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RESEARCH ARTICLE

Near-ultraviolet light reduced Sandhill Crane collisions with a power line by 98%

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ABSTRACT

Midflight collisions with power lines impact 12 of the world's 15 crane species, including 1 critically endangered species, 3 endangered species, and 5 vulnerable species. Power lines can be fitted with line markers to increase the visibility of wires to reduce collisions, but collisions can persist on marked power lines. For example, hundreds of Sandhill Cranes (*Antigone canadensis*) die annually in collisions with marked power lines at the Iain Nicolson Audubon Center at Rowe Sanctuary (Rowe), a major migratory stopover location near Gibbon, Nebraska. Mitigation success has been limited because most collisions occur nocturnally when line markers are least visible, even though roughly half the line markers present include glow-in-the-dark stickers. To evaluate an alternative mitigation strategy at Rowe, we used a randomized design to test collision mitigation effects of a pole-mounted near-ultraviolet light (UV-A; 380–395 nm) Avian Collision Avoidance System (ACAS) to illuminate a 258-m power line span crossing the Central Platte River. We observed 48 Sandhill Crane collisions and 217 dangerous flights of Sandhill Crane flocks during 19 nights when the ACAS was off, but just 1 collision and 39 dangerous flights during 19 nights when the ACAS was on. Thus, we documented a 98% decrease in collisions and an 82% decrease in dangerous flights when the ACAS was on. We also found a 32% decrease in the number of evasive maneuvers initiated within 25 m of the power line along the river, and a 71% increase in the number of evasive maneuvers initiated beyond 25 m when the ACAS was on. Sandhill Cranes reacted sooner and with more control, and experienced substantially fewer collisions, when the ACAS was on. Installation of the ACAS on other high-risk spans, and perhaps on other anthropogenic obstacles where birds collide, may offer a new solution to a long-running conservation dilemma.

Keywords: Antigone canadensis, ACAS, Avian Collision Avoidance System, line marking, Nebraska

La luz ultravioleta cercana redujo las colisiones de *Antigone Canadensis* con una línea eléctrica en un 98%

RESUMEN

Las colisiones a mitad de vuelo con líneas eléctricas afectan a 12 de las 15 especies de grullas del mundo, incluyendo 1 especie en peligro crítico, 3 especies en peligro y 5 especies vulnerables. Las líneas eléctricas pueden ser equipadas con marcadores de línea para aumentar la visibilidad de los cables y reducir las colisiones, pero las colisiones pueden continuar con las líneas eléctricas marcadas. Por ejemplo, cientos de individuos de *Antigone canadensis* mueren anualmente en colisiones con líneas eléctricas marcadas en el Centro Audubon Iain Nicolson en el Santuario Rowe (Rowe), una importante localidad de parada migratoria cerca de Gibbon, Nebraska. El éxito de esta medida de mitigación ha sido limitado debido a que la mayoría de las colisiones ocurren de noche cuando los marcadores de las líneas son menos visibles, aunque aproximadamente la mitad de los marcadores de líneas poseen calcomanías que brillan en la oscuridad. Para evaluar una estrategia alternativa de mitigación en Rowe, usamos un diseño aleatorio para analizar los efectos de mitigación de las colisiones de un Sistema de Prevención de Colisión de Aves (SPCA) con una luz ultravioleta cercana colocada en un poste (UV-A; 380–395 nm) que ilumina un sector de 258 m de una línea eléctrica que atraviesa el Río Platte Central. Observamos 48 colisiones de individuos de *A. canadensis* y 217 vuelos peligrosos de bandadas de *A. canadensis* durante 19 noches cuando el SPCA estuvo apagado, pero solo 1 colisión y 39 vuelos peligrosos durante 19 noches cuando el SPCA estuvo encendido. Por ende, documentamos una reducción del 98% en las colisiones y una disminución del 82% en los vuelos peligrosos cuando el SPCA estuvo encendido. También encontramos una disminución del 32% en el número de maniobras evasivas iniciadas a menos de 25 m de la línea de energía a lo largo del río y un aumento del 71% en el número en maniobras evasivas iniciadas más allá de los 25 m cuando el SPCA estuvo encendido. Los individuos de *A. canadensis* reaccionaron antes y con más control, y sufrieron sustancialmente menos colisiones cuando el SPCA estuvo encendido. La instalación del SPCA en otras porciones de alto riesgo, y tal vez en otros obstáculos antropogénicos donde chocan las aves, puede representar una nueva solución a un dilema de conservación de larga duración.

Palabras clave: Antigone canadensis, marcación de líneas, Nebraska, Sistema de Prevención de Colisión de Aves

INTRODUCTION

Of the world's 15 crane species, 4 (27%) are categorized as critically endangered or endangered, and 7 (47%) are vulnerable (ICF 2018, IUCN 2018). Only 4 species are categorized as of least concern, and of those, the Sandhill Crane (*Antigone canadensis*), the world's most abundant crane species (Gerber et al. 2014), endured decades of decline before continent-wide management actions in North America reversed the trajectory. Even today, the Florida population of Sandhill Cranes remains in decline despite successful population recoveries throughout the rest of the species' range (Gerber et al. 2014). Numerous factors, including habitat loss and degradation, human disturbance, hunting, illegal capture for commercial trade, and impacts from environmental contamination, are contributing factors in the declines of crane populations (Johnsgard 1983, Meine and Archibald 1996, ICF 2018).

Power line collisions have been identified as a threat to 12 crane species, including Sandhill Crane and the only other North American crane species, the Endangered Whooping Crane (*Grus americana*; Table 1). Power line collisions are particularly important for 4 endangered or critically endangered species. Only 3 species of cranes, Black Crowned-Crane (*Balearica pavonina*), White-naped Crane (*Antigone vipio*), and Demoiselle Crane (*Anthropoides virgo*), have not been documented colliding with power lines (IUCN 2018). However, given that these relatively unstudied species share ranges with affected species, and given the ongoing expansion of power lines worldwide (Jenkins et al. 2010), these species are also likely to be, or to become, vulnerable to power line collisions.

Identifying effective mitigation measures for crane collisions with power lines is critically important to global crane conservation and is becoming more important as power line networks expand globally (Jenkins et al. 2010). To mitigate collisions involving cranes (and other birds), electric utilities use line markers to increase the visibility of power lines to birds (Morkill and Anderson 1991, Wright et al. 2009, Murphy et al. 2016a). Line markers tend to reduce avian collision rates by at least 50% in published studies (Morkill and Anderson 1991, Brown and Drewien 1995, Barrientos et al. 2011). However, this statistic may overestimate the true effectiveness of line markers as studies quantitatively demonstrating no significant reductions in collisions may be underrepresented because power line operators hesitate to publish negative data (J. Dwyer personal observation).

At our study area near Rowe, Nebraska, USA (described below), over 300 Sandhill Crane collisions with

TABLE 1. Mortalities from collisions with power lines have been reported[a] for 12 of the world's 15 crane species.

Common name	Scientific name	Status	Trend	Continent(s)	Power line collisions reported
Siberian Crane	*Leucogeranus leucogeranus*	Critically Endangered	decreasing	Asia	Yes
Gray Crowned-Crane	*Balearica regulorum*	Endangered	decreasing	Africa	Yes
Red-crowned Crane	*Grus japonensis*	Endangered	decreasing	Asia	Yes
Whooping Crane	*Grus americana*	Endangered	increasing	North America	Yes
Black Crowned-Crane	*Balearica pavonina*	Vulnerable	decreasing	Africa	No
Sarus Crane	*Antigone antigone*	Vulnerable	decreasing	Asia, Australia	Yes
White-naped Crane	*Antigone vipio*	Vulnerable	decreasing	Asia	No
Wattled Crane	*Bugeranus carunculatus*	Vulnerable	decreasing	Africa	Yes
Black-necked Crane	*Grus nigricollis*	Vulnerable	decreasing	Asia	Yes
Blue Crane	*Anthropoides paradiseus*	Vulnerable	stable	Africa	Yes
Hooded Crane	*Grus monacha*	Vulnerable	increasing	Asia	Yes
Brolga	*Antigone rubicunda*	Least Concern	decreasing	Australia	Yes
Demoiselle Crane	*Anthropoides virgo*	Least Concern	increasing	Asia, Africa	No
Sandhill Crane	*Antigone canadensis*	Least Concern	increasing	North America, Asia	Yes
Common Crane	*Grus grus*	Least Concern	increasing	Asia, Europe, Africa	Yes

[a] Arnol et al. 1984, Brown et al. 1987, White 1987, Windingstad 1988, Masatomi 1991, Goldstraw and Du Guesclin 1991, Morkill and Anderson 1991, Alonso et al. 1994, Meine and Archibald 1996, Janss and Ferrer 2000, Sundar and Choudhury 2005, Stehn and Wassenich 2008, Shaw 2009, Wright et al. 2009, Shaw et al. 2010, Fanke et al. 2011, Folk et al. 2013, Veltheim et al. 2015, Haraguchi et al. 2016, IUCN 2018.

a marked power line were documented during a single spring migration (Murphy et al. 2016a, 2016b), clearly demonstrating the need for improved collision mitigation. At the time of the collisions, and during our study, the power line was marked (Figure 1) with a combination of black, white, yellow, and orange FireFly HW bird diverters that also included a glow-in-the-dark sticker on each side (FireFlys; P&R Tech, Beaverton, Oregon, USA) and marked with yellow spiral Bird Flight Diverters (BFDs; Preformed Line Products, Cleveland, Ohio, USA). Line marking was composed of 22 FireFlys and 22 BFDs installed on each of 2 overhead shield wires (88 line markers total) across a 258-m span for an average line marker spacing of 2.9 m. In general, spacing of 5–30 m between line markers is most commonly recommended and used (APLIC 2012). Even with line markers at 2–10 times as dense as the best available science recommends, hundreds of Sandhill Crane collisions occur annually on the power line (Wright et al. 2009, Murphy et al. 2016a, 2016b).

Because avian collision mortality tends to persist even after power lines are marked, and because of technical limitations for line marking, we questioned whether a more effective solution might be possible. In a review of avian vision, approximately half of avian groups that have been tested to date have been found to be sensitive to ultraviolet (UV) light (Harness et al. 2016), including bird species in the orders Anseriformes (waterfowl), Galliformes (grouse), Gaviiformes (loons), Procellariiformes (some seabirds), Ciconiiformes (storks), Pelecaniformes (pelicans), Strigiformes (owls), and Passeriformes (songbirds), all of which include species that are susceptible to collisions with power lines (APLIC 2012, Sporer et al. 2013, Bernardino et al. 2018). Many avian species not sensitive to UV light are sensitive to a broader violet spectrum than humans see (Harness et al. 2016). Human eyes are sensitive to light with a minimum wavelength of ~400 nm. Although human eyes contain cones capable of sensing shorter wavelengths, the UV-absorbing lens of the human eye prevents entry by those wavelengths (Jacobs 1992). In contrast, avian vision is sensitive to wavelengths as short as 320 nm, depending on the species, due to differences from humans in lens physiology and photoreceptors (Parrish et al. 1984, Aidala et al. 2012, Ödeen and Håstad 2013). Avian sensitivity to light has previously been explored as a potential mechanism of modifying bird behavior. For example, Blackwell et al. (2012) and Doppler et al. (2015) evaluated Canada Goose (*Branta canadensis*) and Brown-headed Cowbird (*Molothrus ater*) responses to "white" and 470 nm lights, respectively, mounted on model aircraft, and Foss et al.

FIGURE 1. Two types of line markers were present on the power line we studied at the Iain Nicolson Audubon Center at Rowe Sanctuary in central Nebraska, but were not effective in preventing Sandhill Crane collisions. (Overview) The span we studied crossing the Central Platte River. (Inset) Close view of a FireFly (left) and a Bird Flight Diverter (right) installed on the power line prior to our study.

(2017) evaluated the responses of Red-tailed Hawks (*Buteo jamaicensis*) when a tethered prey item was illuminated with 445 nm light. In all 3 studies, birds reacted differently in the artificially illuminated situations compared to control situations.

We therefore hypothesized that using near-ultraviolet (UV-A; wavelengths of 320–400 nm) light to illuminate power lines might be more effective in mitigating avian collisions than line markers alone, and may do so without increasing power line visibility to humans. To assess this possibility, we designed and tested the Avian Collision Avoidance System (ACAS), a UV-A illumination system we developed. The ACAS was designed to function on power lines without line markers, although the test described here includes a power line with line markers.

METHODS

Study Area

Over 500,000 Sandhill Cranes migrate annually through Nebraska, and many of these birds use the Platte River Valley as a migratory stopover site (Gerber et al. 2014). We studied the ACAS at a power line crossing the Central Platte River at the Iain Nicolson Audubon Center at Rowe Sanctuary (Rowe; Universal Transverse Mercator 14 T, 509599 m E, 4502114 N) within the Platte River Valley, near Gibbon, Nebraska. This is the same span of power line where hundreds of Sandhill Crane collisions historically occurred annually despite the presence of FireFly and BFD line markers (Wright et al. 2009, Murphy et al. 2016a, 2016b). Rowe was composed of river, river bank, wet meadow, and prairie habitats managed to protect and restore roosting, foraging, and loafing habitat for Sandhill Cranes and Whooping Cranes during migration (A. Pierson, Iain Nicolson Audubon Center at Rowe Sanctuary, personal communication).

Field Methods

The ACAS consisted of 4 UV-A lights, a junction box, 2 solar panels, a power storage and control box, cabling to connect those components, and a remote control (Figure 2). Each UV-A light was mounted on the crossarm of an H-frame structure supporting the power line span we studied, and each light produced peak wavelengths of 380 nm (2 lights; one 50 watt and one 100 watt) or 395 nm (2 lights, one 50 watt and one 100 watt). Each light was built around a Chanzon (Shenzhen, Guangdong, China) High Power LED Chip 100W Purple Ultraviolet light. We estimated production of 8,000–9,000 lumens per light, depending on ambient temperature, but this light did not appear bright to the human eye. The lower-wattage lights ensured that some light would be produced even if cloudy conditions prevented the solar panels from fully charging the batteries on some days. Each light produced a cone of illumination that spread 30° around a central axis. This relatively broad cone ensured that even if the lights were not installed perfectly parallel to the wires, the wires would still be illuminated throughout their entire span. The junction box was mounted just below the crossarm and distributed power to the UV-A lights. The pole-mounted solar panels charged batteries in the power storage and control unit located on the ground at the base of the H-frame structure. The power storage and control unit contained batteries, an inverter, custom-built control boards, and switches to store, convert, and route electrical power from the solar panels, through the junction box, and into the UV-A lights. The total cost for all components was ~$6,000, including various UV lights that we evaluated but did not use in the final construction.

We tested the ACAS by mounting it on an existing H-frame structure on the north bank of the Central Platte River at Rowe and directing the UV-A light along the 258-m span crossing the river. The upper wires of the power line were ~15 m above the surface of the river and adjacent banks. Dawson Public Power (Kearney, Nebraska), the owner and operator of the power line we studied, donated personnel time to install the ACAS on February 14, 2018, prior to the arrival of migrating Sandhill Cranes and Whooping Cranes, and to remove the ACAS on June 18, 2018, after migrating cranes had departed the study area.

We monitored cranes' responses to the ACAS an average of 5.2 nights per week from February 28, 2018, through April 19, 2018, bracketing the historical timing of collisions (March 4 to April 13; Wright et al. 2009, Murphy et al. 2016b). We randomly assigned the ACAS to be on or off during each night of observation. From a blind near the base of the H-frame structure on which the ACAS was installed, each night from 1 hr before sunset until 4.5 hr after sunset we observed collisions with the power line, post-collision flight behavior, reaction behavior as flocks approached the power line, and reaction distances (0–25 m or 26–50 m) perpendicular from the power line along the river (Murphy et al. 2016a). We recorded observations identically regardless of whether the ACAS was on or off. During daylight and dusk, we conducted observations with 8 × 42 binoculars. At night we conducted observations with a 3–12 × 50 thermal imaging monocular (Prometheus 336; Armasight, San Francisco, California, USA).

We recorded flight behavior when flocks of cranes flew over the power line within 25 m above river surface (10 m of the top of the power line) as was done in a previous study (Murphy et al. 2016a). This allowed us to focus specifically on cranes that could be at risk of collision, and to avoid recording cranes flying well above the power line that were not at risk of collision, which would have reduced the sensitivity of our analyses (Murphy et al. 2016a). We used the known height of the power line and known distances between the

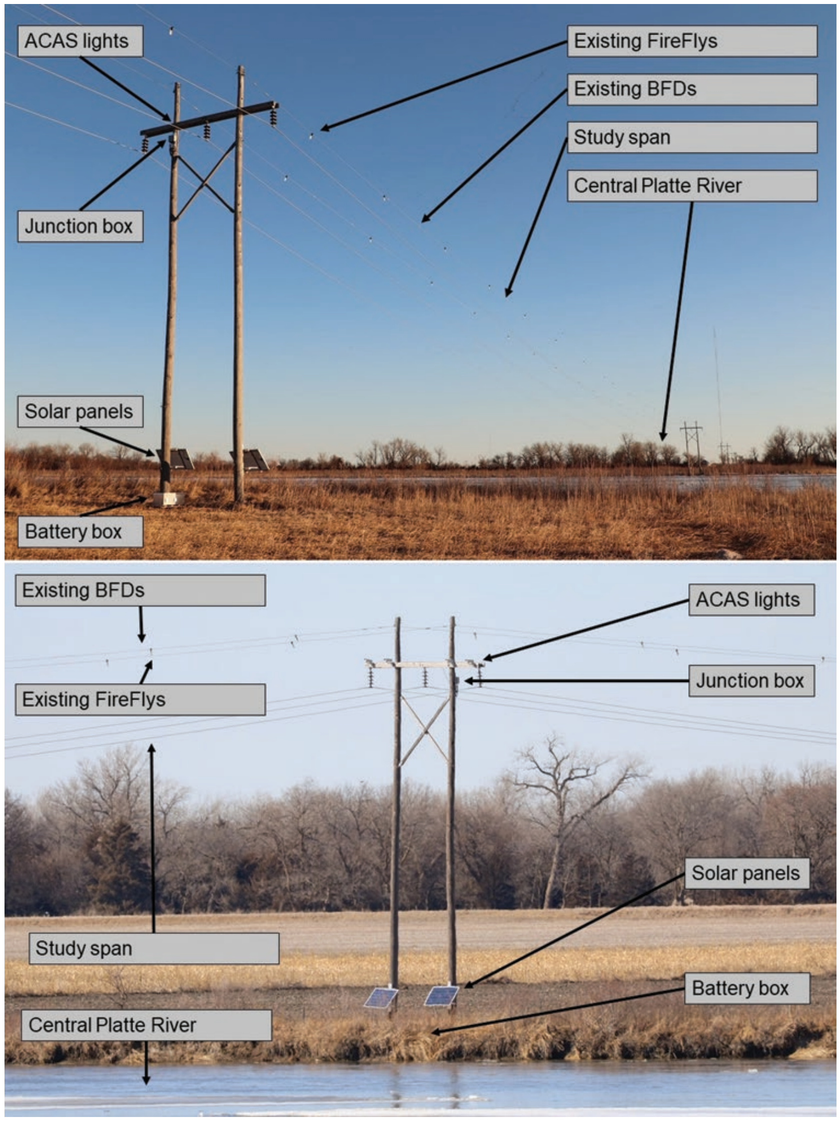

FIGURE 2. The Avian Collision Avoidance System (ACAS). (Top) Viewed from the northwest with the Central Platte River in the background. (Bottom) Viewed from the southeast with the Central Platte River in the foreground.

wires comprising the power line to gauge the flight height of cranes crossing over the power line, and to gauge the distance along the river from the power line at which cranes' flight behavior changed. To maintain consistency with previous studies of Sandhill Crane collisions with power lines in our general study area (Morkill and Anderson 1991), and with a previous study at this site (Murphy et al. 2016a), we defined a flock passing over the power line as an individual or discrete group. Passage over the line was infrequent enough that most flocks were temporally separated by at least 5 min. To ensure independence among data points, we did not record the passage over the line of flocks within 5 min of a previous flock. This approach made flocks, rather than individual Sandhill Cranes, our sampling unit for statistical analyses (Murphy et al. 2016a).

Each time a flock of Sandhill Cranes crossed over the power line within 25 m above the river surface, we recorded whether the ACAS was on or off, whether a collision occurred, whether it was day (1 hr before sunset to the end of civil dusk at 0.5 hr after sunset) or night, whether and how cranes maneuvered to avoid the power line, and the perpendicular distance from the power line at which those maneuvers occurred. If one or more collisions occurred, we also recorded the wire involved and the subsequent flight behavior of the crane involved.

We categorized maneuvers to avoid the power line as no reaction, gradual climb, flare, and reverse (Murphy et al. 2016a). No reaction occurred when the entire flock continued past the power line with the same direction, speed, and elevation above the river level as the flock had when approaching the power line. For this behavior, reaction distance was defined as zero. When no reaction occurred within 25 m above the river surface, we categorized these as dangerous flights. A gradual climb occurred when the entire flock maintained consistent flight direction, speed, and wingbeat, but adjusted flight height gradually to pass above the power line. When a gradual climb did not exceed 25 m above the river surface, we categorized this as a dangerous flight. A flare occurred 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. A reverse occurred when at least one member of the flock altered direction, speed, and wingbeat to suddenly turn away from the power line. We recorded flares and reverses even if only a single member of the flock reacted because those behaviors were previously demonstrated to occur when at least some cranes in the flock were in danger of collision (Murphy et al. 2016a). We recorded post-collision flight as normal flight (steady wingbeats and elevation maintained), hampered flight (unsteady wingbeats and elevation maintained), flapping fall (unsteady wingbeats and elevation not maintained), and limp fall (no wingbeats and elevation not maintained).

The ethical guidelines followed in this study involved not disturbing roosting cranes. To achieve this, we scheduled installation of the ACAS prior to the cranes' arrival, and removal after their departure, and we ensured our observations did not disturb roosting cranes, which could have caused flocks to fly up into the power line.

Analytical Methods

We used 3 Fisher's exact probability tests to compare the proportions of collisions, dangerous flights, and reaction distances of Sandhill Crane flocks observed when the ACAS was off and when it was on. Because we conducted 3 Fisher's exact probability tests on the same data set, we used a Bonferroni correction to adjust our significance level to $\alpha = 0.017$. These tests statistically addressed our hypothesis that UV-A illumination would improve collision mitigation on the marked power line we studied. The Fisher's exact probability tests sacrificed some analytical resolution, however, because no additional information could be accommodated by the test when multiple collisions occurred within a flock. To address this, we also report the percent reduction of events (collisions, dangerous flights, and reaction distances) and the hourly rates of events when the ACAS was off and when it was on. We also report the percent difference in the number of flocks crossing the power line within 25 m above the river surface when the ACAS was off, compared to when the ACAS was on. We also report counts of collisions during the day and night, counts of the wires involved in collisions, and counts of post-collision flight behaviors.

RESULTS

We conducted 38 nights of monitoring including 19 nights when the ACAS was off, and 19 nights when the ACAS was on. We recorded 49 Sandhill Crane collisions from 37 flocks: 48 collisions when the ACAS was off, and 1 when it was on. Multiple collisions sometimes occurred within a single flock (Figure 3; $n = 8$ flocks; when multiple collisions occurred, min = 2 collisions, mean = 2.5 collisions, max = 4 collisions). Collisions occurred at a rate of 1 collision every 2.2 hr of observation when the ACAS was off, and 1 collision every 104.5 hr of observation when it was on. We also observed one American White Pelican (*Pelecanus erythrorhynchos*) collision when the ACAS was off.

We recorded a total of 916 flocks of cranes passing the power line within 25 m of the river surface (Table 2). Flocks with collisions were more likely to occur when the ACAS was off ($P < 0.001$), with 97% of flocks with collisions occurring during those times. Dangerous flights were also more likely to occur when the ACAS was off ($P < 0.001$), with 85% occurring during those times. Reaction distances were more likely to be within 25 m of the power line when the ACAS was off ($P < 0.001$), with 59% occurring during those times.

All of the collisions we observed happened at night ($\bar{x} = 162 \pm 98$ [SD] min after sunset), as did most (63%) dangerous flights ($\bar{x} = 118 \pm 71$ min after sunset). Most (94%) collisions involved the upper 2 wires (the overhead shield wires). Only 3 collisions involved conductors. Of the 49 Sandhill Crane collisions we observed, 17 cranes continued after the collision with normal flight, 14 continued with hampered flight, 12 fell while flapping, 4 fell limply, and 2 were obscured by other cranes which prevented us from identifying an outcome. We never observed any birds, bats, or insects circling the ACAS lights.

DISCUSSION

We observed a 98% reduction in Sandhill Crane collisions when UV-A light emitted by the ACAS illuminated the power line we studied. Our observations of flocks passing over the power line within 25 m above the river surface when the ACAS was on indicated that Sandhill Cranes were present during our study. Based on this, we conclude the ACAS was responsible for reducing collisions. We hypothesize the reason for the success of the ACAS was that it illuminated the entire length of all the wires in the span, including the previously installed line markers, allowing Sandhill Cranes to see and avoid the power line. In contrast, traditional non-illuminated line markers rely

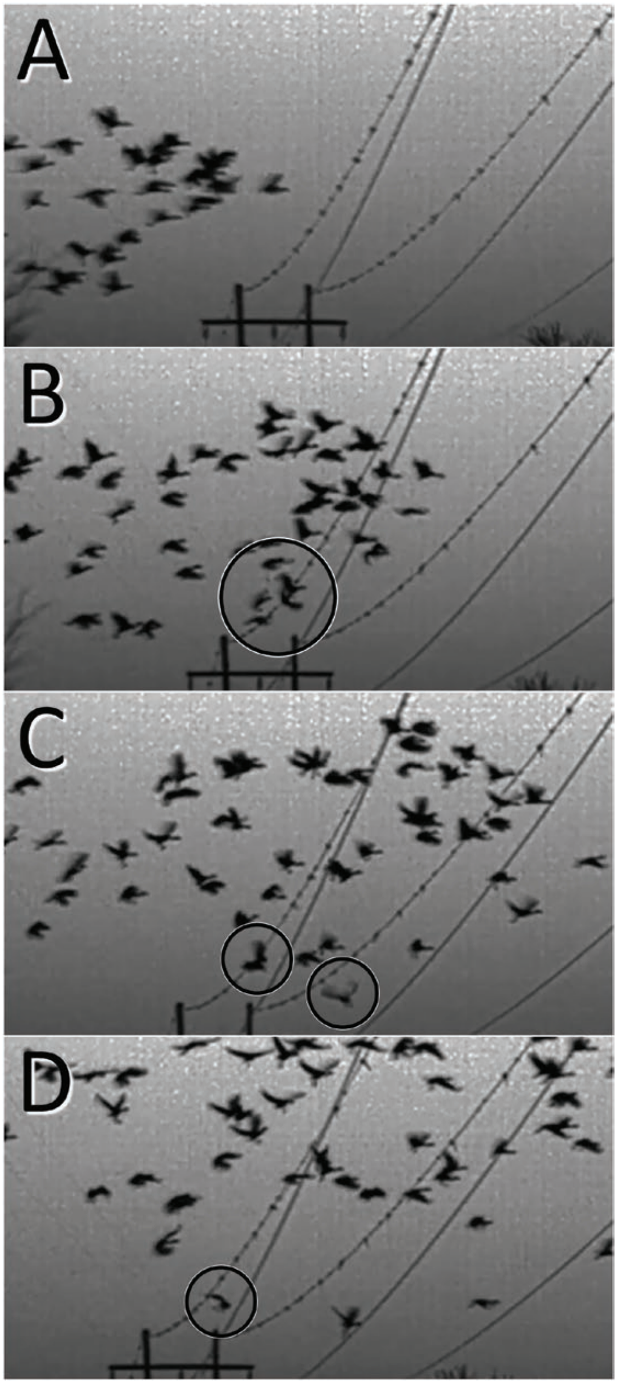

FIGURE 3. Example from thermal imaging monocular of multiple collisions within a single flock of Sandhill Cranes during an observation when the Avian Collision Avoidance System (ACAS) was turned off. (**A**) Organized V-shaped flock approaches the power line in darkness. (**B**) Two adjacent, near-simultaneous collisions (circled). (**C**) A third collision (left circle), and a crane involved in the previous collision falling out of the image frame (right circle). (**D**) The crane involved in the third collision falling out of the image frame (circled), and flock above in disarray.

on birds to infer the presence of suspended wires they may not see between and below the line markers they may see. Our findings of fewer flocks flying within 25 m above the river surface where the river was transected by the power line, and of fewer reaction distances <25 m from the power line along the river suggest that not only were collisions and dangerous flights reduced within the collision risk zone when the ACAS was on, but also that Sandhill Cranes avoided the power line sufficiently early and with sufficient altitude to entirely avoid the area we associated a priori with collision risk. Given the success of the ACAS with Sandhill Cranes, and our observation of one American White Pelican collision when the ACAS was off, it appears that installation of the ACAS on other high-risk spans or other anthropogenic obstacles may offer a relatively simple and easy solution to a problem that has stymied crane conservation in particular, and avian conservation in general, across 5 continents for decades. The ACAS may be especially useful at other river and wetland sites where natural features channel birds into relatively narrow flight corridors.

Though we designed the ACAS to function on power lines without line markers, that scenario was not tested in our study. Consequently, we do not know whether or how much the ACAS's illumination of line markers influenced our results or if our results would have been as positive if line markers were not present, particularly because line markers were unusually dense on this power line as a result of previous attempts to mitigate collisions. Future research should include testing the ACAS on unmarked power lines and on power lines fitted with different types and spacing of line markers than occurred in this study. Future research should also consider UV-reflective line markers to address the possibility that the ACAS is more effective as part of an illumination-plus-line-markers system. Alternatively, perhaps wires could be treated with a UV-reflective coating during installation to minimize the operations and maintenance obligations that line markers can create.

We do not know the specific contribution of power line collision mortality to threatened crane species, but population trajectories should be sensitive to changes in survival rate. Collision mortality is likely additive to other pressures (habitat loss and degradation, human disturbance, hunting, illegal capture for commercial trade, and impacts from environmental contamination), so mitigating collision mortality may have important conservation implications for cranes. More generally, avian collision risk extends well beyond crane species to include birds in groups as diverse as seabirds (Raine et al. 2017), raptors (Mojica et al. 2009), passerines (Rogers et al. 2014), and numerous others (Sporer et al. 2013, Harness et al. 2016, Bernardino et al. 2018). The ACAS would be most widely effective if other

TABLE 2. Occurrences of collisions, dangerous flights (flights in which the flock showed no reaction to the power line, the gradual climb was ≤25 m above the river surface, or a flare or reverse occurred), and reaction distances 0–25 m or 25–50 m from the line along the river in Sandhill Crane flocks observed at a power line crossing the Central Platte River at the Rowe Sanctuary near Gibbon, Nebraska. Of the 916 flocks observed, 521 occurred when the Avian Collision Avoidance System (ACAS) was off, and 395 occurred when the ACAS was on. Counted numbers are followed in parentheses by percentages.

	Flocks with collisions		Dangerous flights		Reaction distances	
ACAS	Yes	No	Yes	No	0–25 m	25–50 m
Off	36 (7)	485 (93)	217 (42)	304 (58)	483 (93)	38 (7)
On	1 (0)	394 (100)	39 (10)	356 (90)	330 (84)	65 (16)
Total	37	879	256	660	813	103

species and groups at risk of collision also perceived and responded to UV light. Numerous other avian species from Mallards (*Anas platyryhnchos*) to Eurasian Kestrels (*Falco tinnunculus*) to Zebra Finches (*Taeniopygia guttata*) are sensitive to UV light (Jane and Bowmaker 1988, Viitala et al. 1995, Lind et al. 2014). The ACAS or some other light-emitting system, if available, should be tested at other sites where vulnerable species are at risk of collision.

The ACAS is not the only collision mitigation technology to attempt to use light to mitigate wildlife collisions with power lines. For example, the solar-powered Overhead Warning Light (OWL) line marker flashes small lights perpendicular to the line on which the OWL is installed (Preformed Line Products 2017). In another example, Kaua'i Island Utility Cooperative (KUIC) used an array of green lasers to illuminate part of a power line on Hawaii during annual breeding seasons of endangered seabirds (KIUC 2015, 2016). To our knowledge, both of these examples are described from marketing materials rather than scientific publications, and unlike the ACAS's UV-A light, both use visible light that human residents may object to. Nevertheless, these systems illustrate the emerging conservation potential of light-based collision mitigation technologies. Unfortunately, light-based collision mitigation technologies have practical limitations that may make them most appropriate for collision hotspots rather than more general use. Specifically, the purchase, operation, and maintenance costs of these technologies likely exceeds that of traditional non-lighted line markers, although the costs of lighted systems may decrease as products reach commercial maturity. Installing these systems over many continuous power line spans is also likely to be impractical and cost-prohibitive in the near term, particularly in areas where collisions are infrequent. In those cases, traditional non-lighted line markers that include phosphorescent glow-in-the-dark materials (e.g., FireFly, or Power Line Sentry's Avian Flight Diverters, Fort Collins, Colorado, USA), may remain the best solution, given the competing considerations (budgets vs. conservation impacts) involved in marking power lines.

UV illumination may also be useful in conservation for other types of tall anthropogenic structures. For example, birds regularly collide with communication towers (Gehring et al. 2009, Longcore et al. 2012), meteorological towers, the guy wires supporting those towers (Gehring et al. 2011, Kerlinger et al. 2012), and wind turbines (Smith and Dwyer 2016). We hypothesize that collisions occur on these structures even when they are lighted because lighting does not illuminate either the guy wires when present, or the entire tower, regardless of the presence of guy wires. Future research should deploy the ACAS at the top or bottom of towers with histories of collisions, orient the ACAS along towers and guy wires, and evaluate whether collisions persist. Future research should also consider potential negative effects of the ACAS. We did not observe any wildlife circling the ACAS lights, but our study was conducted in early spring when nocturnal insects may have not yet emerged, and nocturnal avian and aerial mammalian insectivores may not have yet arrived from migration or emerged from hibernation. Future research on the ACAS should include documentation of nocturnal aerial insectivores around the lights, if present.

Additionally, although bats are commonly thought of as using echolocation for navigation, their ultrasonic pulses attenuate quickly in open space. Gorresen et al. (2015) suggested that bats use dim ambient light for large-scale navigation, a mechanism that could be leveraged for conservation if wind turbines are illuminated with UV light at night. In early testing, illuminating trees with UV light in areas frequented by endangered Hawaiian hoary bats (*Lasiurus cinereus semotus*) reduced bat activity in the lighted area despite an increase in insect activity (Gorresen et al. 2015). Illumination of wind turbines with the ACAS may offer similar benefits for bats and birds at risk of collision in wind resource areas.

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Ethics statement: The ethical guidelines followed in this study involved not disturbing roosting cranes. To achieve this, we scheduled installation of the ACAS prior to the cranes' arrival, and removal after their departure. We also conducted all monitoring from inside an enclosed blind that ensured our activities near the roost would not disturb nearby cranes. We were also prepared to terminate the study if collisions increased.

Author contributions: JFD, AKP, and REH conceived the idea, design, and experiment described here. JFD and LAM performed the experiment. JFD and REH wrote this manuscript. JFD, AKP, LAM, and REH designed the experimental and analytical methodology. JFD analyzed the data. AKP and REH contributed substantial materials and technical expertise.

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