Spatially Explicit Assessment of Sandhill Crane Exposure to Potential Transmission Line Collision Risk

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ABSTRACT Infrastructure development can affect avian populations through direct collision mortality. Estimating the exposure of local bird populations to the risk of direct mortality from infrastructure development requires site- and species-specific data, which managers may find difficult to obtain at the scale over which management decisions are made. We quantify the potential exposure of sandhill cranes (Antigone canadensis) to collision with horizontal structures (e.g., transmission lines) within vital wintering grounds of the Middle Rio Grande Valley (MRGV), New Mexico, USA, 2014–2020. Limited maneuverability and visual acuity make sandhill cranes vulnerable to collisions with infrastructure bisecting their flight paths. We used data from 81 global positioning system (GPS)-tagged cranes to estimate the spatially explicit flight height distribution along the MRGV, the passage rate across hypothetical transmission lines, and the resulting exposure rate (exposed passes/crane/day). The exposure rate ranged from 0–0.28 exposed passes/crane/day (median = 0.015) assuming an exposure zone of 7–60 m above ground level, and identified hotspots of potential exposure within the MRGV. Mapped exposure rates can assist in the siting of proposed high-voltage transmission lines, or other infrastructure, to limit effects on sandhill cranes and other avian species at risk of collision. Our approach can be replicated and applied in similar situations where birds are exposed to possible collision with power lines. © 2021 The Authors. The Journal of Wildlife Management published by Wiley Periodicals LLC on behalf of The Wildlife Society.

KEY WORDS Antigone canadensis, exposure rate, migratory birds, New Mexico, power line, sandhill cranes, transmission line, winter.

Energy development and urbanization often have negative, biologically significant effects on wildlife populations, including volant animals (Beer and Ogilvie 1972, Brown and Drewien 1995, Kuvlesky et al. 2007, Pearce-Higgins et al. 2012). Specifically, energy development can affect birds and bats by causing mortality through collisions with structures, direct destruction or modification of habitat for the building and maintenance of structures, and indirect habitat loss via displacement (Drewitt and Langston 2006, Ludlow et al. 2015, Winder et al. 2015, Pearse et al. 2016, Lange et al. 2018). Researchers and managers should consider wildlife exposure to minimize effects on birds and bats when making siting decisions (Caro and O’Doherty 1999, Pearse et al. 2016); however, because of the influence of site-specific characteristics such as local climate (e.g., seasonal prevailing winds) and biotic and abiotic habitat features (e.g., presence of trees and canopy height, proximity of water bodies), exposure can be difficult to assess. Species traits, weather, landscape features, and the particulars of the exposure risk (e.g., infrastructure design, siting) all interact to determine exposure to collision (Bevanger 1994, Avian Power Line Interaction Committee [APLIC] 2012). For example, species differing in abundance, behavior, and morphology vary in susceptibility to collisions with horizontal structures like power lines (Janss 2000, Janss and Ferrer 2000). Sandhill cranes (Antigone canadensis) may be particularly exposed to collisions (Pearse et al. 2016) because of their wing morphology and body mass, which limit maneuverability (Janss 2000).

Despite the recognized risk of crane collision, available tools fail to effectively predict areas of high risk within
landscapes. For example, Shaw et al. (2010) were unable to accurately predict collision risk for blue cranes (Grus paradisaea) posed by power lines in South Africa using spatial habitat models. They attributed their failure to a mismatch between the fine scales at which power line–crane interactions occurred and the coarser scales represented in the habitat model. Moreover, geospatial data layers that quantify important environmental features may be unavailable (Shaw et al. 2010). Limitations of available habitat and behavioral models prevent landscape-scale risk assessments needed for infrastructure siting decisions.

The Rio Grande in central New Mexico, USA, is the central feature of the Middle Rio Grande Valley (MRGV) and supports agricultural areas and riparian and wetland resources that provide an important corridor and primary wintering area for many migratory birds (Boggie et al. 2018b). The MRGV supports thousands of wintering snow geese (Anser caerulescens), Ross’s goose (A. rossii), and other waterfowl. Thousands of Mid-Continent Population (MCP) lesser sandhill cranes (A. c. canadensis; Krupu et al. 2014, Pacific Flyway Council and Central Flyway Council 2016) and a majority of the Rocky Mountain Population (RMP) of greater sandhill cranes (A. c. tabida; i.e., crane), comprising approximately 22,000 individuals (Thorpe et al. 2019), winter in the MRGV (Figs. 1 and 2A). Researchers identified the MRGV as the most important wintering area for cranes in the RMP (Pacific Flyway Council and Central Flyway Council 2016, Sanchez and Cline 2020).

Important public lands within the MRGV include Ladd S. Gordon Waterfowl Complex and Bosque del Apache National Wildlife Refuge (BdANWR). These areas support abundant wintering waterbirds, including sandhill cranes (Sanchez and Cline 2020) and provide important roosting habitat for cranes in proximity to forage resources, which rely heavily on farming practices such as corn (Zea mays) production. During winter, cranes require highly digestible, high-energy foods rich in carbohydrates. By maintaining a matrix of managed wetlands (i.e., roost and early-season forage sites) and grain crop fields (i.e., supplemental forage; Boggie 2018, Boggie et al. 2018a, Sanchez and Cline 2020), the Ladd S. Gordon Waterfowl Complex and BdANWR support up to 80% of RMP cranes that winter in the MRGV, and historical records show management programs focused on cranes in the RMP have benefited the population (Schroeder et al. 2004). Thus, infrastructure development near these areas has the potential to negatively affect wintering cranes, and ≥3 operational power lines, including 1 high-voltage transmission line, cross the Rio Grande in the MRGV. Two additional high-voltage transmission lines are under construction or proposed for construction in or adjacent to areas that provide winter habitat for cranes in the RMP (Boggie 2018, Boggie et al. 2018a), causing the need for a landscape-scale assessment of risk to cranes from potential development.

Our objective was to assess exposure of wintering cranes to potential high-voltage transmission lines crossing the Rio Grande in the MRGV. We estimated areas of high passage rates by cranes at heights corresponding with potential high-voltage transmission lines to assess risk of collision. Our assessments identified generally where transmission line placement in the MRGV may create either an increased risk or minimized risk of collisions.

**STUDY AREA**

The MRGV extends from Cochiti Dam, Sandoval County, New Mexico to approximately 320 km downstream to the head of Elephant Butte Reservoir, Socorro County, New Mexico, encompassing approximately 278,000 ha (Crawford et al. 1993; Fig. 2B). The mean elevation of the valley floor is 1,470 m, and during winters (Dec–Feb) 2012–2020, the MRGV had a mean precipitation of 293 mm and mean temperature of 6.9°C. The riparian corridor along the Rio Grande is characterized by extensive galleries of Rio Grande cottonwood (Populus deltoides quilltenzii) with an associated understory of native and non-native vegetation, including Goodding’s willow (Salix gooddingii), coyote willow (S. exigua), salt cedar (Tamarix chinensis), New Mexico privet (Forestiera neomexicana), and Russian olive (Elaeagnus angustifolia). The remaining floodplain is a mix of suburban and urban areas with irrigated agricultural lands (Howe and Knopf 1991, Swanson et al. 2011), primarily alfalfa (Medicago sativa), sudangrass (Sorghum × drummondii), and small-grain silage for livestock that are frequented by waterfowl such as mallards (Anas platyrhynchos), snow geese
Figure 2. Movement paths and locations of 81 sandhill cranes telemetered with a global positioning system (GPS) platform transmitter terminal (PTT) tag from 2014–2020. A) Full geographic extent of movement paths during all seasons. B) Movement paths within the study area, the Middle Rio Grande Valley, New Mexico, USA. C) Movement paths within a key resource area, the Bosque del Apache National Wildlife Refuge, New Mexico, USA.
METHODS

From 2014–2020 we used rocket nets to capture wintering sandhill cranes at the BldANWR and areas within the Ladd S. Gordon Waterfowl Complex, along with a small number of sandhill cranes in the RMP on the breeding grounds (Collins et al. 2015, Boggie et al. 2018b). For captured greater sandhill cranes, we applied size 9 United States Geological Survey (USGS) individually numbered aluminum bands on the left tibia. Additionally, we fitted a subset of captured adult greater sandhill cranes (n = 81) with satellite-based telemetry tags, using a modified leg band with auxiliary markers to attach the devices to the right tibia (Collins et al. 2015, Boggie et al. 2018b). We placed the telemetry device and USGS aluminum band above the tibio-tarsus. We focused telemetry efforts on adult cranes in the RMP given their primary conservation concern, using plumage characteristics and morphometrics to determine the age and to identify subspecies of cranes (lesser and greater; Schmitt and Hale 1997).

The majority of telemetry-outfitted cranes (n = 53) carried global system for mobile communication (GSM) platform transmitter terminal (PTT) tags (Evolution Series-400, 15-g units; Cellular Tracking Technologies, Rio Grande, NJ, USA), of which some (n = 26) were programmed to capture high-resolution and detailed location and movement data during flight. Horizontal locational accuracy of GSM PTTs was ±18 m, and the vertical locational accuracy was ±5 m (50% CI). The GSM PTTs collected detailed flight data with an average fix rate of 61.7 locations/crane/day or 20.2 locations/crane/day depending on programming (Table 1). The remaining tags were global positioning system (GPS) PTTs (n = 28 [Boggie et al. 2018b; PTT-100, 22-g Solar Argos/GPS PTT, Microwave Telemetry, Columbia, MD, USA]). These GPS PTTs had a horizontal locational accuracy of ±18 m and vertical locational accuracy of ±22 m (95% CI = 22 m). The GPS PTT transmitters provided an average fix rate of 3.9 locations/bird/day (Table 1); we collected flight paths from all telemetered birds (Fig. 2).

We acquired a permit from the USGS Bird Banding Laboratory to band and attach transmitters to sandhill cranes (permit 23660), and a Scientific Collection permit from the New Mexico Department of Game and Fish (3536) to capture and study sandhill cranes on the BldANWR and Ladd S. Gordon Waterfowl Complex. We acquired a portion of the data analyzed here from New Mexico State University. The New Mexico State University Institutional Animal Care and Use Committee approved collection of these data (protocol 2014–018).

Statistical Analysis

We quantified exposure rates at hypothetical transmission line crossings along the MRGV in 3 steps. First, we pre-processed the data to filter potential errors and to focus the analysis on daytime movements. Second, we fit a model of flight heights as a function of latitude. Third, we applied the model to estimate the passage rate through pre-defined hypothetical transmission lines (i.e., a straight line running east-west to represent a hypothetical transmission line) located every 500 m along the MRGV and extending 10 km beyond the east-west boundaries. We calculated 5 quantities of interest at each hypothetical transmission line: individual passage rate (passes/crane/day), population passage rate (passes/day), individual exposure rate (exposed passes/crane/day), population exposure rate (exposed passes/day), and the population exposure rate over the entire wintering season (exposed passes/winter).

We pre-processed movement data to arrive at a set of movement heights during daytime hours specific to the MRGV. First, we dropped observations falling outside of our focal study area because the full data set included observations from non-winter seasons outside the MRGV. The study area was demarcated by a 10-km east-west buffer around the MRGV polygon defined by Boggie et al. (2018b; Fig. 2); the north-south extent of the corridor was not buffered. Second, we dropped GSM PTT observations with unreliable altitude estimates as indicated by fixes that were not 3-dimensional; we retained all observations collected by GPS PTTs because fix reliability information was not supported by these units. Third, we calculated movement height as the recorded altitude minus the ground elevation at the observation coordinates, using the 10-m USGS 3DEP digital elevation model (DEM) product (https://www.usgs.gov/core-science-systems/ngp/3dep, accessed 14 Feb 2020). Last, we filtered the data to daytime movements by excluding all points falling outside 1.5 hours before sunrise to 1.5 hours after sunset on any given date (sunrise and sunset times

Table 1. Summary and sample sizes of location data collected on sandhill cranes wintering in the Middle Rio Grande Valley (MRGV), New Mexico, USA, 2014–2020. We calculated bird-days for locations observed within our study area.

<table>
<thead>
<tr>
<th>Data set</th>
<th>Years</th>
<th>Type</th>
<th>Birds</th>
<th>Bird-days (in MRGV)</th>
<th>Number of locations</th>
<th>Locations per crane per day</th>
<th>Horizontal error (m)</th>
<th>Vertical error (SD; m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>USFWS</td>
<td>2018–2020</td>
<td>GSM</td>
<td>27</td>
<td>3,417.14</td>
<td>44,970</td>
<td>20.2</td>
<td>18</td>
<td>7</td>
</tr>
<tr>
<td>WEST-GSA</td>
<td>2019–2020</td>
<td>GSM</td>
<td>26</td>
<td>1,510.38</td>
<td>95,081</td>
<td>61.7</td>
<td>18</td>
<td>7</td>
</tr>
<tr>
<td>Boggie et al. (2018b)</td>
<td>2014–2016</td>
<td>GPS</td>
<td>28</td>
<td>5,534.58</td>
<td>19,336</td>
<td>3.9</td>
<td>18</td>
<td>11</td>
</tr>
<tr>
<td>Total</td>
<td>2014–2020</td>
<td></td>
<td>81</td>
<td>10,462.07</td>
<td>159,387</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Data sets are defined by the primary organization that deployed the units or to resulting publication: USFWS = U.S. Fish and Wildlife Service; WEST-GSA = Western EcoSystems Technology and GeoSystems Analysis.

b GSM = Global system for mobile communication; GPS = global positioning system.
were retrieved with the suncalc R package; Thieumel and Elmarhraoui 2019). We excluded 177 recorded nighttime movements out of 253,398 observations to focus on travel between roosts and foraging locations, which mostly occur during dawn and dusk. By excluding nighttime movements, our results were comparable to results from other field studies in the region, which also typically exclude nighttime observations.

We fit a nonparametric spline model (Hastie and Tibshirani 1990) to the movement height data that allowed prediction of movement heights as a function of latitude in the MRGV. The response variable was log(height) and the predictor variable was latitude. We used the R function smooth.spline, which is part of the core stats package in the R computing environment (R Core Team 2020). We used the default algorithm for choosing model complexity. We exponentiated predictions to back-transform from the log scale.

We quantified uncertainty around the spline-based estimate of the movement height distribution using a non-parametric bootstrap with individual birds as the sampling unit (i.e., a block bootstrap; Cameron et al. 2008). We implemented 1,000 bootstrap replications. For each bootstrap replicate, we sampled bird identification without replacement (n = 81) and fitted the smoothing spline to observations corresponding with the sampled bird identifications. We incorporated measurement error by sampling each observation from a truncated (at zero) normal distribution (using the truncnorm R package; Mersmann et al. 2018), with the mean equal to observed height and the standard deviation (SD) equal to the manufacturer-supplied error for each device (SD for GSM/GPS PTT = 7 m, SD for GPS PTT = 11 m). We used the 0.025 and 0.975 quantiles of the bootstrap distribution to define the 95% confidence interval. We used the full bootstrap distribution to calculate the probability of a movement occurring in the exposure zone.

We calculated the individual passage rate at each hypothetical transmission line by overlaying the movement paths of all cranes and summing the number of paths that crossed each hypothetical line; passes included cranes moving at any height. We calculated survey effort by summing the number of days we observed all birds in the MRGV between 15 November and 15 March across all years. We divided the number of passes at each hypothetical line by the survey effort (units = passes/crane days), yielding the individual passage rate (passes/crane/day); we multiplied individual passage rate by population size to calculate the population passage rate (passes/day).

We calculated individual exposure rate (exposed passes/day/crane) by multiplying individual passage rate by the probability that any given pass occurred in the exposure zone. For our purposes, the exposure zone was 7–60 m above ground level because most power lines in the United States are <61 m tall (APLIC 2012) and sandhill cranes rarely fly between or under power lines (Morkill and Anderson 1991; Murphy et al. 2009, 2016). We used 7 m because it is the median of a truncated normal distribution with mean zero and SD equal to 11, which is the largest SD in our data set for vertical location error, and this avoids biasing exposure calculations owing to measurement error. We used the spline model predictions to calculate the probability of a pass occurring within the exposure zone at each hypothetical transmission line. We then multiplied the individual exposure rate by population size to calculate the population exposure rate (exposed passes/day).

We used 3 population size estimates of wintering sandhill cranes in the MRGV to scale the exposure rate, corresponding to a low estimate (20,000; Boggie et al. 2018b), a median estimate (45,000; Pacific Flyway Council and Central Flyway Council 2016), and a high estimate (70,000; Pacific Flyway Council and Central Flyway Council 2016, Sanchez and Cline 2020). The median and high population size estimates combine the RMP and the MCP; the low estimate is approximately the current reported size of the RMP (Thorpe et al. 2019). We used the duration of the winter season to calculate the population exposure rate in a typical winter season (exposed passes/winter). We defined the winter season as 81.1 days, which is the average of the winter residence time we observed in our data (74.3 days) and the residence time reported by Boggie et al. (2018a; 88 days).

RESULTS

After we filtered data, we retained 159,387 locations for 81 individual cranes on 760 dates (Table 1; Fig. 2) and the survey effort amounted to 10,462.07 bird-days. The average recorded flight height was 32.8 m (median = 4 m); flight heights ranged from 0 to 2,606 m. On average, telemetered cranes spent 74.3 days wintering in the MRGV; length of stay ranged from 4.2 to 146.8 days. We estimated a spatially explicit flight height distribution that clearly resolved variation in flight heights across the MRGV (Fig. 3A). Flight heights were generally lowest at key resource areas, including the BdANWR and the Bernardo Wildlife Area within the Ladd S. Gordon Waterfowl Complex (Fig. 3).

Individual passage rates ranged from 0.002 passes/crane/day to 0.47 passes/crane/day across hypothetical transmission lines (median = 0.03; Fig. 4). Population passage rates for a winter season ranged from approximately 2,950 passes at the hypothetical line with the lowest passage rate and assuming the smallest population size, to approximately 2,854,600 passes at the hypothetical line with the highest passage rate and assuming the highest population estimate (median = 92,092 assuming the median population size and the intermediate population size). Passage rates were highest near the Bernardo Wildlife Area, near the BdANWR, and near portions of the Ladd S. Gordon Waterfowl Complex north of the Bernardo Wildlife Area (Fig. 4).

Individual exposure rates (passage rate × exposure probability) ranged from 0.00 exposed passes/crane/day to approximately 0.28 exposed passes/crane/day (median = 0.02; Fig. 4). Population exposure rates for a winter season ranged from 0.00 exposed passes at the hypothetical line with the lowest exposure rate and assuming the smallest population size, to approximately 1,707,050 exposed passes at the
hypothesized line with the highest exposure rate and assuming the largest population size (median = 55,674 assuming the median exposure rate and the intermediate population size). Exposure rates were highest near the Bernardo Wildlife Area, slightly lower near portions of the Ladd S. Gordon Waterfowl Complex north of the Bernardo Wildlife Area, and low near BdANWR because most bird movements occurred below 7 m (Fig. 4). Overall, estimated exposure rates varied substantially across the MRGV (Fig. 4), differentiating exposure hotspots from areas with little exposure.

DISCUSSION

We provide spatially explicit estimates of exposure rates of sandhill cranes to collision with hypothetical transmission lines across the MRGV. Our results suggest low collision exposure on average while also identifying exposure hotspots on the landscape. Development of a transmission line at many locations in the MRGV would pose little risk to sandhill cranes.

Our estimates of flight heights and exposure rates reflected spatial variation in crane behavior. The current matrix of publicly owned properties (i.e., Ladd S. Gordon Waterfowl Complex and BdANWR) managed at least in part for conserving crane populations provide roosting and feeding areas to many overwintering cranes. In these areas, cranes have a high likelihood of interacting with a hypothetical transmission line each time they move from roosting to foraging areas, resulting from high passage rates at low altitudes. Exposure is especially high in areas used for commuting between roosting and foraging sites (McNeil et al. 1985, Janss and Ferrer 2000). In contrast, cranes rarely passed through the exposure zone in and around Albuquerque because they generally traveled over Albuquerque at relatively high altitude when entering or exiting the MRGV.

Although there are likely small numbers of cranes roosting and foraging in Albuquerque that we did not sample, our observations suggest most flights are at high altitudes over the city. Thus, our estimates of exposure rates broadly correspond to differences in how cranes use the landscape (Brown and Drewien 1995, Henderson et al. 1996, Janss and Ferrer 2000) and align with known patterns of increased exposure in flocking species regularly commuting at low altitudes compared to solitary species that fly infrequently and at high altitudes (Jenkins et al. 2010). Similarly, Morkill and Anderson (1991) reported cranes on short foraging or other local flights were more likely to fly at low altitudes and react to power lines.

Figure 3. Flight height distribution of 81 sandhill cranes telemetered with platform transmitter terminal (PTT) tags from 2014–2020 in the Middle Rio Grande Valley, New Mexico, USA. A) Distribution of flight heights across latitudes. Grey points show the observed height, solid and dashed lines show the mean and quantile limits (0.025 and 0.975), respectively, across 1,000 bootstrapped estimates. The red horizontal lines delimit the exposure zone (7–60 m above ground level), and the vertical lines show the locations of 2 key resource areas (i.e., Bosque del Apache National Wildlife Refuge and Bernardo Wildlife Area) and the city of Albuquerque. The y-axis is truncated at an upper bound of 900 m for visualization purposes. B) Estimated probability of any particular flight occurring within the defined exposure zone of 7–60 m.
Disparate roosting and foraging habitats create opportunities for exposure during flights between these 2 areas. Other habitat features can constrain flight paths and funnel birds to riskier areas. For example, Wright et al. (2009) reported that most power line collisions by sandhill cranes occurred when vegetation or topographical features diverted birds towards power lines (Faanes 1987, Bevanger 1994, Savereno et al. 1996). On the Platte River in Nebraska, USA, riverside willows and cottonwoods likely confined crane movements to and from the roost and exacerbated mortality caused by power line collisions (Wright et al. 2009). Tall shrubs and trees expanded along the Platte River during the past century, coinciding with decreased river flows resulting from construction of dams and diversion canals (Johnson 1994). Other factors reducing visibility, especially strong winds and precipitation, can increase the likelihood of collision by cranes with power lines (Stehn and Wassenich 2008). Although we did not explicitly link exposure to habitat features or environmental conditions in this study, our use of round-the-clock GPS telemetry data means risk-inducing habitat features and environmental conditions were present in our data set in proportion to the rate at which cranes encounter them in the MRGV.

Exposure rates are highly sensitive to the definition of the exposure zone (i.e., how much the flight height distribution overlaps the exposure zone). Our decision to set the exposure zone at a minimum of 7 m, representing 0 m given the error associated with our data, is corroborated by studies indicating sandhill cranes react and fly over power lines or

Figure 4. Estimated individual passage rate (left panel) and individual exposure rate (center panel) for sandhill cranes across the Middle Rio Grande Valley, New Mexico, USA, 2014–2020. Each color ramp uses 5 equal-interval bins with upper limits inclusive (e.g., the lowest-value bin in the left panel includes 0.10 passes/crane/day) and scaled to the range of values observed for each statistic. Histograms (right panel) show flight height distributions of sandhill cranes at Albuquerque, Bernardo Wildlife Area, and Bosque del Apache National Wildlife Refuge. Flight height distributions come from bootstrapped replicates of the fitted spline model. Vertical dashed lines show the boundaries of the 7–60-m exposure zone. Text in each histogram panel shows the individual passage rate (passes/crane/day), the probability of any given flight occurring in the exposure zone (Pr(exposed)), and the resulting individual exposure rate (exposed passes/crane/day).
change flight direction to avoid collision (e.g., flare; Brown et al. 1987; Faanes 1987; Murphy et al. 2009, 2016). For example, Morkill and Anderson (1991) reported cranes tended to fly 1–5 m above the overhead shield or static wires of power lines.

Even with our conservatively broad exposure zone, we estimated low exposure rates to collision with hypothetical transmission lines throughout most of the MRGV. The median exposure rate we estimated across all hypothetical transmission lines was 0.015 exposed pass/crane/day, resulting in 25,000 (low population size estimate) to 93,000 (high population size estimate) exposed crane passes/winter season (assuming an 81.1-day residence period). We described risk hotspots in key resource areas at which crane collisions with infrastructure would be expected to be high relative to infrastructure sited elsewhere. Nevertheless, 50% of the hypothetical transmission lines we evaluated had exposure rates under 0.015 exposed pass/crane/day. Using even the most pessimistic collision probabilities of 30 fatal collisions/100,000 exposed passes estimated for cranes encountering power lines while flying in Colorado, USA (Brown and Drewien 1995), a median exposure rate of 0.015 exposed pass/bird/day, a population size of 45,000, and a residence period of 81.1 days would result in 17 or fewer sandhill cranes being killed each year at 50% of the hypothetical transmission lines we evaluated. At 25% of the hypothetical lines we evaluated, ≤2 sandhill cranes would be killed each year (0.25 quantile of exposure rate = 0.002).

To put this in context, 1,524 cranes in the RMP were known to be removed from the population through recreational hunting in 2018, with 623 of those harvested in New Mexico (Dubovsky 2019). Thus, there are many locations along the MRGV where infrastructure such as transmission lines would likely have a negligible effect on crane populations relative to other pressures. Our analysis also suggests cranes migrating into and out of the MRGV are often at heights well above the exposure zone, allowing for safe entry into and exit from this crucial wintering area.

Translating our results into estimates of crane mortality associated with transmission lines requires an estimate of collision probability (i.e., the probability that a collision occurs when a crane encounters a transmission line when flying within the defined exposure zone). Existing estimates of collision probability associated with sandhill cranes encountering power lines are highly uncertain (Brown and Drewien 1995) and were not suitable to apply to this study. More specifically, the collision probabilities estimated in Brown and Drewien (1995) are unlikely a reasonable surrogate for collision rates for modern high-voltage transmission lines in the MRGV because Brown and Drewien (1995) observed cranes at power lines that were much lower voltage (≤145 kilovolts [kV]) than current high-voltage transmission lines (often 138–700 kV; APLIC 2018), and voltage is a primary determinant of the height, number, configuration, and diameter (and hence visibility) of power line conductor and ground wires (APLIC 2012). Lacking a reliable estimate of collision probability, we chose not to estimate the total number of collisions that would occur at each hypothetical transmission line. Future research in this important wildlife corridor should focus on estimating collision probabilities, which could then be coupled with our exposure estimates to estimate number of collisions. In particular, estimates of collision probability that could be scaled relative to the height and width of the exposure zone would have the greatest utility.

**MANAGEMENT IMPLICATIONS**

Responsibly siting energy infrastructure requires a landscape-level assessment of potential exposure of wildlife to collision or other harmful interactions with that infrastructure. Our analysis provides a spatially explicit, quantitative, landscape-level risk assessment identifying hotspots of collision risk for sandhill cranes that can be used in the siting of high-voltage transmission lines in the MRGV. Using our analysis, managers can work to balance collision risk with other pressures on sandhill cranes in the MRGV, such as hunting, and our analysis can be adapted to perform detailed, site-specific evaluations of proposed or actual transmission structures based on design specifications. Managers could also readily adapt our analysis to evaluate exposure to other linear or horizontal features with different exposure zones (e.g., distribution power lines, pipelines, bridges). For the construction of potential high-voltage transmission lines, our analysis suggests there are many locations within the MRGV where a transmission line would present a relatively low collision risk to wintering sandhill cranes. Siting transmission lines in the areas along the MRGV with relatively low exposure likely poses little risk to crane populations, and optimal siting can be coupled with additional mitigation measures, such as increasing line visibility (Dwyer et al. 2019), to minimize exposure.

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