilities (Kosciuch et al. 2020), wind turbines (Smith and Dwyer 2016), and power lines (Bernardino et al. 2018). Most avian collisions involve migrating birds (Barrios and Rodriguez 2004, Longcore et al. 2013), which may experience substantial exposure to anthropogenic infrastructure along their migratory routes, and therefore, increased mortality risk (Rogers et al. 2014, Smith and Dwyer 2016). Coues (1876) published one of the first North American reports of avian collisions with suspended wires, reporting > 100 passerine carcasses observed across 4.8 km, and concluded, “Since we cannot conveniently abolish the telegraph, we must be content with fewer birds.” In the 150 years since Coues (1876) made his observation, telegraph wires have become obsolete, but other types of suspended wires, including power lines and guy wires, have proliferated, and avian collisions have continued and increased (Barrientos et al. 2011, Rioux et al. 2013, Bernardino et al. 2018).

Mitigating avian collisions with suspended wires can involve a variety of methods, with each method involving specific advantages and drawbacks. For example, power line collisions can be completely prevented by burying wires (Raab et al. 2012, APLIC 2012). However, burying transmission lines is infrequently used specifically to address avian collisions because construction costs can be millions of dollars per kilometer more than for overhead transmission systems (Hall 2009) and because other environmental impacts must be considered (Brockbank 2015, D’Amico et al. 2018). Removing overhead shield wires can reduce collisions (Bevanger and Brøseth 2001) but is rarely practical because shield wires are installed to protect electrical systems from lightning strikes (APLIC 2012). Both shielding power lines by building them adjacent to trees or terrain that birds will intuitively fly over, and routing lines away from sensitive areas are suggested practices for mitigating collisions (APLIC 2012). Those approaches are often impractical for existing lines because the lines are already in place, and are also often impractical for new construction because numerous other factors (e.g., construction costs, land use, land ownership, existing infrastructure, etc.) must be considered simultaneously (Fernandez-Jimenez et al. 2017; Dwyer, *personal observation*). Because other methods are not always cost-effective or practical, collision mitigation currently focuses primarily on installing line markers on power lines to make wires more visible to birds in flight (Bernardino et al. 2018).

The effectiveness of line markers has been studied globally, producing equivocal results (Alonso et al. 1994, Cooper and Day 1998, Anderson 2002, Yee 2008, De La Zerda 2012, Raab et al. 2012, Sporer et al. 2013, Dashnyam et al. 2016, Ferrer et al. 2020, Travers et al. 2021). Barrientos et al. (2011) estimated a 78% reduction in collision rates, whereas Bernardino et al. (2019) who included additional peer-reviewed and grey literature, only reported an overall effectiveness of 50%. Furthermore, Bernardino et al. (2019) reported that the risk of publication bias could not be entirely excluded and may be still overestimating the true overall effectiveness of wire markers. In addition to often limited effectiveness and durability (Sporer et al. 2013, Dashnyam et al. 2016), line markers create technical and logistical challenges. For example, line markers typically cannot be installed on the conductor wires of transmission lines because they result in noise emissions, radio interference, and reductions in power transmission efficiency caused by corona discharges (Hurst 2004). Consequently, line markers are typically installed on overhead shield wires and optical ground wires. These installations are frequently completed by helicopter because it is usually unsafe to install line markers on transmission shield wires by reaching from the ground past conductors to the wires above. Reliance on helicopters creates levels of safety risk, cost, and logistical challenges that are difficult for many electric utilities to accommodate. One recent advance in deploying line markers is the use of unmanned aircraft systems (Acklen et al. 2020), which provides a safer, less expensive, and less logistically challenging alternative to helicopters.

Dwyer et al. (2019) hypothesized that illuminating power lines with near-ultraviolet light (UV-A; 380–395 nm, hereafter “UV”) may reduce avian collisions with all wires in a treated span, either working with line markers or replacing the need for them. A span is defined as the distance between two adjacent power poles, pylons, or towers across which a wire is suspended. UV light is defined as light with wavelengths < 400 nm. The lens of the human eye absorbs UV light, but humans lack photosensitive cone cells capable of perceiving it (Jacobs 1992). When UV light enters avian eyes, however, unique combinations of a cone photoreceptor cell type not found in humans, cone pigments with spectral sensitivity in the UV-sensitive range of 355–400 nm, and pigmented oil droplets on those cone cells determine the physiological basis for taxon-specific and species-specific UV perception in birds (Bowmaker et al. 1997, Hart and Hunt 2007, Ödeen and Håstad 2013, Toomey et al. 2016). Combinations of these features enabling UV perception have been identified in approximately half of avian groups examined (Harness et al. 2016). Studies exploring the behavioral implications of UV sensitivity have focused primarily on behaviors such as foraging and sexual selection (Cuthill et al. 2000, Gill and Prum 2019). Some studies have documented declines in avian flight activity in UV-illuminated areas (May et al. 2017), whereas others have not (Goller et al. 2018). Presumably, the differences are attributable to differences in either the species being tested or the experimental design. Additional research is needed to assess these competing hypotheses.

Conservation applications of UV sensitivity are being explored in efforts to reduce avian collisions with windows and power lines. For example, UV-reflective films reduce the likelihood of passerine collisions with windows (Klem 2009, Swaddle et al. 2020) and reduce flight speeds toward windows, potentially reducing the impact force when collisions occur (Swaddle et al. 2020). Regarding power lines, UV illumination of a power line reduced Sandhill Crane (*Antigone canadensis*) collisions by 98% and may also offer an effective collision mitigation strategy for guyed communication and meteorological towers (Dwyer et al. 2019). In both window and power line applications, using UV to alert birds to a suspended obstacle is intended to leverage differences in human and avian visual perception so that birds are cued but humans are not. Presumably, if effective, this aspect will increase human acceptance of UV-based mitigation strategies.

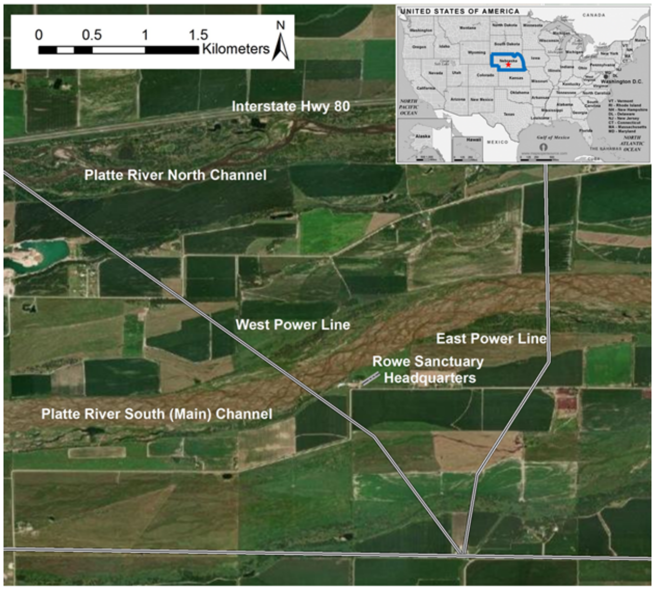
Dwyer et al. (2019) found that UV light reduced Sandhill Crane collisions while remaining inconspicuous to surrounding communities. The study was successful, but the first-generation Avian Collision Avoidance System (ACAS) described by Dwyer et al. (2019) was experimental. In an effort to refine the experimental ACAS to a version that could be deployed commercially, UV illumination was fine-tuned to consume less power while more precisely focusing light on the power line. Here, we evaluate the second-generation ACAS model to identify whether it is also successful in mitigating avian collisions. We also expand on the previous study in two important ways. First, we expand our observations from a single power line to two adjacent power lines. Second, we examine how various environmental covariates influence collision rates and ACAS effectiveness. Consequently, our study objective was to determine: (1) the efficacy of two ACASs at minimizing avian collisions with two adjacent power lines, and (2) other factors influential in patterns of avian–power-line collision risk at the study site. If successful, installation of ACAS on other power lines, and perhaps on other anthropogenic obstacles, may offer a more effective and affordable long-term solution than previous mitigation strategies for a long-standing conservation dilemma.

METHODS

Study area

We studied two ACASs, one installed on each of two Dawson Public Power (Kearney, Nebraska, USA) 69-kV power line spans crossing the Platte River at the Iain Nicolson Audubon Center at Rowe Sanctuary (Rowe; Fig. 1; 40.669845, -98.886429). Rowe straddles the Platte River southwest of Gibbon, Nebraska, and is a major migratory stopover location for Sandhill Cranes, Whooping Cranes (*Grus americana*), and a variety of duck and goose (Anatidae) species, which are all affected by collisions with power lines (Gerber et al. 2020, Urbanek and Lewis 2020). The segment of the Platte River and surrounding habitats that Rowe manages comprise a restored braided river channel with emergent sandbars, wet meadow, lowland prairie, and riparian woodlands within a matrix of row crop agriculture, including corn, soybeans, and alfalfa (Nagel and Kolstad 1987, Brei and Bishop 2008, Caven et al. 2020*a*). Rowe is managed to create and protect roosting, foraging, and loafing habitat for migrating birds, particularly cranes, and for breeding birds, particularly grassland species, endangered Piping Plovers (*Charadrius melodus*), and recently delisted Interior Least Terns (*Sterna antillarum athalassos;* Strom 1987, Baasch 2011). Every spring, > 1 million Sandhill Cranes migrate through central Nebraska (Caven et al. 2020*b*), and as much as 23% of the Aransas-Wood Buffalo Whooping Crane population has used the Platte River during a single spring migration season (118/505 individual Whooping Cranes; Fehlhafer and Peterson 2018). During the Nebraska portion of their migration, Sandhill Cranes gather each evening in pre-roost aggregations in meadows and agricultural habitats within 0.8 km of the Platte River to continue foraging and socializing before moving to their overnight roost locations on sandbars near dusk (Johnsgard 1983, APLIC 2012), where the cranes, depending on roost locations, are exposed to power lines suspended over the river and adjacent habitats (Wright et al. 2009). We termed the two power line spans we studied the "west crossing" and the "east crossing". The west crossing is located 200 m west of Rowe headquarters, and the east crossing is located 1700 m northeast of headquarters. These two lines are approximately 2 km apart along the river. We conducted our study at Rowe because Rowe staff (Taddicken, *personal observation*) and three previous data sets provided documentation of annual Sandhill Crane collisions there (Wright et al. 2009, Murphy et al. 2016*a,* Dwyer et al. 2019).

Fig. 1. Aerial view of the locations of 69-kV transmission power lines (white lines) near the Iain Nicolson Audubon Center at Rowe Sanctuary (Rowe; red star, inset map). The two transmission lines that cross the central Platte River at Rowe in Nebraska, USA (blue polygon, inset map) were the focus of our 25 February to 06 April 2021 evaluation of two ultraviolet light-emitting Avian Collision Avoidance Systems.



Taddicken and others (*personal observation*) have observed Sandhill Crane collisions and carcasses involving the east and west crossings annually since the late 1990s. These observations led to the installation of yellow spiral Bird-Flight Diverters (Preformed Line Products, Cleveland, Ohio, USA) on the west and east crossings at Rowe during the early 2000s. The bird flight diverters were intended to increase the visibility of the power lines to Sandhill Cranes in flight. Exploring the effectiveness of the bird flight diverters, Wright et al. (2009) estimated that 165–219 Sandhill Crane collisions occurred at the west and east crossings combined during each of two study years and concluded that FireFly line markers with glow-in-the-dark panels on a swiveling plate (P&R Tech, Beaverton, Oregon, USA), which were newly available on the market at the time, may more effectively reduce collisions. After FireFly line markers were installed in 2007, Murphy et al. (2016*a,b*) documented 321 Sandhill Crane collisions during a 2009 study of the east crossing. Although collisions persisted, Sandhill Cranes reacted at greater distances and with fewer sudden evasive maneuvers at the east crossing compared to another study nearby (Morkill and Anderson 1991), suggesting that FireFly line markers did have some collision-mitigating effect. Collisions persisted, however (Taddicken et al., *personal observation*), so Rowe replaced the swiveling FireFly line markers, which were breaking at the swivels, with non-swiveling FireFly line markers in 2009. Thereafter, Dwyer et al. (2019)

hypothesized that adding UV illumination to the crossings at Rowe might more effectively reduce collisions than line marking alone. Subsequently, Dwyer et al. (2019) documented 48 Sandhill Crane collisions and one American White Pelican (*Pelecanus erythrorhynchos*) collision when the crossing was not illuminated, and one collision when it was illuminated, during a 2018 study examining the effectiveness of a first-generation ACAS on the east crossing.

Field methods

We installed two ACASs: one on each of the study crossings. Each power line consisted of two overhead shield wires suspended approximately 15 m above the river surface, and three conductor wires suspended approximately 10 m above the river surface. Each ACAS comprised two solar panels, a battery box, and two light boxes. The total weight of each system was approximately 182 kg near the base (solar panels and battery box) and 11 kg (light boxes) on the crossarm. Each 200-W solar panel was 1.3 m wide by 1.0 m tall and was mounted 3–4 m above the ground at a 45° angle facing south to maximize mid-day sun exposure. The solar panels charged four sealed lead acid batteries housed in a 7.6 × 0.9 × 0.4 m battery box mounted 1–2 m above the ground. The battery box also contained electrical hardware and switching to allow the ACAS to be powered on and off manually or triggered by a photocell to power them automatically on at dusk and off at dawn. Each light box contained three light-emitting diode UV lights (6868 UV LED; Inolux Corporation, Santa Clara, California, USA) with peak illumination in the range of 390–400 nm. Light boxes were mounted on the crossarm of one of the H-frame structures supporting the span to be illuminated, so the light was projected along the length of each 260 m span (Fig. 2). Each light projected UV illumination primarily in an 8° cone, with lesser amounts of light emitted in a 45° cone. Each cone of illumination was offset from the others by 2°. This arrangement created a primary illumination zone of 8° horizontal and 12° vertical to illuminate the entire length of each of the five wires in each illuminated span, except for the portions of wires immediately adjacent to the tower upon which the ACAS was mounted. Those portions of the wires were illuminated by the 45° cones of light emitted around the faces of the light boxes.

Fig. 2. Illustration of the Avian Collision Avoidance System's field of ultraviolet light illumination of power line crossings.

We coordinated with Dawson Public Power (Kearney, Nebraska), the owner and operator of the power lines we studied, to install both ACASs on existing H-frame structures on 08 February 2021 before the spring arrival of migrating birds. On the east crossing, we installed an ACAS on the north bank and directed illumination south across the Platte River. On the west crossing, we installed an ACAS on the south bank and directed illumination north. At each crossing, we installed the ACAS on the single H-frame accessible via bucket truck. In both cases, the opposite end of the span was not accessible to a bucket truck due to river flow on both sides of the H-frame.

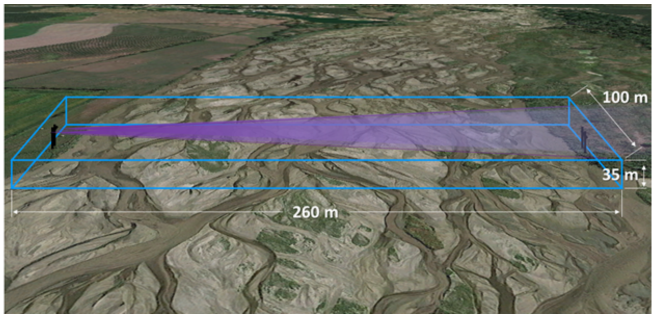
To assess the effects of ACAS illumination, we documented collisions, flight behaviors, and numbers (individuals and flocks) of medium- to large-bodied birds crossing the study area. We followed Dwyer et al. (2019) in monitoring crossings from a blind from 25 February through 06 April 2021 to bracket the period when most collisions at Rowe occur (Wright et al. 2009, Murphy et al. 2016*a*), and randomly assigned each ACAS to be off or on during each day of observation. Similar to previous studies at Rowe (Wright et al. 2009, Murphy et al. 2016*a,* Dwyer et al. 2019), we created a conceptual box around each crossing within which we recorded avian flights (Fig. 3). This box was 35 m tall from the surface of the Platte River, ~260 m wide to match the river's width, and 100 m long, including 50 m along the Platte River on each side of the power line. We differed from Dwyer et al. (2019) in monitoring two crossings instead of only one, so we assigned the on-off schedule of each ACAS independently. To distinguish the effect of the ACAS on each power line from any potential effect of the ACAS on the other power line, we refer to the "focal line" as the crossing being monitored during any given observation, and "distal line" as the other crossing. This distinction allowed us to consider influences of ACAS illumination not only on the illuminated (focal) crossing, but also on the adjacent (distal) crossing. We also differed from previous studies in monitoring 7 d/wk, weather permitting. When medium- to large-bodied birds flew along the river through the conceptual box of our study area, we recorded information on collisions, flight behaviors, and flock size. We conducted observations from 1 h before sunset until 4.5 h after sunset and recorded observations identically regardless of ACAS status. We began collision monitoring 1 h before sunset to allow us to validate the finding of previous studies that most collisions occur at night, defined as after civil twilight. During daylight, we conducted observations using 8 × 42 binoculars. At night, we conducted observations using a 3–12 × 50 thermal imaging monocular (Prometheus 336; Armasight, San Francisco, California, USA) and a 0–4× thermal imaging monocular (Scout III; FLIR, Wilsonville, Oregon, USA).

We planned to record two ACAS statuses, on and off; however, midway through the season, one of the ACASs failed and was partially repaired such that it powered only one light box after it was repaired, rather than two light boxes as had been intended. The one light box was also incorrectly installed following repair and was not properly pointed along the power line. Consequently, on the west crossing, we recorded ACAS statuses as either "on" (when functioning properly), "off", and "partially on" after repair. For the east crossing, we recorded ACAS status as either "on" or "off".

Table 1. Collision risk categories for Sandhill Cranes and other large-bodied birds flying past power lines crossing the Platte River at the Iain Nicholson Audubon Rowe Sanctuary in central Nebraska, USA.

Risk category	Risk description	Flight height (m above river) when crossing the power line	Behavior
0	No risk	26–35	No reaction well above power line
1	Low risk	26–35	Climb, flare, or reverse well above power line
2	Moderate	16–25	Climb, flare, or reverse above power line
3	High	16–25	No reaction above power line
3	High	0–15	Climb, flare, reverse, or no reaction below or between power lines
4	Collision	10–15	Climb, flare, or no reaction resulting in a collision with power lines

Fig. 3. Conceptual box (blue lines) around the area of each power line crossing within which we recorded avian flights. The Avian Collision Avoidance System's field of ultraviolet light illumination is indicated by purple shading.



As in previous studies (Murphy et al. 2016*a,* Dwyer et al. 2019), we recorded behavior when individuals or flocks of birds flew within 25 m of the river surface and within 50 m upstream or downstream of the study crossing. We expanded on previous studies by also including birds flying 26–35 m above the river surface. This approach facilitated comparing flight behaviors for birds potentially at risk of collision (within 25 m of the river surface; i.e., within 10 m of the power line) to birds not likely to be at risk of collision (25–35 m above the river surface). We used the known height of the power lines and known distances between the wires comprising the power lines to gauge the flight height of birds 50 m from the power line and as they flew over the power lines.

Similar to previous studies of Sandhill Crane collisions with power lines in south-central Nebraska generally (Morkill and Anderson 1991), and at Rowe specifically (Murphy et al. 2016*a,* Dwyer et al. 2019), we defined a flock as any number of birds (1 – ∞) separated from their nearest neighbor by < 100 m horizontally. To ensure independence among data points, we did not record approaches or passages over power lines by flocks within 100 m of a previous flock unless a different species was observed approaching the power line. This approach made flocks, rather than individual birds, our sampling unit for statistical analyses (Murphy et al. 2016*a*).

Each time a flock of birds crossed over the power line within 35 m above the river surface, we recorded the species, whether the ACAS was on, off, or partially on, whether a collision occurred, whether the flock passed during the day (1 h before sunset to the end of civil twilight at ~0.5 h after sunset) or at night (civil twilight to 4.5 h after sunset), the approximate midspan distance for the center of the flock from the H-frame structure upon which the ACAS was installed, whether and how birds maneuvered to avoid the power line, the perpendicular distance from the power line at which maneuvers occurred (if they occurred), and the midspan distance that any reaction occurred (if a reaction occurred). If one or more collisions occurred, we recorded the wire involved, the approximate midspan distance from the H-frame structure upon which the ACAS was installed, and the subsequent flight behavior of the bird(s) involved.

Similar to previous studies of avian collisions at Rowe (Murphy et al. 2016*a,* Dwyer et al. 2019), we used combinations of four behaviors as birds approached the power line and four flight height categories as birds crossed the power line to define five categories of collision risk (Table 1). The four behaviors were climb, flare, reverse, and no reaction. We recorded a climb when the entire flock maintained consistent flight direction, speed, and wingbeat, but adjusted flight height gradually to pass over the power line. We recorded a flare when at least one member of the flock altered direction, speed, and wingbeat to suddenly gain the elevation needed to pass over the power line. We recorded no reaction when the entire flock maintained the same direction, speed, and elevation above the river level before and after approaching the power line. We recorded a reverse when at least one member of the flock altered direction, speed, and wingbeat to turn away from and not cross the power line. When a collision occurred, we recorded the outcome as "normal flight" when wingbeats were steady and elevation was maintained, "hampered flight" when wingbeats were unsteady but elevation was maintained, "flapping fall" when wingbeats were unsteady and elevation was not maintained, and "limp fall" when there were no wingbeats and elevation was not maintained.

Each time we recorded data on a flock passing through the study area, we also recorded environmental conditions so we could evaluate whether they influenced the likelihood of collisions. We recorded whether the moon was visible (yes/no), percentage of cloud cover (estimated to the nearest 5%), the occurrence of precipitation (yes/no), and the presence of fog limiting visibility to < 800 m (yes/no). During data entry, we recorded moon visibility and status (full, waxing, waning, new) as percentages (full = 100%), and we recorded temperature, humidity, precipitation measurements, and wind speed and direction logged by a permanent weather station operating at Rowe. Also, during data entry, we recorded river flow volumes from the nearest United States Geological Survey gaging station on the Platte River near Kearney, Nebraska, USA (USGS 06770200).

Ethics Statement: To ensure we did not disturb roosting birds and thereby potentially cause the collisions we observed, we scheduled installation of ACASs before the arrival of spring migrants. We conducted all monitoring from blinds and entered those blinds during daylight before the daily return of birds from foraging areas. We were careful to depart blinds quietly under cover of darkness when observations were completed.

Statistical analyses

We conducted two suites of analyses. In the first suite, we conducted a two-tiered modeling approach that allowed us to consider the effects of ACAS illumination on avian collisions while simultaneously accounting for other influential factors on a survey period basis. In the second suite, we conducted a series of bivariate statistical tests to evaluate questions related to collision frequency and behavior, particularly on a per-observation basis, which were not addressed by our modeling approach. We conducted all statistical analyses in the open-source statistical software program R version 3.6.0 (R Core Team 2019).

We used a tiered, multistage approach to model selection because this approach improved the clarity of the model selection process by reducing the number of competing models being considered at each stage (Burnham and Anderson 2002, Ranglack et al. 2017). To determine the appropriate model type for our analyses, we tested several categories of count-based regression models by using the number of collisions per survey period as the outcome variable and ACAS treatment condition as the predictor variable. Specifically, we used the zeroinfl() function in the pscl R package (Zeileis et al. 2008, Jackman 2020) to run zero-inflated Poisson and zero-inflated negative binomial regression models. We used the glm() tool in the stats package, and the glm.nb() function in the MASS package, respectively (Nelder and Baker 1972, Venables and Ripley 2002), to run standard Poisson and negative binomial generalized linear models with appropriate log link functions. We used the dispersiontest() function in the AER package (Kleiber and Zeileis 2008) to examine models for overdispersion, and we used the logLik() function in the stats package (Harville 1974) and the Akaike Information Criterion (AIC; Burnham and Anderson 2002) to compare models for fit. We found that both traditional and zero-inflated negative binomial models outperformed models in the Poisson family but performed similarly to one another. To determine which of these two models to use in our analyses, we used an AIC-corrected Vuong's non-nested hypothesis test employing the vuong() function in the pscl package (Vuong 1989, Jackman 2020) to compare negative binomial models to identically configured zero-inflated models. We determined that the standard negative binomial model better fit the data, and thus used this model form for all multivariate analyses.

We developed a suite of a priori candidate models based on combinations of factors that could influence the number of observations in the study area or avian power line collisions (Bernardino et al. 2018). To avoid issues of multicollinearity, we examined the bivariate relationship between all ordinal, interval, and continuous predictor variables using Pearson product-moment correlation coefficients using the cor() function in the stats package (R Core Team 2019). No two variables with > |0.6| correlation or association (binary) were included in the same model (Dormann et al. 2013). Candidate model sets included independent variables and uncorrelated combinations of them that reflected our research questions. To ensure that standard errors in our models were not inflated as a result of collinearity between more than two variables, we conducted variance inflation tests on each candidate model using the vif() function in the car package and dropped all models scoring > 5.0 from our analyses (Fox and Weisberg 2019). Models were compared using AIC corrected for small sample sizes (AICc) using the model.sel() function in the MuMIn package (Burnham and Anderson 2002, Barton 2020).

Each stage investigated a themed set of predictor variables, related to detection probability and environmental conditions, respectively, that could influence the rate of collisions observed and potentially influence the effectiveness of ACAS units. We advanced variables from models with a ΔAIC < 2.0 and/or a model weight > 0.10 and that were better than the null model from the two parallel stages in tier one to tier two of the model selection process (Wagenmakers and Farrell 2004, Burnham et al. 2011). In the first stage of tier-one analyses, we assessed only models predicting the number of observations recorded per survey period in relation to independent variables that could influence the number of cranes in the study area. We included variables related to Sandhill Crane migration, river flow, observers, and date (Appendix 1). These can be considered "detection probability" variables (Table 2; Appendixes 1 and 2). We derived Sandhill Crane migration metrics from weekly aerial surveys of the Central Platte River Valley conducted by the Crane Trust (https://cranetrust.org/news-events/; see Caven et al. 2020*b*). These data included the number of days from the peak of migration observations were made, and a daily index of Sandhill Crane abundance developed by using Kalman smoothing and linear missing value imputation via the imputeTS R package (Moritz and Bartz-Beielstein 2017). In the second stage of tier-one analyses, we repeated this process using collisions recorded per survey period as the outcome variable and only "environmental" variables, which could influence flight behavior (e.g., wind) or potentially alter the ability of birds to see power lines during flight (e.g., fog; Table 2; Appendixes 2 and 3). In the second tier of analyses, we integrated the treatment variable, which tested the status of both ACASs (on, partially on, and off), with the top variables from tier-one analyses into a set of competing multivariate models predicting the number of collisions per survey period (Table 2; Appendixes 1–3).

We intended the top-performing models from the second tier of analyses to assess the effectiveness of the ACAS in the context of potentially confounding environmental and detection-related variables, as well as to determine which, if any, environmental variables influenced the probability of power line collisions. To improve the interpretability of our models, we transformed parameter estimates altered by the log link function to percent change in the dependent variable per unit increase in the independent variable following the recommendation of K. Benoit (https://kenbenoit.net/assets/courses/ME104/logmodels2.pdf). We also used the predictorEffect() function in the effects R package (Fox 2003) to plot the predicted effects of individual covariates on the dependent variable (i.e., collisions per survey period) while holding all other predictor variables constant.

Table 2. Selection table for the second tier of the model selection process, including treatment variables predicting the number of power line collisions recorded during the survey period. The final model set was intended to assess the effects of Avian Collision Avoidance System (ACAS) operational status in the contexts of other covariates that could influence collision probability and alter experimental ACAS effectiveness. Model covariates included focal ACAS and distal ACAS status, the quadratic transformation of day of year (Date [quadratic]), number of days from the peak of migration that observations were made (Days to peak), river flow via U.S. Geological Survey gage station 06770200, Kearney, NE (Flow), the quadratic transformation of mean wind speed (Mean wind [quadratic]), the presence of fog that reduced visibility to < 0.5 km (Fog), and the proportional occurrence of precipitation. Models were ranked via the Akaike Information Criterion corrected for small sample sizes (AICc) and are presented with a priori themes, coefficient estimates, and significance levels for individual covariates (factors and quadratic predictor variables are indicated with "+"), as well as model degrees of freedom (df), log-likelihood (Log lik.), AICc, ΔAICc, and model weight (Wt). Models that had ΔAICc < 2.0, model weight > 0.10, and outperformed the null model from stages 1 and 2 of tier one were advanced to the second tier of the model selection process and incorporated detection probability variables, including Date (quadratic), Days to peak, and Flow, as well as environmental variables, including Mean wind (quadratic), Precipitation, and Fog.

	Treatment		Detection probability			Environment							
Model theme[†]	Focal ACAS	Distal ACAS	Date (quadratic)	Days to peak	Flow	Mean wind (quadratic)	Precipitation	Fog	df	Log lik.	AICc	ΔAICc	Wt
Treat & Env	+***	+				+**	−25.42		9	−78.5	177.6	0.00	0.551
Treat, Env, & Det	+***	+		−0.03178		+*	−23.13		10	−78.1	179.4	1.73	0.232
Treat, Env, & Det	+***	+		−0.03536	−0.005389	+*	−23.65		11	−78.0	182.0	4.32	0.064
Treat & Env	+***	+				+*		−9.66	9	−80.8	182.2	4.54	0.057
Treat	+***								4	−87.7	183.9	6.26	0.024
Treat, Env, & Det	+***	+		−0.03596		+*			9	−82.0	184.6	6.91	0.017
Treat, Env, & Det	+***	+	+		−0.002350	+*	−23.82		12	−78.0	184.6	6.94	0.017
Env						+**	−16.26		5	−87.5	185.8	8.19	0.009
Treat, Env, & Det	+***	+		−0.03843	−0.002926	+*		−10.43	11	−80.3	186.4	8.74	0.007
Treat	+***	+							6	−86.6	186.4	8.79	0.007
Treat, Env, & Det	+***	+		−0.04083	−0.007433	+*			10	−81.9	187.0	9.36	0.005
Env						+*		−6.34	5	−88.4	187.6	9.99	0.004
Treat & Det	+**	+		−0.05389	−0.009249				8	−85.6	189.3	11.67	0.002
Env & Det				−0.04369	−0.002671	+*	−13.42		7	−86.9	189.3	11.70	0.002
Env & Det				−0.04626	−0.002629	+*		−6.36	7	−87.7	191.0	13.35	0.001
Treat & Det	+**	+	+		−0.004063				9	−85.3	191.2	13.53	0.001
Null									2	−94.4	193.0	15.39	0.000

***$P < 0.001$, **$P < 0.01$, *$P < 0.05$.

[†] Treat = Treatment, i.e., whether the focal or distal ACAS was on, partially on, or off; Env = environmental variables included in the model; Det = detection probability variables included in the model.

Given that the preceding analyses were conducted on a survey-period basis, there were several questions related to bird collision frequency and behavior on a per-observation basis that our model results could not address. To evaluate those questions, we conducted a series of bivariate statistical tests. We employed Kruskal-Wallis H tests with Dunn's post hoc tests (Z) to compare numeric variables across multiple nominal categories (e.g., flight height by ACAS status; McDonald 2009, Zar 2010, Dinno 2015, Mangiafico 2015). We also used Welch's two-sample two-way t-tests to examine differences in numeric variables across two-level factors (e.g., flock size when collisions occurred vs. when they did not; McDonald 2009, Mangiafico 2015). Finally, we used Pearson's chi-squared tests to examine contingency tables of nominal variables, including Bonferroni post hoc tests for pairwise comparisons (e.g., reaction type by ACAS status; McDonald 2009, Mangiafico 2015). We used the ggplot2 package (Wickham 2016) to create visual graphics corresponding to Kruskal-Wallis H, Welch's t, and Pearson's chi-squared tests.

RESULTS

Modeling results

The top models from the first stage of tier-one analyses predicting the number of observations per survey period included combinations of migration, date, and river flow variables (Appendix 1). The top model included the number of days from the peak of Sandhill Crane migration when observations were made ($\beta \pm$ standard error [SE] $= -0.0381 \pm 0.0094$, $P < 0.001$) and river flow ($\beta \pm SE = -0.0153 \pm 0.0049$, $P = 0.002$). However, the second-best model was within ΔAICc < 2 and included the quadratic transformation of day of year ($\beta 1 \pm SE1 = 1.1697 \pm 0.4911$, $P = 0.017$; $\beta 2 \pm SE2 = -1.9020 \pm 0.4948$, $P < 0.001$) and flow ($\beta \pm SE = -0.0124 \pm 0.0047$, $P = 0.009$). Our top model predicted that the number of avian flocks detected decreased 3.7% for every day surveys were conducted before or after the peak of migration. The number of observations made also decreased 1.4% for every one unit (m^3/s) increase in river flow.

Top environmental models (stage two of tier-one analyses) predicting the number of collisions per survey period generally included wind- and precipitation-related variables (Appendix 3). The top model included the quadratic function of mean wind speed (km/h; $\beta 1 \pm SE1 = -0.1605 \pm 2.891$, $P = 0.956$; $\beta 2 \pm SE2 = -9.559 \pm 3.496$, $P < 0.006$) and the proportion of observations indicating precipitation occurrence ($\beta \pm SE = -16.259 \pm 17.069$, $P = 0.341$) per survey period (Appendix 3). However, there were three other models with a ΔAICc < 2, including the second-best model, which included the quadratic function of maximum wind speed (km/h) recorded (β*1* ± SE1 = 0.1985 ± 3.0963, *P* = 0.949; β*2* ± SE2 = −8.700 ± 4.012, *P* = 0.030) as well as the proportion of observations with precipitation (β ± SE = −12.317 ± 16.894, *P* = 0.466). The predicted number of collisions per survey period was maximized at approximately 14 km/h mean windspeed and declined as wind speeds increased beyond that point. The predicted number of collisions per survey period decreased approximately 15.0% for each unit increase in the percentage of time it rained during surveys; however, only 10% of surveys (*N* = 8) included precipitation, and therefore, confidence intervals were generally wide for this parameter. Despite the quadratic forms of both mean and max wind speed being present within ΔAICc ≤ 2, we only advanced the quadratic form of mean wind speed to tier-two analyses to reduce the complexity of the model set because it out-performed like models with the quadratic of maximum wind speed in every case.

The top model from the second tier of analyses integrated variables from the first two stages of tier one together with the treatment variables (e.g., focal and distal ACAS status; Table 2). The final model predicted having the focal ACAS on (β ± SE = −2.1179 ± 0.5578, *P* < 0.001; Table 2) decreased collisions by 88.0% relative to the unit being off. The focal unit being partially on (β ± SE = −0.6418 ± 0.5787, *P* = 0.267) was predicted to reduce collisions by 47.4% (Fig. 4). However, the focal ACAS being partially on did not have a statistically significant influence, based on the *P*-value, on collisions per day, controlling for other covariates. Similarly, our model predicted that the distal ACAS being on reduced collisions on the focal power line by 39.4%, but the effect was not significant from a *P*-value perspective (β ± SE = −0.5010 ± 0.4430, *P* = 0.258; Table 2, Fig. 5). However, including distal ACAS operational status improved model performance over competing models (Table 2). The top model also included the quadratic transformation of mean wind speed as a significant predictor of collisions per survey period (β*1* ± SE1 = −1.954 ± 2.964, *P* = 0.510; β2 ± SE2 = −8.728 ± 3.309, *P* = 0.008; Fig. 6). Finally, the top model included precipitation (β ± SE = −0.2542 ± 0.1556, *P* = 0.102) as a nonsignificant but contributing variable (Table 2, Fig. 7). This model predicted that collisions would decrease 22.5% for every 1% increase in the percentage of observations in which rain occurred. The only other model that was within ΔAICc of 2 was similar to the top model, aside from including the insignificant covariate, number of days from the peak of Sandhill Crane migration when observations were made (β ± SE = −0.0318 ± 0.0323, *P* = 0.325; Table 2).

Summary results

During 40 days of observation, 25 February to 06 April 2021, of the two power lines we studied (i.e., 80 power-line days), we documented 6643 avian flocks within the focal area of our study (0–35 m above the river surface). We documented 2608 flocks before civil twilight and 4035 flocks after civil twilight. Flock sizes were larger before civil twilight (87 birds/flock) than at night (54 birds/flock; *t* = 2.87, *P* = 0.004). In total, we documented flocks of Sandhill Cranes (*N* = 5562), geese (Canada Geese and Snow Geese (*Chen caerulescens*) combined; *N* = 559), ducks (numerous species; *N* = 411), Bald Eagles (*Haliaeetus leucocephalus; N* = 93), unidentified raptors (*N* = 11), American White Pelicans (*Pelecanus erythrorhynchos; N* = 4), unidentified gull species (*N* = 2), and Wild Turkeys (*Meleagris gallopavo; N* = 1) within the study area. Of all flocks, 4287 (65%) occurred within 25 m of the river surface and were classified as moderate- or high-risk flights. We also recorded 2356 low- or no-risk flights (35%; 26–35 m above the river surface). The number of observations increased as Sandhill Crane numbers increased mid-way through the study.

Fig. 4. Predicted effect and 95% confidence intervals of the focal Avian Collision Avoidance System (ACAS) operational status on collisions during the survey period, holding all other model covariates constant. This relationship was estimated from final models while holding other variables in the model at their mean.

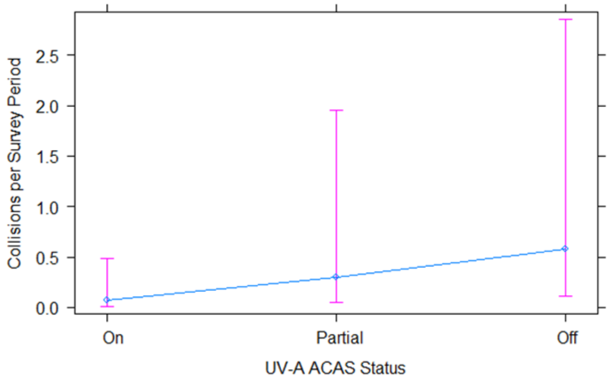
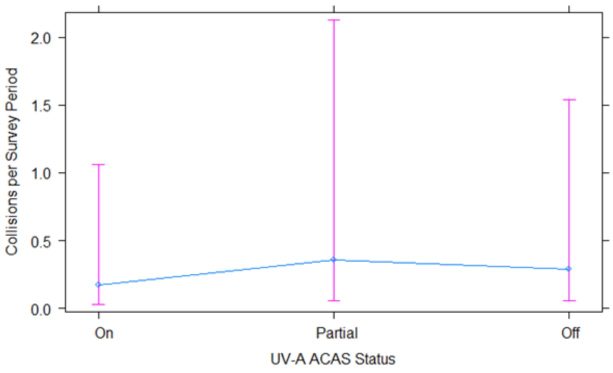


Fig. 5. Predicted effect and 95% confidence intervals of the distal Avian Collision Avoidance System (ACAS) operational status on collisions during the survey period, holding all other model covariates constant. This relationship was estimated from final models while holding other variables in the model at their mean.



Throughout the entire study period, we documented one collision before civil twilight and 63 collisions at night (see Fig. 8). Of these collisions, six were Canada Geese (one before civil twilight and five at night) and 58 were Sandhill Cranes (all at night). Of the collisions that we observed at night, 52 (2 Canada Geese and 50 Sandhill Cranes) were observed during 41 power-line days of observation when the focal ACAS was off (1.27 collisions/day),

Fig. 6. Predicted effect and 95% confidence intervals of mean wind speed (km/h) on the total number of collisions during the survey period, holding all other model covariates constant. This relationship was estimated from final models while holding other variables in the model at their mean. Tick marks along the x-axis represent actual values upon which the model was based.

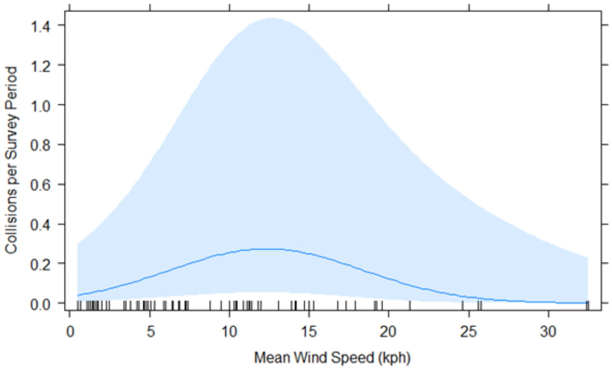
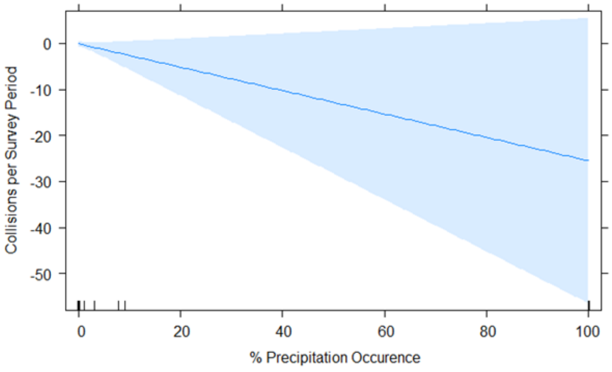


Fig. 7. Predicted effect and 95% confidence intervals of the percentage of time precipitation occurred during observations of collisions during the survey period, holding all other model covariates constant. This relationship was estimated from final models while holding other variables in the model at their mean. Tick marks along the x-axis represent actual values upon which the model was based.



6 collisions (2 Canada Geese and 4 Sandhill Cranes) were observed during 9 power-line days of observation when the focal unit was partially on (0.67 collisions/day), and 5 collisions (1 Canada Goose and 4 Sandhill Cranes) were observed during 30 power-line days of observation when the ACAS was on (0.17 collisions/day). A significantly higher proportion of collision events was observed at night ($\chi^2 = 30.39$, $P < 0.001$). A significantly higher proportion of collision events was also observed when the ACASs were off ($\chi^2 = 27.69$, $P < 0.001$). We documented 36 collisions with the smaller, higher shield wires and 28 collisions with conductor wires. Following collision, 7 birds maintained normal flight, 29 had hampered flight, 11 weakly flapped or glided to the river some distance away from the power line, and 17 fell limp to the river near the power line. Flock size did not differ significantly when collisions occurred (mean = 86.5) to when they did not (mean = 66.9; $t = -0.39$, $P = 0.70$). However, flock size averaged 411.1 birds when two or more collisions occurred, though this difference was not statistically significant due to relatively high variance and low sample size ($t = -1.13$, $P = 0.295$). The frequency of collisions did not differ between power lines ($\chi^2 = 2.60$, $P = 0.11$). Similarly, there was no difference in the amount of time elapsed since sunset between observations when collisions occurred and when they did not ($t = 0.46$, $P = 0.64$). Finally, there was no difference in the midspan for observations of flocks including a collision and those that did not ($t = -1.25$, $P = 0.217$).

Fig. 8. Sandhill Crane power line collision documented when the Avian Collision Avoidance System was off (white circle) using a Forward Looking InfraRed (FLIR) night vision scope with an attached video recorder.

Reaction types differed significantly with the focal ACAS's status ($\chi^2 = 167.3$, $P < 0.001$). Flares occurred more frequently than expected when the ACAS was off and less than expected when it was on (Table 3). Low-risk climbs occurred less frequently than expected when the focal ACAS was off and more frequently than expected when it was on. Low-risk flares occurred above expected levels when the ACAS was partially on. No-risk flights occurred less than expected when the focal ACAS was off and more than expected when it was on. No reaction 0–10 m above the power line occurred more frequently than expected when the focal ACAS was partially on and less frequently than expected when it was on. No reaction below the power line occurred more than expected when the focal ACAS was off and less than expected when it was on. All other recorded behaviors (climb, reverse, etc.) did not differ in frequency by focal ACAS operational status.

When considering all potential reaction types, response distances for the focal power line differed significantly across ACAS operational statuses ($H = 28.27$, $P < 0.001$). Response distances occurred significantly further away from the power line when the focal ACAS was on than when it was off ($Z = -4.67$, $P < 0.001$) or partially on at night ($Z = 4.36$, $P < 0.001$; Fig. 9). However,

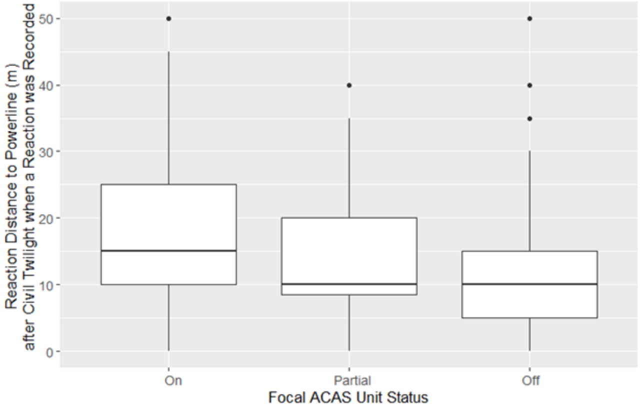
Table 3. Deviation from the expected value (residual) regarding the frequency of reaction types to power lines observed at night based on Avian Collision Avoidance System (ACAS) operational status (off, partially on, or on). Residuals and significance tests were determined using a Pearson χ^2 test with a Bonferroni correction factor.

	ACAS operational status		
Reaction type[†] to power lines	Off	Partially on	On
High risk: no reaction between	−0.4118	−0.7694	0.8670
High risk: no reaction below	3.6065**	0.3747	−4.2458***
Moderate risk: flare 0–10 m above	5.1161***	−2.3914	−3.9521**
Moderate risk: climb 0–10 m above	1.9862	−3.1718*	0.0552
Moderate risk: reverse 0–10 m above	1.0022	−0.3574	−0.8529
Moderate risk: no reaction 0–10 m above	1.9047	3.7729**	−4.7753***
Low risk: flare 11–20 m above	−1.9314	−1.2440	3.0130^
Low risk: climb 11–20 m above	−5.2226***	1.9897	4.3543***
No risk: no reaction 11–20 m above	−8.7027***	0.5876	9.1886***

***$P < 0.001$, **$P < 0.01$, *$P < 0.05$, ^$P < 0.10$.

[†] Reaction types are ranked from highest to lowest collision risk: No reaction between = at least one member of the flock maintained the same direction, speed, and elevation above the river level before and after approaching the power line and passed between the power lines within 10–15 m of the river surface; No reaction below = at least one member of the flock maintained the same direction, speed, and elevation above the river level before and after approaching the power line and passed within 10 m of the river surface, i.e., below the power lines; Flare = at least one member of the flock altered direction, speed, and wingbeat to suddenly gain the elevation needed to pass over the power line within 0–10 m of it; Climb = at least one member of the flock maintained consistent flight direction, speed, and wingbeat, but adjusted flight height gradually to pass over the power line within 0–10 m of it; No reaction above = the entire flock maintained the same direction, speed, and elevation above the river level before and after approaching the power line and passed within 0–10 m of it; Low risk flare = at least one member of the flock altered direction, speed, and wingbeat to suddenly gain the elevation needed to pass over the power line within 11–20 m of it; Low risk climb = at least one member of the flock maintained consistent flight direction, speed, and wingbeat, but adjusted flight height gradually to pass over the power line within 11–20 m of it; No risk = the entire flock maintained the same direction, speed, and elevation above the river level before and after approaching the power line and passed within 11–20 m of it.

Fig. 9. Boxplots of reaction distance (m) at night (civil twilight to 4.5 h after sunset) relative to the observed power line by the operational status of the focal Avian Collision Avoidance System (ACAS). Black horizontal lines represent median values, box tops and bottoms denote upper and lower interquartile ranges, extended whiskers signify values of 1.5 times the interquartile range, and points represent outliers.

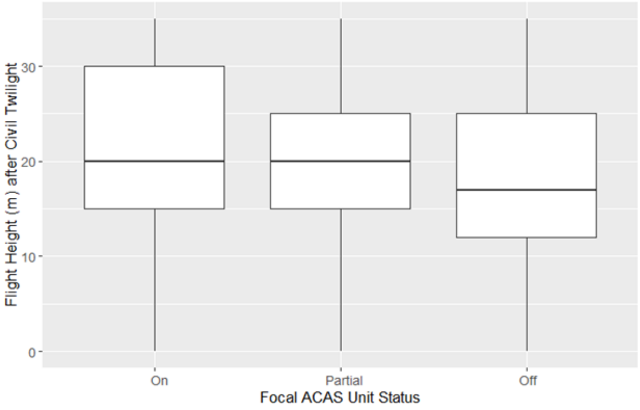


there was no significant difference between response distances when the focal ACAS was partially on or off ($Z = 1.44$, $P = 0.149$). Additionally, there was no difference in reaction distances when the distal ACAS was on or off ($Z = -0.62$, $P = 0.531$). When a response occurred (climb, reverse, flare, or low-risk climb or flare), average response distance to power lines before civil twilight was 20.2 m and at night was 12.7 m ($t = 17.93$, $P = < 0.001$). We observed a slight but significant difference in the average response distance between observations occurring before civil twilight with ACAS illumination (mean = 21.8 m) and without (mean = 19.5; $Z = 3.29$, $P = 0.003$), when a response occurred. However, there was a large difference in the average response distance between observations occurring at night with ACAS illumination (mean = 17.6 m) and without (mean = 10.7 m; $Z = 13.8$, $P < 0.001$), when a response occurred.

Flight heights 50 m from the power line were higher before civil twilight (mean = 25.1 m) than after (mean = 19.4; $t = 26.2$, $P = < 0.001$). Flight heights 50 m from the power line at night differed by focal ACAS status ($H = 120.9$, df = 2, $P < 0.001$; Fig. 10). Flight heights were higher when the focal ACAS was on than when it was off ($Z = -10.44$, $P < 0.001$). Similarly, flight heights were higher when the focal ACAS was partially on than when it was off ($Z = -5.48$, $P < 0.001$). However, flight heights did not differ significantly between partially on and on ($Z = 1.74$, $P = 0.083$). Flight height did not differ by focal ACAS status during the day ($H = 0.43$, $P = 0.81$). Flight height at night also differed based on distal ACAS status ($H = 10.17$, $P = 0.006$). Flight heights were significantly higher when the distal ACAS was on than off ($Z = -2.36$, $P = 0.0.037$). Similarly, flocks were higher when the distal ACAS was partially on vs. off ($Z = -2.66$, $P = 0.024$), but were statistically similar to the on condition. We observed similar numbers of moderate and high-risk flights per survey before civil twilight when the focal ACAS was on, partially on, or off ($\chi^2 = 3.7$, $P = 0.16$). However, we observed 138% more moderate- and high-risk flights per survey at night when the focal ACAS was off (residual = +10.8) than on (residual = −10.98; $\chi^2 = 133.5$, $P = < 0.001$).

During our study, the average temperature was 9.12°C (range: −5.6 to 26.1°C), humidity averaged 60.65% (range: 21–99%), and average wind speed was 9.86 km/h (range 0–46.7 km/h). The moon

Fig. 10. Boxplots of flight height (m) at night (civil twilight to 4.5 h after sunset) at 50 m from the focal power line by the operational status of the focal Avian Collision Avoidance System (ACAS). Black horizontal lines represent median values, box tops and bottoms denote upper and lower interquartile ranges, and extended whiskers signify values of 1.5 times the interquartile range.



was visible during at least a portion of 18 days of observation and was not observed during 22 days. We made 4907 observations when the moon was not visible and 1736 when it was. We recorded many more observations when it was not precipitating (*N* = 6398) than when it was (*N* = 245); however, precipitation only occurred during four days of observation. Similarly, because there was only fog present during six days of observation, we recorded more observations when it was clear (*N* = 6548) than when it was foggy (*N* = 95). We observed two collisions during days when it was precipitating or foggy. However, during periods of rain and fog, the visibility of the power line and birds with our night vision equipment was reduced to an unknown degree, likely leading to fewer observations and thus a lower likelihood of observing collisions.

DISCUSSION

The visibility of power lines can influence the number and frequency of avian collisions (Brown et al. 1987, Faanes 1987, Faanes and Johnson 1992). During our study, significantly higher proportions of collisions occurred at night and when the ACAS was off. This finding is similar to many studies wherein collisions were more likely at night when the power line and line markers were less visible (Erickson et al. 2001, Wright et al. 2009, Shaw et al. 2010, Murphy et al. 2016*a,b,* Dwyer et al. 2019, Johnsgard and Mangelsen 2020). We found that ACAS illumination of power lines reduced avian collisions substantially. Dwyer et al. (2019) previously tested the effectiveness of ACAS illumination at Rowe and found that UV light reduced Sandhill Crane (*Antigone canadensis*) collisions by 98% without any reported disturbance to surrounding communities. However, that study tested only one power line, used a first-generation ACAS that had a wider field of illumination than the second-generation ACASs used here and thus required more power to operate, and did not consider the effects of environmental covariates. Similar to Dwyer et al. (2019), we found the status of the focal ACAS (i.e., on or off) was the most influential predictor of collisions (ACAS status was included in all models within ΔAIC of 7 of the top model), with the likelihood of collisions decreased by 88% when the focal ACAS was on. While not statically significant, distal ACAS status also improved model performance and decreased collisions by 39.4% when the distal ACAS was on.

We wondered how we could have recorded only 52 collisions during 41 power-line nights when the focal ACAS was off when Dwyer et al. (2019) recorded 48 Sandhill Crane collisions during 19 nights of ACAS-off observations of one of the same power line spans we studied. If all variables were equal, we would have expected slightly > 100 collision records in our study because we conducted 2.2 times the number of power-line nights of observations when the ACAS was off. We attribute the reduction in collisions when the focal ACAS was off to the fact that there were only 13 nights when both the focal and the distal ACASs were both off. It was during those nights that 39 of 63 collisions were observed to have occurred. In other words, 62% of collisions occurred during 16% of nights when both ACASs were off. This finding has two important implications. First, the results reported by Dwyer et al. (2019) likely underestimated the positive effect of ACAS because they did not quantify collisions on the distal power line (west crossing) when they evaluated the ACAS on the east crossing. Our results demonstrate that there likely was an undetected, unsuspected collision-mitigating effect on the distal line during the Dwyer et al. (2019) study. Second, given the distal effect of the ACAS, if ACASs are deployed in the future at other spans of power lines with high collision numbers, monitoring, if it occurs, should include not only the ACAS-illuminated power line, but any other adjacent power lines in the habitat to better quantify "neighbor effects" of illumination. Power lines closer to each other than those we studied may display even larger neighbor effects.

Our results also indicate that UV illumination of power lines not only decreases the number of collisions, but may alter flight behavior. For instance, we observed fewer flocks flying at power line height when the focal ACAS was on, particularly at night. Additionally, highest risk flight types (flares, no reaction within 10 m above the power line, flights below the power line, and flights between power lines) occurred more frequently than expected when the focal ACAS was off, less frequently than expected when it was on, and at the expected level when the focal ACAS was partially on. This finding was similar to that of Murphy et al. (2016*a*) in that higher risk flight types were observed more often at night when the lines were less visible than during the day when they were more visible. Furthermore, what we deemed to be "extremely dangerous flights" (i.e., flights below or between the power lines) were significantly more likely to occur when the ACAS was off than when it was on. Conversely, low-risk flight types (low-risk climbs, low-risk flares, and no-risk flights 11–20 m above the power line) were significantly less likely to occur when the focal ACAS was off and more likely to occur when it was on, which is a further indication that the ACAS illuminated the power lines sufficiently to provide warning to birds in flight.

The location of reactions relative to the power line also differed between ACAS treatments. Brown et al. (1987) found that most birds reacted to power lines when they were within 25 m of them. Reaction distances were greater when the focal ACAS was on than when it was off. Though focal ACASs being on increased reaction distances by 64% (~6.9 m) on average, reactions still generally took place within 25 m of the power lines (17.6 m). This finding, in conjunction with the five collisions we recorded when the focal ACAS was on, suggests that ACAS decreased collision risk by increasing avoidance of the line through improved visibility. However, although behavior was altered, visibility of the lines likely remained imperfect, and therefore, collision risk was reduced but not eliminated. We found it interesting that flight heights were similar between "partially on" and "on" conditions, whereas reaction distances were similar between "partially on" and "off" conditions. These results help to explain why the partially on category was less effective and not significantly different from the off category regarding daily collision count via our multivariate analysis. If noticed, the partially on ACAS may serve as a cognitive primer (Emery 2006) indicating the presence of a hazard to avian species in flight, thereby prompting an increase in flight height. However, the partially on ACAS likely failed to alert birds to the exact placement of all power lines, so it did not necessarily improve their reaction distance.

In addition to testing the effects of ACAS illumination, we tested the effects of several weather covariates on avian collisions. Inclement weather increases collision risk by reducing the visibility of power lines and changing flight behavior (Ward and Anderson 1992, APLIC 2012). We found that collisions were more likely to occur at moderate wind speeds (10–16 km/h) than at lower or higher wind speeds. The reduced probability of collisions at low wind speeds was likely related to the higher ability to maneuver at lower wind speeds, whereas the reduced risk of collisions at higher wind speeds was likely due to a decreased frequency of flights (Lishman et al. 1997). Brown et al. (1987) found that high winds impaired Sandhill Crane maneuverability and that a majority of mortalities occurred on days with high winds, fog, or precipitation. Kirsch et al. (2015) also found Sandhill Crane flight behavior was different (i.e., reduced flight distances and increased circling) during times of low visibility. However, Murphy et al. (2016*a*) found that weather conditions had no influence on rates of collisions. Interestingly, we found that collisions were less likely to occur when it was precipitating than when it was not. This finding is likely also attributable to Sandhill Cranes flying less frequently and shorter distances during precipitation (Kirsch et al. 2015). However, it could also be influenced by our observers not being able to see the entire length of the power line (i.e., reduced detection probability) during precipitation, particularly at night. This issue highlights a limitation of our study that could be corrected by using passive monitoring equipment such as sensors to detect collisions (Sporer et al. 2013, Suryan et al. 2016).

Time (in days) since peak migration was negatively correlated with the likelihood of collision because more avian collisions occurred when Sandhill Crane abundance was at its highest. Although abundance affected the sheer number of birds in the study area and thus increased the likelihood of collisions, we found that the number of birds in flocks did not significantly affect the number of collisions (i.e., large and small flocks were equally likely to collide), contradicting the findings of Murphy et al. (2016*a*). However, flock sizes did tend to be larger when two or more birds within a flock collided with the power line. One explanation for this observation is that collisions commonly involved birds in the middle or back of large flocks, where birds in the front of flocks may have obscured the visibility and perhaps maneuverability of trailing birds. Another possible explanation is that there tended to be Sandhill Cranes roosting closer to power lines (field crew, *personal observations*) during the peak of migration, which may have facilitated collisions. Anderson (1978) found that Mallard duck (*Anas platyrhynchos*) collisions occurred most frequently when birds were disturbed. Similarly, Murphy et al. (2016*a*) reported that most collisions occurred at night when ≥ 1000 Sandhill Cranes were flushed from the river.

Overall, most collisions observed during our study occurred at night and involved the shield wires (59.4%), presumably due to the small diameter and greater height relative to conductor wires, as well as the lower average flight height of flocks after dark (19 m above the water surface) vs. flight heights before civil twilight (25 m above the water surface), which increased the likelihood of low-flying birds hitting the top wire. This finding is similar to that of Morkill and Anderson (1991) wherein Whooping Cranes reacted more than expected to large transmission lines and less than expected to smaller, less visible distribution lines. However, it differed from the findings of Bernardino et al.'s (2018) systematic review of five studies reporting observed collisions, wherein 84% (175 of 208) of collisions involved shield wires. Although we observed more collisions with the shield wires, it was statistically similar to the rate at which birds struck conductor wires. This result may suggest that the FireFly markers placed on shield wires, which most studies indicate are struck more often, may have improved the relative visibility of those lines. It is possible that ACAS unit effectiveness is improved on marked lines, which highlights an important topic for future research. Although there was a strong tendency for birds to collide with shield wires in particular, there were no apparent patterns in the location on the wires where collisions occurred (i.e., midspan). This result indicates that the ACAS illuminated the entire length of power lines sufficiently to reduce collisions.

Several methods, including carcass searches and direct observation, have been used to quantify collisions with the crossings at Rowe. Wright et al. (2009) used carcass surveys, and after correcting for bias and differences in annual survey intensity, estimated 165–219 Sandhill Crane collisions occurred at the west and east crossings combined. Murphy et al. (2016*a,b*) documented 321 Sandhill Crane collisions during a 2009 study of the east crossing, indicating the bias correction that generally is used in carcass retrieval studies may not adequately capture the number of collisions that actually occur. Our study corroborates this finding, as we found that 47 of 64 birds (73.4%) were able to continue flying after collisions, suggesting that surveys likely underestimate the total number of collisions that actually occur.

Although numerous power lines within the central Platte River valley and throughout the world have been fitted with line markers, avian power line collisions still persist at high numbers because most occur nocturnally, when line markers are least visible (Erickson et al. 2001, Wright et al. 2009, Shaw et al. 2010, Murphy et al. 2016*a,b,* Dwyer et al. 2019, Johnsgard and Mangelsen 2020). Because collisions are still reported despite the presence of line markers, total line UV illumination could provide the necessary coverage to mitigate collisions and electrocutions resulting from midspan contact with two separate wires. UV illumination is a promising emerging conservation strategy for mitigating avian collisions with anthropogenic structures that may be feasible in other areas (Dwyer et al. 2019). UV light-based collision technologies such as the ACAS used in our study may be especially effective when placed on structures where collisions are likely to occur, such as at Rowe.

ACAS outperformed line markers alone in Dwyer et al.'s (2019) and our studies, but an important limitation in understanding ACAS is that neither Dwyer et al. (2019) nor our study tested the effectiveness of UV illumination on unmarked lines. It is possible that when combined with ACAS illumination, line markers increase the visibility of power lines and thus influenced the extent of behaviors and collisions observed. Future studies should compare marked and unmarked lines to determine how various types and positions of line markers influence the effectiveness of ACAS.

A complicating factor in our study was that one ACAS failed and was repaired with only half of the UV lights functioning but not focused properly on the power line, leading to the creation of a third treatment type: partially on. Although the focal ACAS being partially on did not have a statistically significant influence on collisions, models predicted that half the number of UV lights functioning resulted in the focal ACAS being nearly half as effective at reducing collisions as the on condition. Although our sample size for the partially on treatment was low (*N* = 9), differences between collisions based on the three treatment types provide useful information in that partial illumination may still be detectable by large-bodied birds. Given the costs and effort involved in deploying ACAS, and the potential population-level effects of collisions, it is important that ACASs are robust to field conditions and aimed precisely at the wires where they are needed.

In addition to logistical limitations, the potential benefits or effects of the ACAS on other fauna are unknown. Several studies document collisions of birds and bats with structures such as power lines, guy wires, communication towers, meteorological towers (Markus 1972, Banks 1979, Haas 1980, Ferrer and Hiraldo 1991, Janss 2000, Shire et al. 2000, Erickson et al. 2005, Wright et al. 2009, Gehring et al. 2011, Kerlinger et al. 2012, Longcore et al. 2012, Klem and Saenger 2013, Bernardino et al. 2018, Dwyer et al. 2019), and wind turbines (Hein and Schirmacher 2016, Katzner et al. 2016, Smith and Dwyer 2016). It is possible that other collision-prone species could benefit from ACAS illumination of dangerous structures. However, negative outcomes are also possible. For example, perhaps insects could be attracted to ACAS light and could in turn attract nocturnal aerial foragers who subsequently collide with the power line. Neither we nor Dwyer et al. (2019) observed this effect, but future research should continue to watch for unintended consequences. It is also possible that some animals avoid UV-illuminated areas, as speculated by Tyler et al. (2014). Although the steady, directed, and narrow-wavelength UV illumination of ACAS differs substantially from the unsteady, omni-directional, and wide-wavelength firework-like UV discharges associated with corona, the potential for similar reactions should be considered. We did not quantify avoidance, but we did observe qualitatively that Sandhill Cranes roosted and foraged along the Platte River normally during ACAS illumination. Quantitative assessment is needed in the future. If avoidance by any species is found, it will be important to evaluate whether collision reduction and increased survival of Sandhill Cranes and perhaps Whooping Cranes outweigh presumably short-term avoidance behavior associated with a few weeks of ACAS illumination. If side effects are found, they could perhaps be mitigated by using ACAS units when conditions associated with significant collision risk occur (e.g., high bird densities, wind speeds). Given the benefits of ACAS demonstrated here, we hypothesize that illuminating power lines, guy wires, towers, wind turbines, and other anthropogenic structures with the UV technologies deployed here may offer similar benefits for bats and birds by lowering the risk of collisions while increasing human acceptance of these structures in urban areas.

MANAGEMENT IMPLICATIONS

Our study provides support for Dwyer et al.'s (2019) finding that UV illumination can significantly reduce power line collisions on marked lines and expands upon their work by demonstrating that ACAS with less UV light output and smaller fields of projected light (i.e., range and width of view) can be highly effective at reducing collisions with power lines. In addition, we tested the effect of environmental variables on collisions and found that moderate wind speeds may increase power line collisions, likely because birds could maneuver better to avoid collisions at low winds speeds and because flight frequencies were reduced at high wind speeds. However, our results are likely reflective of the species assessed, and variable wind speed ranges may be associated with contrasting collision risks for different species. These findings could allow targeting the use of ACAS to periods of highest collision risk, reducing the potential for unintended effects of UV light on other wildlife. Furthermore, areas such as migratory stopover sites like the Platte River in central Nebraska, where collisions are appreciable for large-bodied avian species, including the endangered Whooping Crane, are likely to benefit from increased power line visibility provided by ACASs. For decades, Sandhill Cranes have been used as surrogates for Whooping Cranes (Ward and Anderson 1992). Although neither Dwyer et al.'s (2019), Pearse et al.'s (2019), nor our study documented Whooping Crane collisions, Stehn and Haralson-Strobel (2016) outline historic records of power line collisions involving this endangered species, especially during migration. The Aransas-Wood Buffalo population of Whooping Cranes has experienced near exponential growth in the past several decades, but further increases in annual survival through management actions such as installation of ACASs in high-risk areas may allow the population to reach recovery status more quickly (CWS and USFWS 2007, Pearse et al. 2019). Future applications of ACASs would benefit from additional study of unmarked power lines and should continue to be alert to potential effects of ACASs on wildlife populations other than the collision-prone species the ACAS is deployed to protect.

Responses to this article can be read online at:
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LITERATURE CITED

Acklen, J. C., J. F. Dwyer, K. Kowalski, and J. Goldberg. 2020. Can drones help prevent bird collisions? An unmanned aircraft system successfully deploys power line markers on electric T&D spans over open water to reduce bald eagle collision risks. Transmission and Distribution World 72:36-40. https://www.tdworld.com/overhead-distribution/article/21128547/can-drones-help-prevent-bird-collisions

Alonso, J. C., J. A. Alonso, and R. Muñoz-Pulido. 1994. Mitigation of bird collisions with transmission lines through groundwire marking. Biological Conservation 67(2):129-134. https://doi.org/10.1016/0006-3207(94)90358-1

Anderson, M. D. 2002. The effectiveness of two different marking devices to reduce large terrestrial bird collisions with overhead electricity cables in the eastern Karoo, South Africa. Karoo Large Terrestrial Bird Powerline Project Report 1. Eskom, Johannesburg, South Africa.

Anderson, W. L. 1978. Waterfowl collisions with power lines at a coal-fired power plant. Wildlife Society Bulletin 6(2):77-83. https://www.jstor.org/stable/3781293

Avian Power Line Interaction Committee (APLIC). 2012. Reducing avian collisions with power lines: the state of the art in 2012. Edison Electric Institute and APLIC, Washington, D.C., USA. https://www.aplic.org/uploads/files/15518/Reducing_Avian_Collisions_2012watermarkLR.pdf

Banks, R. C. 1979. Human related mortality of birds in the United States. Special Scientific Report—Wildlife 215. United States Department of the Interior, Fish and Wildlife Service, Washington, D.C., USA.

Barrientos, R., J. C. Alonso, C. Ponce, and C. Palacín. 2011. Meta-analysis of the effectiveness of marked wire in reducing avian collisions with power lines. Conservation Biology 25(5):893-903. https://doi.org/10.1111/j.1523-1739.2011.01699.x

Barrios, L., and A. Rodríguez. 2004. Behavioural and environmental correlates of soaring-bird mortality at on-shore wind turbines. Journal of Applied Ecology 41(1):72-81. https://doi.org/10.1111/j.1365-2664.2004.00876.x

Barton, K. 2020. MuMIn: multi-model inference. R package version 1.43.17. https://CRAN.R-project.org/package=MuMIn

Bernardino, J., K. Bevanger, R. Barrientos, J. F. Dwyer, A. T. Marques, R. C. Martins, J. M. Shaw, J. P. Silva, and F. Moreira. 2018. Bird collisions with power lines: state of the art and priority areas for research. Biological Conservation 222:1-13. https://doi.org/10.1016/j.biocon.2018.02.029

Bernardino, J., R. C. Martins, R. Bispo, and F. Moreira. 2019. Re-assessing the effectiveness of wire-marking to mitigate bird collisions with power lines: a meta-analysis and guidelines for field studies. Journal of Environmental Management 252:109651. https://doi.org/10.1016/j.jenvman.2019.109651

Bevanger, K., and H. Brøseth. 2001. Bird collisions with power lines — an experiment with ptarmigan (*Lagopus* spp.). Biological Conservation 99(3):341-346. https://doi.org/10.1016/S0006-3207(00)00217-2

Bowmaker, J. K., L. A. Heath, S. E. Wilkie, and D. M. Hunt. 1997. Visual pigments and oil droplets from six classes of photoreceptor in the retinas of birds. Vision Research 37(16):2183-2194. https://doi.org/10.1016/S0042-6989(97)00026-6

Brei, J., and A. A. Bishop. 2008. Platte River vegetation mapping project: 2005 land cover methods summary. Headwaters Corporation, Platte River Recovery Implementation Program, Kearney, Nebraska, USA. https://www.rwbjv.org/wp-content/uploads/Platte-River-2005-Land-Cover-Methods.pdf

Brockbank, R. A. 2015. Environmental effects of underground and overhead transmission line construction and maintenance. Pages 37-69 *in* G. J. Doucet, editor. Proceedings of the 11th international symposium on environmental concerns in rights-of-way management. Utility Arborist Association, Forest Lake, Minnesota, USA. https://www.cclmportal.ca/resource/environmental-concerns-right-way-management-11th-international-symposium-proceedings

Brown, W. M., R. C. Drewien, and E. G. Bizeau. 1987. Mortality of cranes and waterfowl from powerline collisions in the San Luis Valley, Colorado. Pages 128-136 *in* J. C. Lewis, editor. Proceedings of the 4th North American crane workshop. Platte River Whooping Crane Habitat Maintenance Trust, Grand Island, Nebraska, and United States Fish and Wildlife Service, Washington, D.C., USA. http://www.nacwg.org/proceedings4.html

Burnham, K. P., and D. R. Anderson. 2002. Model selection and multimodel inference: a practical information-theoretic approach. Second edition. Springer, New York, New York, USA. https://doi.org/10.1007/b97636

Burnham, K. P., D. R. Anderson, and K. P. Huyvaert. 2011. AIC model selection and multimodel inference in behavioral ecology: some background, observations, and comparisons. Behavioral Ecology and Sociobiology 65:23-35. https://doi.org/10.1007/s00265-010-1029-6

Canadian Wildlife Service and U.S. Fish and Wildlife Service (CWS and USFWS). 2007. International recovery plan for the whooping crane (*Grus americana*). Third revision. Recovery of Nationally Endangered Wildlife (RENEW), Ottawa, Canada, and U.S. Fish and Wildlife Service, Albuquerque, New Mexico, USA. https://www.nrc.gov/docs/ML1118/ML111880004.pdf

Caven, A. J., E. M. Brinley Buckley, K. C. King, J. D. Wiese, D. M. Baasch, G. D. Wright, M. J. Harner, A. T. Pearse, M. Rabbe, D. M. Varner, B. Krohn, N. Arcilla, K. D. Schroeder, and K. F. Dinan. 2020*a.* Temporospatial shifts in Sandhill Crane staging in the Central Platte River valley in response to climatic variation and habitat change. Monographs of the Western North American Naturalist 11(1):33-76. https://doi.org/10.3398/042.011.0104

Caven, A. J., D. M. Varner, and J. Drahota. 2020*b.* Sandhill Crane abundance in Nebraska during spring migration: making sense of multiple data points. Transactions of the Nebraska Academy of Sciences and Affiliated Societies 40:6-18. https://doi.org/10.32873/unl.dc.tnas.40.2

Cooper, B. A., and R. H. Day. 1998. Summer behavior and mortality of Dark-rumped Petrels and Newell's Shearwaters at power lines on Kauai. Colonial Waterbirds 21(1):11-19. https://doi.org/10.2307/1521726

Coues, E. 1876. The destruction of birds by telegraph wire. American Naturalist 10(12):734-736. https://doi.org/10.1086/271788

Cuthill, I. C., J. C. Partridge, A. T. D. Bennett, S. C. Church, N. S. Hart, and S. Hunt. 2000. Ultraviolet vision in birds. Advances in the Study of Behavior 29:159-214. https://doi.org/10.1016/S0065-3454(08)60105-9

D'Amico, M., I. Catry, R. C. Martins, F. Ascensão, R. Barrientos, and F. Moreira. 2018. Bird on the wire: landscape planning considering costs and benefits for bird populations coexisting with power lines. Ambio 47:650-656. https://doi.org/10.1007/s13280-018-1025-z

Dashnyam, B., T. Purevsuren, S. Amarsaikhan, D. Bataa, B. Buuveibaatar, and G. Dutson. 2016. Malfunction rates of bird flight diverters on powerlines in the Mongolian Gobi. Mongolian Journal of Biological Sciences 14(1-2):13-20. https://www.biotaxa.org/mjbs/article/view/27055

De La Zerda, S. 2012. Testing the effectiveness of a Colombian-designed bird flight diverter to mitigate collisions with transmission lines. Pages 209-220 *in* J. M. Evans, J. W. Goodrich-Mahoney, D. Mutrie, and J. Reinemann, editors. Proceedings of the 9th international symposium on environmental concerns in rights-of-way management. International Society of Arboriculture, Atlanta, Georgia, USA.

Dinno, A. 2015. Nonparametric pairwise multiple comparisons in independent groups using Dunn's test. Stata Journal 15 (1):292-300. https://doi.org/10.1177/1536867X1501500117

Dormann, C. F., J. Elith, S. Bacher, C. Buchmann, G. Carl, G. Carré, J. R. García Marquéz, B. Gruber, B. Lafourcade, P. J. Leitão, T. Münkemüller, C. McClean, P. E. Osborne, B. Reineking, B. Schröder, A. K. Skidmore, D. Zurell, and S. Lautenbach. 2013. Collinearity: a review of methods to deal with it and a simulation study evaluating their performance. Ecography 36(1):27-46. https://doi.org/10.1111/j.1600-0587.2012.07348.x

Dwyer, J. F., A. K. Pandey, L. A. McHale, and R. E. Harness. 2019. Near-ultraviolet light reduced Sandhill Crane collisions with a power line by 98%. Condor 121(2):duz008. https://doi.org/10.1093/condor/duz008

Emery, N. J. 2006. Cognitive ornithology: the evolution of avian intelligence. Philosophical Transactions of the Royal Society B 361(1465):23-43. https://doi.org/10.1098/rstb.2005.1736

Erickson, W. P., G. D. Johnson, M. D. Strickland, D. P. Young Jr., K. J. Sernka, and R. E. Good. 2001. Avian collisions with wind turbines: a summary of existing studies and comparisons to other sources of avian collision mortality in the United States. Technical Report. National Wind Coordinating Committee, Washington, D.C., USA. https://doi.org/10.2172/822418

Erickson, W. P., G. D. Johnson, and D. P. Young Jr. 2005. A summary and comparison of bird mortality from anthropogenic causes with an emphasis on collisions. Pages 1029-1042 *in* C. J. Ralph and T. D. Rich, editors. Bird conservation implementation and integration in the Americas: proceedings of the third international partners in flight conference. General Technical Report PSW-GTR-191. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, California, USA. https://doi.org/10.2737/PSW-GTR-191

Faanes, C. A. 1987. Bird behavior and mortality in relation to power lines in prairie habitats. Technical Report 7. U.S. Fish and Wildlife Service, Washington, D.C., USA. https://pubs.er.usgs.gov/publication/2000102

Faanes, C. A., and D. H. Johnson. 1992. Cranes and powerlines: an analysis of the issue. Pages 197-202 *in* D. A. Wood, editor. Proceedings 1988 North American crane workshop. Technical Report 12. State of Florida Game and Fresh Water Fish Commission Nongame Wildlife Program, Tallahassee, Florida, USA. http://digitalcommons.unl.edu/nacwgproc/301

Fehlhafer, D., and B. Peterson. 2018. Implementation of the Whooping Crane monitoring protocol: 2018 spring – final report. Ecological Solutions, Doniphan, Nebraska, USA. https://platteriverprogram.org/sites/default/files/2019-05/Implementation%20of%20
the%20Whooping%20Crane%20Monitoring%20Protocol%20-%20Spring%202018.pdf

Fernandez-Jimenez, L. A., M. Mendoza-Villena, E. Garcia-Garrido, P. M. Lara-Santillan, P. J. Zorzano-Santamaria, E. Zorzano-Alba, and A. Falces. 2017. High voltage overhead power line routing under an objective observability criterion. Energies 10(10):1576. https://doi.org/10.3390/en10101576

Ferrer, M., and F. Hiraldo. 1991. Evaluation of management techniques for the Spanish Imperial Eagle. Wildlife Society Bulletin 19(4):436-442. https://www.jstor.org/stable/3782155

Ferrer, M., V. Morandini, R. Baumbusch, R. Muriel, M. De Lucas, and C. Calabuig. 2020. Efficacy of different types of "bird flight diverter” in reducing bird mortality due to collision with transmission power lines. Global Ecology and Conservation 23: e01130. https://doi.org/10.1016/j.gecco.2020.e01130

Fox, J. 2003. Effect displays in R for generalised linear models. Journal of Statistical Software 8(15):1-27. https://doi.org/10.18637/jss.v008.i15

Fox, J., and S. Weisberg. 2019. An R companion to applied regression. Third edition. Sage, Thousand Oaks, California, USA. https://socialsciences.mcmaster.ca/jfox/Books/Companion/

Garcês, A., F. Queiroga, J. Prada, and I. Pires. 2020. A review of the mortality of wild fauna in Europe in the last century: the consequences of human activity. Journal of Wildlife and Biodiversity 4(2):34-55. https://doi.org/10.22120/jwb.2019.116495.1102

Gehring, J., P. Kerlinger, and A. M. Manville II. 2011. The role of tower height and guy wires on avian collisions with communication towers. Journal of Wildlife Management 75 (4):848-855. https://doi.org/10.1002/jwmg.99

Gerber, B. D., J. F. Dwyer, S. A. Nesbitt, R. C. Drewien, C. D. Littlefield, T. C. Tacha, and P. A. Vohs. 2020. Sandhill Crane (*Antigone canadensis*). Version 1.0. *In* A. F. Poole, editor. Birds of the world. Cornell Lab of Ornithology, Ithaca, New York, USA. https://doi.org/10.2173/bow.sancra.01

Gill, F. B., and R. O. Prum. 2019. Ornithology. Fourth edition. W. H. Freeman, New York, New York, USA.

Goller, B., B. F. Blackwell, T. L. DeVault, P. E. Baumhardt, and E. Fernández-Juricic. 2018. Assessing bird avoidance of high-contrast lights using a choice test approach: implications for reducing human-induced avian mortality. PeerJ 6:e5404. https://doi.org/10.7717/peerj.5404

Haas, D. 1980. Endangerment of our large birds by electrocution —a documentation. Okölogie der Vögel 2:7-57.

Hager, S. B., B. J. Cosentino, M. A. Aguilar-Gómez, M. L. Anderson, M. Bakermans, T. J. Boves, D. Brandes, M. W. Butler, E. M. Butler, N. L. Cagle, R. Calderón-Parra, A. P. Capparella, A. Chen, K. Cipollini, A. A. T. Conkey, T. A. Contreras, R. I. Cooper, C. E. Corbin, R. L. Curry, J. J. Dosch, M. G. Drew, K. Dyson, C. Foster, C. D. Francis, E. Fraser, R. Furbush, N. D. G. Hagemeyer, K. N. Hopfensperger, D. Klem Jr., E. Lago, A. Lahey, K. Lamp, G. Lewis, S. R. Loss, C. S. Machtans, J. Madosky, T. J. Maness, K. J. McKay, S. B. Menke, K. E. Muma, N. Ocampo-Peñuela, T. J. O’Connell, R. Ortega-Álvarez, A. L. Pitt, A. L. Puga-Caballero, J. E. Quinn, C. W. Varian-Ramos, C. S. Riding, A. M. Roth, P. G. Saenger, R. T. Schmitz, J. Schnurr, M. Simmons, A. D. Smith, D. R. Sokoloski, J. Vigliotti, E. L. Walters, L. A. Walters, J. T. Weir, K. Winnett-Murray, J. C. Withey, and I. Zuria. 2017. Continent-wide analysis of how urbanization affects bird-window collision mortality in North America. Biological Conservation 212(A):209-215. https://doi.org/10.1016/j.biocon.2017.06.014

Hall, K. L. 2009. Out of sight, out of mind revisited: an updated study on the undergrounding of overhead power lines. Hall Energy Consulting report. Edison Electric Institute, Washington, D.C., USA.

Harness, R. E., E. K. Mojica, J. F. Dwyer, and M. A. Landon. 2016. Power line collision mitigation and avian vision. Electric Power Research Institute, Palo Alto, California, USA.

Hart, N. S., and D. M. Hunt. 2007. Avian visual pigments: characteristics, spectral tuning, and evolution. American Naturalist 169(S1):S7-S27. https://doi.org/10.1086/510141

Harville, D. A. 1974. Bayesian inference for variance components using only error contrasts. Biometrika 61(2):383-385. https://doi.org/10.1093/biomet/61.2.383

Hein, C. D., and M. R. Schirmacher. 2016. Impact of wind energy on bats: a summary of our current knowledge. Human-Wildlife Interactions 10(1):4. https://doi.org/10.26077/x7ew-6349

Hurst, N. 2004. Corona testing of devices used to mitigate bird collisions. PIER final project report 500-04-086F for California Energy Commission. EDM International, Fort Collins, Colorado, USA. https://meridian.allenpress.com/jfwm/article-supplement/209662/pdf/052016-jfwm-037_s4/

Jackman, S. 2020. pscl: classes and methods for R developed in the political science computational laboratory. United States Studies Centre, University of Sydney, Sydney, Australia. R package version 1.5.5. https://github.com/atahk/pscl/

Jacobs, G. H. 1992. Ultraviolet vision in vertebrates. American Zoologist 32(4):544-554. https://doi.org/10.1093/icb/32.4.544

Janss, G. F. E. 2000. Avian mortality from power lines: a morphologic approach of a species-specific mortality. Biological Conservation 95(3):353-359. https://doi.org/10.1016/S0006-3207(00)00021-5

Johnsgard, P. A. 1983. Cranes of the World. Indiana University Press, Bloomington, Indiana, USA.

Johnsgard, P. A., and T. D. Mangelsen. 2020. The lives, lore, and literature of cranes: a catechism for crane lovers. Zea E-Books, Lincoln, Nebraska, USA. https://doi.org/10.32873/unl.dc.zea.1103

Katzner, T., V. Bennett, T. Miller, A. Duerr, M. Braham, and A. Hale. 2016. Wind energy development: methods for assessing risks to birds and bats pre-construction. Human-Wildlife Interactions 10(1):6. https://doi.org/10.26077/phxc-zh11

Kerlinger, P., J. Guarnaccia, A. Hasch, R. C. E. Culver, R. C. Curry, L. Tran, M. J. Stewart, and D. Riser-Espinoza. 2012. Avian collision mortality at 50- and 60-m guyed towers in central California. Condor 114(3):462-469. https://doi.org/10.1525/cond.2012.110157

Kirsch, E. M., M. J. Wellik, M. Suarez, R. H. Diehl, J. Lutes, W. Woyczik, J. Krapfl, and R. Sojda. 2015. Observation of sandhill cranes’ (*Grus canadensis*) flight behavior in heavy fog. Wilson Journal of Ornithology 127(2):281-288. https://doi.org/10.1676/wils-127-02-281-288.1

Kleiber, C., and A. Zeileis. 2008. Applied econometrics with R. Springer, New York, New York, USA. https://doi.org/10.1007/978-0-387-77318-6

Klem, D. Jr. 2009. Preventing bird–window collisions. Wilson Journal of Ornithology 121(2):314-321. https://doi.org/10.1676/08-118.1

Klem, D., and P. G. Saenger. 2013. Evaluating the effectiveness of select visual signals to prevent bird–window collisions. Wilson Journal of Ornithology 125(2):406-411. https://doi.org/10.1676/12-106.1

Kosciuch, K., D. Riser-Espinoza, M. Gerringer, and W. Erickson. 2020. A summary of bird mortality at photovoltaic utility scale solar facilities in the Southwestern U.S. Plos One 15(4):e0232034. https://doi.org/10.1371/journal.pone.0232034

Lishman, W. A., T. L. Teets, J. W. Duff, W. J. L. Sladen, G. G. Shire, K. M. Goolsby, W. A. Bezner Kerr, and R. Urbanek. 1997. A reintroduction technique for migratory birds: leading Canada geese and isolation-reared sandhill cranes with ultralight aircraft. Pages 96-104 *in* Proceedings of the seventh North American crane workshop. North American Crane Working Group, Grand Island, Nebraska, USA. https://digitalcommons.unl.edu/nacwgproc/221/

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. https://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. https://doi.org/10.1016/j.biocon.2012.09.019

Loss, S. R. 2016. Avian interactions with energy infrastructure in the context of other anthropogenic threats. Condor 118 (2):424-432. https://doi.org/10.1650/CONDOR-16-12.1

Loss, S. R., T. Will, and P. P. Marra. 2015. Direct mortality of birds from anthropogenic causes. Annual Review of Ecology, Evolution, and Systematics 46:99-120. https://doi.org/10.1146/annurev-ecolsys-112414-054133

Mangiafico, S. S. 2015. An R companion for the handbook of biological statistics. Version 1.3.2. Rutgers Cooperative Extension, New Brunswick, New Jersey, USA. https://rcompanion.org/rcompanion/

Markus, M. B. 1972. Mortality of vultures caused by electrocution. Nature 238:228. https://doi.org/10.1038/238228b0

May, R., J. Åström, Ø. Hamre, and E. L. Dahl. 2017. Do birds in flight respond to (ultra)violet lighting? Avian Research 8:33. https://doi.org/10.1186/s40657-017-0092-3

McDonald, J. H. 2009. Handbook of biological statistics. Sparky House Publishing, Baltimore, Maryland, USA.

Moritz, S., and T. Bartz-Beielstein. 2017. imputeTS: time series missing value imputation in R. R Journal 9(1):207-218. https://doi.org/10.32614/RJ-2017-009

Morkill, A. E., and S. H. Anderson. 1991. Effectiveness of marking powerlines to reduce sandhill crane collisions. Wildlife Society Bulletin 19(4):442-449. https://www.jstor.org/stable/3782156

Murphy, R. K., J. F. Dwyer, E. K. Mojica, M. M. McPherron, and R. E. Harness. 2016*a*. Reactions of sandhill cranes approaching a marked transmission power line. Journal of Fish and Wildlife Management 7:480-489. https://doi.org/10.3996/052016-JFWM-037

Murphy, R. K., E. K. Mojica, J. F. Dwyer, M. M. McPherron, G. D. Wright, R. E. Harness, A. K. Pandey, and K. L. Serbousek. 2016*b*. Crippling and nocturnal biases in a study of sandhill crane (*Grus canadensis*) collisions with a transmission line. Waterbirds 39(3):312-317. https://doi.org/10.1675/063.039.0312

Nagel, H. G., and O. A. Kolstad. 1987. Comparison of plant species composition of Mormon Island Crane Meadows and Lillian Annette Rowe Sanctuary in central Nebraska. Transactions of the Nebraska Academy of Sciences 15:37-48. https://digitalcommons.unl.edu/tnas/201/

Nelder, J. A., and R. J. Baker. 1972. Generalized linear models. *In* Encyclopedia of statistical sciences. Wiley, Hoboken, New Jersey, USA.

Ödeen, A., and O. Håstad. 2013. The phylogenetic distribution of ultraviolet sensitivity in birds. BMC Evolutionary Biology 13:36. https://doi.org/10.1186/1471-2148-13-36

Pearse, A. T., D. A. Brandt, B. K. Hartup, and M. T. Bidwell. 2019. Mortality in Aransas-Wood Buffalo whooping cranes: timing, location, and causes. Pages 125-138 *in* P. J. Nyhus, J. B. French Jr., S. J. Converse, J. E. Austin, and J. H. Delap, editors. Whooping cranes: biology and conservation. Academic Press, Cambridge, Massachusetts, USA. https://doi.org/10.1016/B978-0-12-803555-9.00006-2

R Core Team. 2019. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/

Raab, R., C. Schütz, P. Spakovszky, E. Julius, and C. H. Schulze. 2012. Underground cabling and marking of power lines: conservation measures rapidly reduced mortality of West-Pannonian Great Bustards *Otis tarda.* Bird Conservation International 22(3):299-306. https://doi.org/10.1017/S0959270911000463

Ranglack, D. H., K. M. Proffitt, J. E. Canfield, J. A. Gude, J. Rotella, and R. A. Garrott. 2017. Security areas for elk during archery and rifle hunting seasons. Journal of Wildlife Management 81(5):778-791. https://doi.org/10.1002/jwmg.21258

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(2):7. https://doi.org/10.5751/ACE-00614-080207

Rogers, A. M., M. R. Gibson, T. Pockette, J. L. Alexander, and J. F. Dwyer. 2014. Scavenging of migratory bird carcasses in the Sonoran Desert. Southwestern Naturalist 59(4):544-549. https://doi.org/10.1894/MCG-08.1

Shaw, J. M., A. R. Jenkins, J. J. Smallie, and P. G. Ryan. 2010. Modelling power-line collision risk for the Blue Crane *Anthropoides paradiseua* in South Africa. Ibis 152(3):590-599. https://doi.org/10.1111/j.1474-919X.2010.01039.x

Shire, G. G., K. Brown, and G. Winegrad. 2000. Communication towers: a deadly hazard to birds. American Bird Conservancy, Washington, D.C., USA. https://abcbirds.org/wp-content/uploads/2015/05/towerkillweb.pdf

Smith, J. A., and J. F. Dwyer. 2016. Avian interactions with renewable energy infrastructure: an update. Condor 118 (2):411-423. https://doi.org/10.1650/CONDOR-15-61.1

Sporer, M. K., J. F. Dwyer, B. D. Gerber, R. E. Harness, and A. K. Pandey. 2013. Marking power lines to reduce avian collisions near the Audubon National Wildlife Refuge, North Dakota. Wildlife Society Bulletin 37(4):796-804. https://doi.org/10.1002/wsb.329

Stehn, T. V., and C. L. Haralson-Strobel. 2016. An update on mortality of fledged whooping cranes in the Aransas/Wood Buffalo population. Pages 43-50 *in* D. A. Aborn and R. Urbanek, editors. Proceedings of the twelfth North American crane workshop. North American Crane Working Group, Grand Island, Nebraska, USA. https://digitalcommons.unl.edu/nacwgproc/372/

Strom, K. J. 1987. Lillian Annette Rowe Sanctuary on the Platte River. Pages 328-330 *in* J. C. Lewis, editor. Proceedings of the 4th North American crane workshop. Platte River Whooping Crane Habitat Maintenance Trust, Grand Island, Nebraska, and United States Fish and Wildlife Service, Washington, D.C., USA. http://www.nacwg.org/proceedings4.html

Suryan, R., R. Albertani, and B. Polagye. 2016. A synchronized sensor array for remote monitoring of avian and bat interactions with offshore renewable energy facilities. Final report DOE-OSU-EE0005363. Oregon State University, Corvallis, Oregon, USA. https://doi.org/10.2172/1323469

Swaddle, J. P., L. C. Emerson, R. G. Thady, and T. J. Boycott. 2020. Ultraviolet-reflective film applied to windows reduces the likelihood of collisions for two species of songbird. PeerJ 8:e9926. https://doi.org/10.7717/peerj.9926

Tacha, T. C. 1988. Social organization of Sandhill Cranes from midcontinental North America. Wildlife Monographs 99:3-37. https://www.jstor.org/stable/3830635

Toomey, M. B., O. Lind, R. Frederiksen, R. W. Curley Jr., K. M. Riedl, D. Wilby, S. J. Schwartz, C. C. Witt, E. H. Harrison, N. W. Roberts, M. Vorobyev, K. J. McGraw, M. C. Cornwall, A. Kelber, and J. C. Corbo. 2016. Complementary shifts in photoreceptor spectral tuning unlock the full adaptive potential of ultraviolet vision in birds. eLife 5:e15675. https://doi.org/10.7554/eLife.15675

Travers, M. S., S. Driskill, A. Stemen, T. Geelhoed, D. M. Golden, S. Koike, A. A. Shipley, H. E. Moon, T. Anderson, M. Bache, and A. F. Raine. 2021. Post-collision impacts, crippling bias, and environmental bias in a study of Newell's Shearwater and Hawaiian Petrel powerline collisions. Avian Conservation and Ecology 16(1):15. https://doi.org/10.5751/ACE-01841-160115

Tyler, N., K.-A. Stokkan, C. Hogg, C. Nellemann, A.-I. Vistnes, and G. Jeffery. 2014. Ultraviolet vision and avoidance of power lines in birds and mammals. Conservation Biology 28(3):630-631. https://doi.org/10.1111/cobi.12262

Urbanek, R. P., and J. C. Lewis. 2020. Whooping Crane (*Grus americana*). Version 1.0. *In* A. F. Poole, editor. Birds of the world. Cornell Lab of Ornithology, Ithaca, New York, USA. https://doi.org/10.2173/bow.whocra.01

Venables, W. N., and B. D. Ripley. 2002. Modern applied statistics with S. Fourth edition. Springer, New York, New York, USA. https://doi.org/10.1007/978-0-387-21706-2

Vuong, Q. H. 1989. Likelihood ratio tests for model selection and non-nested hypotheses. Econometrica 57(2):307-333. https://doi.org/10.2307/1912557

Wagenmakers, E. J., and S. Farrell. 2004. AIC model selection using Akaike weights. Psychonomic Bulletin and Review 11:192-196. https://doi.org/10.3758/BF03206482

Ward, J. P., and S. H. Anderson. 1992. Sandhill Crane collisions with power lines in southcentral Nebraska. Pages 189-196 *in* D. A. Wood, editor. Proceedings of the 1988 North American crane workshop. State of Florida Game and Fresh Water Fish Commission,Tallahassee, Florida, USA. https://digitalcommons.unl.edu/nacwgproc/327

Wickham, H. 2016. ggplot2: elegant graphics for data analysis. Second edition. Springer, New York, New York, USA.

Wright, G. D., T. J. Smith, R. K. Murphy, J. T. Runge, and R. R. Harms. 2009. Mortality of cranes (Gruidae) associated with powerlines over a major roost on the Platte River, Nebraska. Prairie Naturalist 41(3-4):116-120. https://digitalcommons.unl.edu/tpn/209/

Yee, M. L. 2008. Testing the effectiveness of an avian flight diverter for reducing avian collisions with distribution power lines in the Sacramento Valley, California. PIER final report for California Energy Commission. Public Interest Energy Research, Sacramento, California, USA. https://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/california_waterfix/exhibits/docs/SOSC/sosc_59.pdf

Zar, J. H. 2010. Biostatistical analysis. Fifth edition. Pearson Prentice Hall, Upper Saddle River, New Jersey, USA.

Zeileis, A., C. Kleiber, and S. Jackman. 2008. Regression models for count data in R. Journal of Statistical Software 27(8):1-25. https://doi.org/10.18637/jss.v027.i08

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Appendix 1. Selection table for detection models used to predict the number of observations recorded per survey period. This represented the first stage of our two-tier model selection process and was intended to determine which variables most influenced detection probability. Model covariates included Sandhill Crane migration related variables derived from weekly aerial surveys (see Caven et al. 2019 for methods) of the Central Platte River Valley such as the number of days from the peak of migration that observations were made (Days to Peak), daily Sandhill Crane abundance estimated using Kalman smoothing (SACR-Kalman) and linear (SACR-Linear) missing value imputation as well as date-related variables (day of calendar year – Date and the quadratic transformation of day of year – Date (quadratic)), flow (river flow via USGS gage station 06770200, Kearney, NE), and observer (Obs.). All models outperforming the null model are presented in this table. Models were ranked via Akaike Information Criterion corrected for small sample sizes (AICc) and are presented with coefficient estimates and significance levels (***$p < 0.001$, **$p < 0.01$, *$p < 0.05$, ^$p < 0.10$) for individual covariates, as well as model degrees of freedom (df), log-likelihood (Log Lik.), AICc, ΔAICc, and model weight (Wt.). Covariates in models outperforming the null model with ΔAIC < 2.0 and a model weight > 0.10 included Days to Peak, Flow, and Date (quadratic) and were advanced to the second tier of model selection.

Model†	**Days to Peak**	**SACR-Kalman**	**SACR-Linear**	**Date**	**Date (quadratic)**	**Flow**	**Obs.**	**df**	**Log Lik.**	**AICc**	**ΔAICc**	**Wt.**
Mig. & Flow	-0.03806***					-0.01530**		4	-402.5	813.5	0.000	0.433
Date & Flow					+***	-0.01243**		5	-401.4	813.6	0.100	0.413
Date					+***			4	-404.3	817.1	3.640	0.070
Mig. & Flow			9.88E-07**			-0.01306**		4	-405.1	818.7	5.200	0.032
Mig.	-0.03035**							3	-406.5	819.3	5.820	0.024
Mig. & Flow		7.37E-07*				-0.01259*		4	-406.3	821.0	7.550	0.010
Mig.			8.06E-07*					3	-408.0	822.3	8.800	0.005
Date & Flow				0.01002*		-0.00972$^{\wedge}$		4	-407.6	823.7	10.190	0.003
Mig.		5.77E-07*						3	-408.9	824.1	10.590	0.002
Obs.							+**	8	-403.1	824.2	10.750	0.002
Date				0.00915$^{\wedge}$				3	-409.3	824.9	11.400	0.001
Flow						-0.00894$^{\wedge}$		3	-409.3	824.9	11.420	0.001
Null								2	-410.7	825.6	12.060	0.001

† "Mig." = "Migration" or migration related variables derived weekly from aerial surveys conducted by the Crane Trust. "Flow" indicates the flow recorded at the nearest USGS gaging station near Kearney, Nebraska USA (06770200). "Date" indicates variables related to the day of year. "Obs." indicates observers performing surveys.

Appendix 2. Names and descriptions of variables included in analyses along with the scale of investigation at which it was employed (Per Observation or Per Survey) and the tier and stage of analysis it was used in including Bivariate post-hoc test or Stages I and II of the first tier or tier two of the negative binomial generalized linear model development and comparison process using Akaike Information Criterion.

		Scale Used		**Analyses Included**	**Tier 1**		
Name	**Description**	**Per Observation**	**Per Survey**	**Bivariate**	**Stage I**	**Stage II**	**Tier 2**
Collision Count	Count of birds observed colliding with the power line on a per observation or per survey period basis.	X	X	X		X	X
Fog Occurrence	The proportion of observations per survey period in which fog reduced visibility to <800 m.		X			X	
Maximum Wind Speed	Maximum wind speed for the survey period measured via a permanent onsite weather station at Rowe Sanctuary.		X			X	
Mean Wind Speed	Mean wind speed for the survey period measured via a permanent onsite weather station at Rowe Sanctuary.		X			X	X
Precipitation Occurrence	The proportion of observations per survey period in which precipitation occurred.		X			X	X
Flow	Mean river discharge or colloquially "flow" from the United States Geological Survey gage station near Kearney, NE (USGS 06770200).		X		X		X
Julian Date	Day of year in which each survey period began.		X		X		X
Distal ACAS	Operational status of the ACAS on the power line located 2 km away as ON, Partially On (50% of light boxes functional on west span), or OFF.	X	X	X			X
Focal ACAS	Operational status of the ACAS on the power line being monitored as ON, Partially On (50% of light boxes functional on west span), or OFF.	X	X	X			X
% Cloud Cover	Percent of the sky that was obscured by cloud cover on a per observation basis.	X				X	
% Humidity	Average percent humidity for the survey period via a permanent onsite weather station at Rowe Sanctuary.		X			X	
% Moon	Percent of the moon that was illuminated (i.e., mathematic expression of moon phase) during each survey period.		X			X	
Moon Visibility	The proportion of observations per survey period in which the moon was visible.		X			X	
Temperature	Mean temperature, in Celsius, for the survey period via a permanent onsite weather station at Rowe Sanctuary.		X			X	
Optical Method	Method for observing passing flocks and recorded collisions including Binoculars, Armasight thermal imaging monocular, FLIR thermal imaging monocular, or the naked eye during daylight.		X		X^*		
Days from Peak	Absolute value of the number of days from the peak of migration that observations were made estimated using Crane Trust aerial surveys. Project description from *Caven et al. 2020. Transactions of the Nebraska Academy of Sciences 40:6-18*.		X		X		
Observation	Number of flocks separated by ≥100 m approaching or flying over the power line during each survey period.		X		X		
Observer	Primary person observing the power line for avian interactions.		X		X		

(con'd)

Sandhill Crane - Kalman	Estimated Sandhill Crane abundance during each survey period based on weekly aerial surveys completed by the Crane Trust and using Kalman smoothing imputation to estimate missing daily values. Project description from *Caven et al. 2020. Transactions of the Nebraska Academy of Sciences 40:6-18*.		X		X
Sandhill Crane - Linear	Estimated Sandhill Crane abundance during each survey period based on weekly aerial surveys completed by the Crane Trust and using linear imputation to estimate missing daily values. Project description from *Caven et al. 2020. Transactions of the Nebraska Academy of Sciences 40:6-18.*		X		X
Collision Occurrence	Observation of a collision within a passing flock during an observation period or the entire survey period.	X	X	X	
Day or Night	Indication of whether observations were made before (Day) or after (Night) civil twilight.	X		X	
Flight Height	Approach height at 50 m lateral distance from the power line estimated in the field by observers using structure heights as a guide. Overhead shield/Top wires ≈ 15 m above ground level and Conductor/Bottom wires ≈10 m above ground level.	X		X	
Flock Count	Estimated number of birds in each flock observed passing the studied power lines. We defined flock as all individuals of the same species within 100 m of each other.	X		X	
Midspan	Visual estimate of the location of the center of the flock expressed as the percentage of the way across the span of river from the ACAS unit to the opposite edge of the channel. 0% = at the H-frame where the ACAS unit was placed; 100% = opposite bank line from the ACAS unit.	X		X	
Power Line	Whether an individual collision or observation occurred at the East or West power line crossing.	X		X	
Reaction Distance	Distance in meters perpendicular to the span at which a reaction to the wire occurred or "0" if no reaction occurred.	X		X	
Reaction Type	Classification of the riskiest reaction of at least one member of the flock to the focal power line as "No Reaction Between" (maintained the same direction, speed, and elevation above the river level before and after approaching the power line and passed between the power lines within 10-15 m of the river surface), "No Reaction Below" (maintained the same direction, speed, and elevation above the river level before and after approaching the power line and passed within 10 m of the river surface), "Flare" (altered direction, speed, and wingbeat to suddenly gain the elevation needed to pass over the power line within 15-25 m of the river surface), "Low Risk Flare" (altered direction, speed, and wingbeat to suddenly gain the elevation needed to pass over the power line within 26-35 m of the river surface), "Climb" (maintained consistent flight direction, speed, and wingbeat, but adjusted flight height gradually to pass over the power line 15-25 m above the river surface), "Low Risk Climb" (maintained consistent flight direction, speed, and wingbeat, but adjusted flight height gradually to pass over the power line 26-35 m above the river surface), or classification of the entire flock's behavior as "No Reaction Above" (maintained the same direction, speed, and elevation above the river level before and after approaching the power line and passed within 15-25 m of the river surface), and "No Risk" (maintained the same direction, speed, and elevation above the river level before and after approaching the power line and passed within 26-35 m of the river surface).	X		X	

(con'd)

Risk Category	Risk of collision resulting from various flight behaviors based on published literature and expert opinion. Categories included "No Risk", "Low Risk", "Moderate Risk", "High Risk", and "Collision Observed". Please see Table 1 for descriptive details.	X	X
Species Observed	The species comprising each flock observed passing the power line within the study area.	X	
Time Since Sunset	The number of minutes before or after sunset that an observation was made.	X	X
Wire Type	In cases of collision, which wire (East shield wire, West shield wire, East conductor, Center conductor, West conductor) or the type of wire (Shield vs. Conductor) that was struck.	X	X

*Variable included in the analysis via poorly performing models and therefore was not explicitly reported in the model selection table.

Appendix 3. Selection table for environmental models used to predict the number of power line collisions recorded per survey period. This represented the second stage of the first tier of model selection and was intended to determine the environmental variables that most influenced collision probability. Model covariates included mean wind speed (Mean Wind) and its quadratic transformation (Mean Wind (quadratic)) and the quadratic of max observed windspeed (max Wind (quadratic), percent cloud cover (% Clouds), whether the moon was visible to the observer (Moon visibility), the daily percent moon fullness (% Moon), the presence of fog (Fog), whether or not precipitation occurred (Precipitation), ambient air temperature (Temperature), and percent humidity (Relative Humidity). Additional models were examined, but only those that outperformed the null are presented. Models were ranked via Akaike Information Criterion corrected for small sample sizes (AICc) and are presented with coefficient estimates and significance levels (*** p < 0.001, **p < 0.01, *p < 0.05, ^p < 0.10) for individual covariates, as well as model degrees of freedom (df), log-likelihood (Log Lik.), AICc, ΔAICc, and model weight (Wt.). Covariates from models that outperformed the null model with ΔAIC < 2.0 and/or a model weight > 0.10, included Mean Wind (quadratic), and Precipitation and were advanced to the second tier of model selection along with covariates from the first stage of tier one.

Model †	**Mean Wind**	**Mean Wind (quadratic)**	**Max Wind (quadratic)**	**% Clouds**	**Moon Visibility**	**% Moon**	**Fog**	**Precipitation**	**Temperature**	**Relative Humidity**	**df**	**Log Lik.**	**AICc**	**ΔAICc**	**Wt.**
Precip. & Wind		$+^{**}$						-16.26			5	-87.5	185.8	0.00	0.194
Precip. & Wind			$+^{***}$					-12.32			5	-88.0	186.9	1.03	0.116
Wind		$+^{**}$									4	-89.4	187.4	1.57	0.088
Wind & Vis.		$+^{**}$					-6.34				5	-88.4	187.6	1.80	0.079
Wind & Vis.		$+^{*}$		-0.0083							5	-88.6	188.1	2.21	0.064
Wind			$+^{*}$								4	-90.0	188.6	2.75	0.049
Wind & Vis.			$+^{*}$		0.8022						5	-89.0	188.7	2.90	0.045
Wind & Vis.		$+^{*}$			0.5451						5	-89.0	188.8	2.92	0.045
Wind & Vis.			$+^{*}$				-5.68				5	-89.1	189.1	3.24	0.038
Wind & Humid.		$+^{*}$								-0.0095	5	-89.2	189.1	3.29	0.037
Wind, Vis. & Precip.		$+^{*}$		-0.0043	0.3408			-12.56			7	-87.0	189.6	3.73	0.030
Wind & Vis.			$+^{*}$	-0.0069							5	-89.5	189.8	3.94	0.027
Wind & Temp.			$+^{*}$						-0.0346		5	-89.6	190.0	4.20	0.024
Precip. & Wind	0.0738^{*}							-11.49			4	-91.0	190.6	4.73	0.018
Wind & Humid.			$+^{*}$							-0.0051	5	-90.0	190.7	4.88	0.017

(con'd)

Wind & Vis.	+*			-0.0003			5	-90.0	190.9	5.03	0.016
Precip.						-8.57	3	-92.6	191.6	5.73	0.011
Wind & Vis.	+*	-0.0097		-0.0065			6	-89.2	191.6	5.81	0.011
Precip. & Vis.			0.70180			-7.24	4	-91.9	192.3	6.48	0.008
Precip. & Vis.					-11.09	-8.53	4	-92.1	192.7	6.89	0.006
Null							2	-94.4	193.0	7.20	0.005

† “Wind” indicates wind speeds, “Precip.” represents precipitation measures, “Temp.” represents hourly temperature measures, and “Humid.” Represents the relative humidity which all were recorded at the Iain Nicholson Audubon Rowe Sanctuary weather station. “Vis.” indicates whether or not fog was present, as documented by the observers, during each observation.