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RESEARCH ARTICLE

Wintering Sandhill Crane exposure to wind energy development in the central and southern Great Plains, USA

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ABSTRACT

Numerous wind energy projects have been constructed in the central and southern Great Plains, USA, the main wintering area for midcontinental Sandhill Cranes (*Grus canadensis*). In an initial assessment of the potential risks of wind towers to cranes, we estimated spatial overlap, investigated potential avoidance behavior, and determined the habitat associations of cranes. We used data from cranes marked with platform transmitting terminals (PTTs) with and without global positioning system (GPS) capabilities. We estimated the wintering distributions of PTT-marked cranes prior to the construction of wind towers, which we compared with current tower locations. Based on this analysis, we found 7% spatial overlap between the distributions of cranes and towers. When we looked at individually marked cranes, we found that 52% would have occurred within 10 km of a tower at some point during winter. Using data from cranes marked after tower construction, we found a potential indication of avoidance behavior, whereby GPS-marked cranes generally used areas slightly more distant from existing wind towers than would be expected by chance. Results from a habitat selection model suggested that distances between crane locations and towers may have been driven more by habitat selection than by avoidance, as most wind towers were constructed in locations not often selected by wintering cranes. Our findings of modest regional overlap and that few towers have been placed in preferred crane habitat suggest that the current distribution of wind towers may be of low risk to the continued persistence of wintering midcontinental Sandhill Cranes in the central and southern Great Plains.

Keywords: Grus canadensis, Sandhill Crane, resource selection function, risk assessment, satellite telemetry, wind energy

Exposición de individuos invernantes de *Grus canadensis* al desarrollo de energía eólica en el centro y sur de las Grandes Planicies, EEUU

RESUMEN

Numerosos proyectos de energía eólica han sido construidos en el centro y sur de las Grandes Planicies, EEUU, la principal área de invernada para individuos del centro del continente de *Grus canadensis*. En una evaluación inicial del riesgo potencial de las torres eólicas para las grullas, estimamos la superposición espacial, investigamos el comportamiento de una potencial evasión y determinamos las asociaciones de hábitat de las grullas. Usamos datos de grullas marcadas con terminales transmisoras de plataforma (TTPs) con y sin sistemas de posicionamiento global (SPG). Estimamos la distribución invernal de individuos marcados con TTP antes de la construcción de las torres eólicas, y la comparamos con la localización actual de las torres. Basados en este análisis, encontramos un 7% de superposición espacial entre las distribuciones de las grullas y las torres. Cuando analizamos individualmente las grullas marcadas, encontramos que 52% habrían estado dentro de los 10 km de las torres en algún momento durante el invierno. Usando datos de grullas marcadas luego de la construcción, encontramos indicadores de potencial evasión, donde las grullas marcadas con SPG generalmente usaron áreas ligeramente más distantes de las torres eólicas existentes de lo que se esperaría por azar. Los resultados de los modelos de selección de hábitat sugirieron que las distancias entre las localizaciones de las grullas y las torres habrían sido ocasionadas por selección de hábitat más que por evasión, ya que la mayoría de las torres eólicas fueron construidas en lugares no altamente seleccionados por las grullas invernantes. Nuestros resultados de una baja superposición regional y de que unas pocas torres han sido ubicadas en hábitat de preferencia de las grullas sugieren que la distribución actual de las torres eólicas pueden ser de bajo riesgo para la persistencia de los individuos del centro del continente de *G. canadensis* en esta región.

Palabras clave: energía eólica, evaluación de riesgo, función de selección de recursos, *Grus canadensis*, telemetría satelital

INTRODUCTION

Initiatives to develop renewable energy sources in the United States have resulted in the installation of thousands of wind towers, with the capacity to generate >61,000 megawatts of energy as of 2013 (Diffendorfer et al. 2014, Wiser et. al 2014). One main purpose of developing such capacity is to generate energy with reduced environmental harm compared with conventional means, yet there is the potential for wildlife to be negatively affected by structures used to generate and distribute energy from wind (Arnett et al. 2007, Marques et al. 2014, Smith and Dwyer 2016). As energy infrastructure has developed, information has been gained regarding interactions between wind energy structures and wildlife, providing an initial basis for understanding how wildlife populations may be negatively affected (Johnson and Stephens 2011, Diffendorfer et al. 2015). Wind energy infrastructure can affect wildlife populations, especially those of bats and birds, by increasing mortality through animals striking structures, direct habitat destruction for the building and maintenance of structures, and indirect habitat loss via displacement (Drewitt and Langtson 2006, Ludlow et al. 2015, Winder et al. 2015, Mahoney and Chalfoun 2016). Assessing the potential risk of wind energy development to wildlife species is especially critical for species of conservation concern, game species, and surrogate species (Caro and O'Doherty 1999). Accordingly, numerous assessments of wind energy infrastructure–wildlife impacts have been conducted by determining the occurrence of species in relation to proposed sites (e.g., Bright et al. 2008, Pocewicz et al. 2013, Loring et al. 2014, Watson et al. 2014).

The installation of commercial wind energy facilities in the central and southern Great Plains, USA, has increased rapidly, from fewer than 100 towers active in 2000 to nearly 10,000 towers constructed by 2014 (Diffendorfer et al. 2014). The central and southern Great Plains also are used extensively by the midcontinental population of Sandhill Cranes (*Grus canadensis*), which remain in the region for up to 6 mo each winter (Krapu et al. 2011, 2014). A lack of information regarding the potential risks posed by wind energy facilities to Sandhill Cranes and other crane species presents a knowledge gap toward furthering the conservation of cranes worldwide (Harris and Mirande 2013).

Certain morphological traits suggest that Sandhill Cranes may be at risk of colliding with wind towers. Many bird species have a limited ability to perceive structures (Martin 2011), and cranes specifically may have a reduced capability of avoiding obstacles due to their wing morphology and body mass (i.e. wing loading), which can limit their maneuverability (Janss 2000). Documented mortalities of Sandhill Cranes related to power line strikes are common (Tacha et al. 1979, Windingstad 1988, Morkill and Anderson 1991, Brown and Drewien 1995). Yet, even with thousands of wind towers in a region where 80% of the entire population resides for up to half of the year, few Sandhill Cranes have been found killed due to collisions with towers (Grodsky et al. 2013, Loss et al. 2013, Bird Studies Canada 2014, Navarrete and Griffis-Kyle 2014).

Perhaps of greater concern than collision mortality is the potential for avoidance of areas near towers, thereby reducing available roosting and foraging habitat. Sandhill Cranes generally prefer roosting sites with a large field of view, within which they can detect danger visually (Lewis 1976, Lovvorn and Kirkpatrick 1981, Krapu et al. 1984, Navarrete 2011); hence, large features such as wind towers on a previously open landscape may preclude the use of otherwise suitable roosting and foraging sites, causing effective habitat loss or influencing behavior (Navarrete 2011). Avoidance and displacement effects postconstruction have been observed in various bird species (e.g., Devereux et al. 2008, Pearce-Higgins et al. 2009, Loesch et al. 2013, Niemuth et al. 2013, Luzenski et al. 2016; but see Hale et al. 2014).

We assessed the exposure of wintering Sandhill Cranes to the current distribution of wind towers in the central and southern Great Plains by estimating overlap using location data from platform transmitting terminals (PTT) collected during the winters of 1998–2004. Because 90% of wind towers in the region were installed in 2004–2013 (Diffendorfer et al. 2014), comparing an established distribution of wind towers (as of January 2014) with preconstruction crane distribution provides an initial assessment of the midcontinental population's exposure. We determined the potential displacement behavior of individual cranes in proximity to established wind towers using postconstruction location data from Sandhill Cranes marked with transmitters that provided global positioning system (GPS) location data. We also used GPS location data to estimate resource selection functions (RSF) and to compare locations used by cranes with the placement of wind towers (Loring et al. 2014, Miller et al. 2014, Watson et al. 2014). Simultaneous assessments of exposure, avoidance, and habitat associations provided the opportunity to gain a regional perspective on how tower placements overlap with wildlife populations, assess potential avoidance of towers, and identify specific sites and towers where risks may be significant.

METHODS

Study Site and Species

Given the wintering distribution of midcontinental Sandhill Cranes, we limited our assessment to portions of the south-central semiarid prairies of the Great Plains ecoregion within the states of Kansas, New Mexico, Oklahoma, and

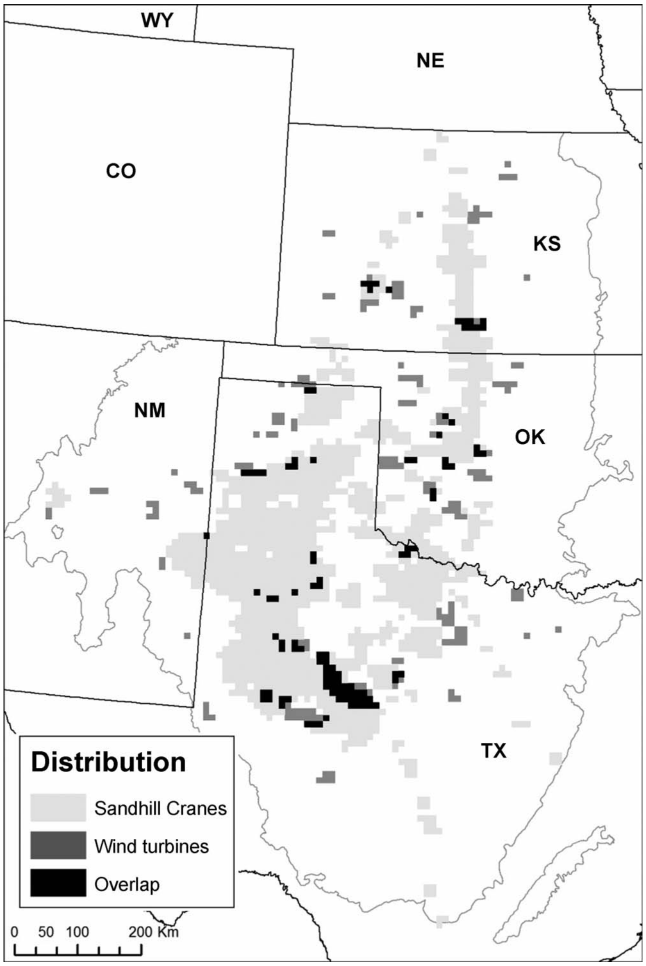

FIGURE 1. Geographic distributions of midcontinental Sandhill Cranes during the winters of 1998–2004 and wind energy towers constructed in 1999–2013 (Diffendorfer et al. 2014), and the overlap of cranes and towers within the central and southern Great Plains, USA. The geographic unit of analysis was 100-km^2 grid cells. The study area is outlined in gray, with state borders drawn in black.

Texas (Commission for Environmental Cooperation 1997). The resulting study area was 76.8 million ha (Figure 1). This region represents the central and southern Great Plains and includes short-, mid- and tallgrass prairie ecosystems. The dominant land use was agricultural production, mainly livestock grazing and cultivation of crops (Wilkins et al. 2009). Wetlands of various types were found throughout the region, including major river systems, isolated playa wetlands, reservoirs (primarily for flood control), and impoundments associated with livestock production. The region resides within the administrative boundaries of the Central Flyway, and provides migrating and wintering habitat for millions of migratory waterfowl and other waterbirds, including the midcontinental population of Sandhill Cranes (Central Flyway Webless Migratory Game Bird Technical Committee 2006, Krapu et al. 2011).

The midcontinental population of Sandhill Cranes is the most abundant population of the 2 crane species in North America, with >500,000 individuals (Kinzel et al. 2006, Gerber et al. 2014), and long-term surveys suggest that the population has been relatively stable over the past 30 yr (Kruse and Dubovsky 2015). Midcontinental Sandhill Cranes are popular for sport harvest in North America (Central Flyway Webless Migratory Game Bird Technical Committee 2006), and this population also attracts tens of thousands of wildlife watchers during spring staging along the Platte River in central Nebraska (Lingle 1992). Individuals from this population breed in a variety of ecoregions, from Arctic tundra to temperate grasslands, from western Quebec in the east across the Canadian Arctic and Alaska to northeastern Russia in the west. They spend ~4–6 mo on their wintering grounds, arriving from mid-October and departing in early March (Krapu et al. 2011).

Field Methods and Location Data

We captured cranes using taxidermy-mounted decoys and rocket-propelled nets; further descriptions of capture, handling, and marking methods are detailed in Krapu et al. (2011, 2014). During February–April in 1998–2003, a sample of midcontinental Sandhill Cranes was captured and marked with PTTs in the North and Central Platte River Valleys of Nebraska (Microwave Telemetry, Columbia, Maryland, USA, and North Star Science and Technology, Baltimore, Maryland, USA). Krapu et al. (2011) described procedures designed to mark and monitor cranes from the midcontinental population using a sampling scheme that approximated the migration chronology and geographical distribution of cranes using the region. During March–April of 2009 and 2011, Sandhill Cranes in the Central and North Platte River Valleys were captured and marked with PTTs capable of collecting GPS locations (North Star Science and Technology).

The methods that we used to prepare location data from PTTs for analysis followed those described by Krapu et al. (2011, 2014). The transmission rates of PTTs varied with the generation of transmitter and season; generally, they were set to transmit every ≤10 days. Locations of PTT-marked cranes were resolved by the Argos satellite system (Service Argos 2008), and we processed all locations with the Douglas Argos-Filter Algorithm, version 6.5, combined with further subjective review (Douglas et al. 2012). For each location, quality codes or location classes (LC) were assigned by Argos to identify relative accuracy based on multiple factors (Service Argos 2008). We used accuracy estimates from transmitters similar to those reported in Douglas et al. (2012; also see Appendix Table 4). Each location was binned into 1 of 4 life history categories (i.e. breeding, fall migration, spring migration, wintering), based on manual inspection of movement patterns with respect to time of year. For this study, we used only wintering locations. To further refine PTT location data, we retained only locations within the study area of interest and then removed spatially redundant points by selecting the best location (i.e. greatest precision based on LC) of all locations collected within 5 km during each transmission cycle for each bird. Therefore, our final dataset included $\geq$1 location from each marked crane during each transmission, including all locations >5 km from each other.

Transmitters that provided GPS data collected 3–4 locations daily at equal time intervals. We retained only GPS data from within the study area and those that recorded an instantaneous velocity of <2.5 m s^{-1}, which we assumed was indicative of locations acquired while the crane was on the ground rather than flying. We identified each point as having been collected during winter using procedures described in Krapu et al. (2011) and above.

We identified all wind towers within our study area listed by Diffendorfer et al. (2014), resulting in 9,577 locations. From this group, we removed any records for which analysts were unable to confirm locations from available imagery, those identified as decommissioned, those identified as water windmills, and smaller installments (type = 'small trestle'). Our final set for analyses included 9,233 wind towers. Towers were installed between 1999 and 2013, with 1% reporting an unknown installation date. Ninety percent were constructed after 2004. The majority of towers were located within the state of Texas (61%), followed by Oklahoma (19%), Kansas (15%), and New Mexico (5%).

Data Analyses

Potential spatial overlap and individual exposure. We estimated the spatial distribution of wintering Sandhill Cranes throughout the study area using PTT data from 1998 to 2004. We employed a grid-based method that incorporated position error expected with PTT data (Tougaard et al. 2008, Douglas et al. 2012; Appendix Table 4). We divided the study area into 10 km $\times$ 10 km (100 km^2) units, and estimated the probability that cranes provided a location for each 100-km^2 cell and the likely number of locations (relative intensity of use) within each cell, assuming that location error could be described by an uncorrelated bivariate Gaussian distribution (Tougaard et al. 2008). Douglas et al. (2012) reported the error for transmitters similar to those that we deployed and with similar data filtering techniques. We used the supplementary data provided to derive errors (68% percentiles) for use in calculations (Douglas et al. 2012; Appendix Table 4).

We used the same grid system as above to determine the distribution of wind towers in the region. For each cell, we determined if at least 1 tower existed and the total number of towers within the cell. Potential spatial exposure was defined as the percentage of cells that had >10% probability of $\geq$1 crane locations and occurrence of $\geq$1 wind tower.

Distance from wind towers. We calculated the percentage of crane GPS locations $\leq$10 km from constructed towers during the winters of 2009–2013, because recent work suggests that potential avoidance occurs within 8 km (Navarrete 2011). We calculated the distance between each location and the nearest established wind tower <10 km away, as determined by the year the tower was identified as initially becoming active by Diffendorfer et al. (2014). We estimated mean distance using a linear model that included year and bird identity as random effects. We compared mean distance against a value of 5.0 km, which would be the average from a random uniform distribution (i.e. no attraction or displacement in relation to the presence of wind towers).

Resource selection functions. We investigated the habitat selection of wintering cranes to determine whether towers have been placed in areas with habitat characteristics preferred by cranes. We used GPS data from cranes wintering exclusively within Texas because of the limited number of bird locations obtained outside Texas. We generated minimum convex polygons around GPS locations for each individual crane and winter season. Within these winter home ranges, we selected 10 random locations for each use location to serve as points available to cranes within a particular home range that winter. We collected 5 covariates to model RSFs (Table 1). Land cover was a categorical representation of the region (30-m^2 resolution; U.S. Geological Survey 2011). We included 6 categories for our analyses (cropland, grassland, forest or scrubland, wetland or water, development, and other). Additionally, we generated a covariate that described the distance to potential surface water (i.e. wetland basin). Initially, we collapsed all National Wetland Inventory basins identified as lacustrine and palustrine and attached to them the modifier describing the deepest water regime of all wetland polygons in each contiguous basin (Cowardin et al. 1995, Reynolds et al. 1996, U.S. Fish and Wildlife Service 2014). Using all water regimes for lacustrine wetlands and only water regimes identified as semipermanently or permanently flooded for palustrine wetlands, we calculated a distance raster with a cell size of 10 m $\times$ 10 m to identify the distance of used and available points to potential surface water features. We also included a relative measure of human disturbance (Sanderson et al. 2002). Values were derived by identifying human influences on the environment from factors such as population density and various forms of infrastructure, resulting in a spatially explicit relative index score calculated for each 1-km^2 cell (scale: 0–64). Finally, we included elevation and

TABLE 1. Summaries of covariates used to model resource selection functions at locations used by and available to Sandhill Cranes wintering on the Texas High Plains, 2011–2013.

	Used			Available		
Covariate	Mean	Median	Range	Mean	Median	Range
Distance to water (km)	0.46	0.00	0.00–7.25	1.22	0.97	0.00–8.46
Elevation (m)	1,070	1,130	432–1,299	1,050	1,074	448–1,300
Slope (°)	0.2	0.0	0.0–8.0	0.6	0.0	0.0–47.0
Index of human activity	12.5	9.0	4.0–46.0	12.7	9.0	0.0–60.0
Land cover (%)						
Cropland	33			54		
Development	1			5		
Forest	2			10		
Grassland	15			29		
Wetland	48			1		
Other	1			1		

slope as covariates of interest (30-m^2 resolution; U.S. Geological Survey 2011).

We constructed 16 models to describe the RSFs of wintering cranes (Table 2). All models included the distance to a wetland basin and all combinations of the other main effects using the remaining covariates described above. We estimated RSFs using a mixed-model logistic regression, in which individual crane-seasons were included as random effects. This method has been identified as preferable with an unbalanced design (Gillies et al. 2006); locations per individual crane-season ranged from 101 to 487. We fit models using the 'glmer' function within the lme4 library as implemented in R 3.1.1 (Bates et al. 2015; R Foundation for Statistical Computing, Vienna, Austria). We selected candidate models using Akaike's Information Criterion (AIC), ranked models based on differences in AIC values, and calculated model weights (w_i; Burnham and Anderson 2002). We evaluated model fit by using the k-fold cross-validation methods described by Johnson et al. (2006). We partitioned our data into 4 k-folds based on the Huberty (1994) rule of thumb, and classified all resource units into 5 categories for validation analyses. We compared observed

TABLE 2. Model selection results for resource selection functions of wintering GPS-marked Sandhill Cranes on the Texas High Plains, 2011–2013.

Model structure [a]	K [b]	ΔAIC [c]	ΔAIC [c]	w_i [d]	Dev [e]
DW + LC + ELV + SLP + HI	11	0.0	0.0	0.995	26960.1
DW + LC + ELV + SLP	10	10.5	10.6	0.005	26972.6
DW + LC + ELV + HI	10	197.6	197.6	0.000	27159.7
DW + LC + ELV	9	207.8	207.8	0.000	27171.9
DW + LC + SLP + HI	10	386.1	386.1	0.000	27348.2
DW + LC + SLP	9	398.4	398.4	0.000	27362.5
DW + LC + HI	9	659.2	659.2	0.000	24623.3
DW + LC	8	670.6	670.6	0.000	27636.7
DW + ELV + SLP + HI	6	7662.7	7662.8	0.000	34632.8
DW + ELV + SLP	5	7692.6	7692.7	0.000	34664.7
DW + ELV + HI	5	7981.6	7981.6	0.000	34953.7
DW + ELV	4	8006.5	8006.5	0.000	34980.6
DW + SLP + HI	5	8077.1	8077.1	0.000	35049.2
DW + SLP	4	8105.7	8105.8	0.000	35079.8
DW + HI	4	8524.2	8524.3	0.000	35498.3
DW	3	8544.8	8544.9	0.000	35520.9

[a] DW = Distance to nearest semipermanent or permanent lacustrine wetland basin; LC = categorical land cover variable with 6 levels (cropland [reference], wetland, forest, grassland, developed, other); ELV = elevation; SLP = degree of slope; HI = index of human activity.
[b] Number of estimated parameters.
[c] Difference between the minimum Akaike's Information Criterion (AIC) value and the AIC of the current model. The AIC of the top model = 26982.1.
[d] Model weight.
[e] Model deviance.

numbers of used resource units for each k-fold with those expected after weighting by the proportions within each bin (Johnson et al. 2006). These comparisons included a linear regression to determine whether the intercept was different from 0 and the slope different from 1.0, and chi-square goodness-of-fit tests.

We determined covariate values for wind tower locations within the Texas High Plains that were within areas used by Sandhill Cranes ($n = 4{,}956$). Using the RSF results from the crane analysis, we predicted the RSFs of tower locations from the top model for cranes, which allowed us to determine a relative measure of the probability of use by cranes where each tower was located. We compared the RSFs predicted at crane and tower locations to evaluate the presence of wind towers within habitats generally selected by wintering cranes.

RESULTS

Spatial Overlap

Eighty-nine Sandhill Cranes provided PTT data between 1998 and 2004 from a total of 153 individuals marked at the Platte River (Krapu et al. 2011). Some marked cranes provided data in multiple seasons, resulting in 96 crane-seasons during winter. We selected 3,852 location points from PTT data for co-occurrence analyses. We used all LCs, which refer to different levels of location data quality, for our analyses; 19% of data were LC-3, 13% LC-2, 18% LC-1, 27% LC-0, 12% LC-A, 10% LC-B, and 1% LC-Z. Although we included data from 1998 to 2004, most locations were collected during 2001–2003 (1% in 1998, 5% in 1999, 7% in 2000, 13% in 2001, 35% in 2002, 33% in 2003, and 6% in 2004). The majority of locations occurred in Texas (83%, plus 8% in Kansas, 8% in Oklahoma, and 1% in New Mexico).

Sandhill Cranes occurred in 18% of grid cells within the study area (≥10% chance of occurrence and location acquisition). Their winter distribution included large contiguous portions of northern Texas and central portions of Oklahoma and Kansas (Figure 1). Wind towers occurred within 3% of grid cells. We found 7% spatial overlap between grid cells with evidence of Sandhill Crane occurrence during 1998–2004 and wind towers constructed during 1999–2013.

During winter, 48 individual cranes had PTT locations within grid cells containing established towers; 2 cranes used such locations in multiple winters. Therefore, 52% (50/96) of cranes using the region would have had some potential exposure to wind towers. Levels of potential exposure for individual wintering cranes varied, with 25% of birds recording a single location only in grid cells containing towers and 33% recording ≥10 locations (each location generally represented 4–10 days during winter; see Krapu et al. 2011).

Distance from Wind Towers

During the winters of 2009–2013, cranes with GPS transmitters provided 458 locations that were ≤10 km from established wind towers (7% of locations), and the mean distance from crane locations to the nearest tower was 6.5 km (SE = 0.4, 95% CI: 5.1–7.8) for 9 cranes in the winters of 2009–2013. The mean distance from towers was greater than 5.0 km, the distance that would be expected if cranes were randomly distributed in relation to towers. Cranes were ≤10 km from established wind towers for 1–42 days per winter (mean exposure = 16.2 days, SE = 3.6, median = 11.0).

Resource Selection Functions

We included 6,110 GPS locations from 10 birds (18 bird-years) during the winters of 2009–2013 for habitat selection analyses within the Texas High Plains. The most parameterized model was selected above reduced models in the candidate model set ($w_i = 0.995$; Table 2). The cross-validation analyses indicated a positive correlation between observed and expected use points within resource selection categories, providing evidence of the model's ability to predict crane use. The intercept of the averaged k-folds was not different from 0 (0.030; 95% CI: –0.002, 0.069), and the slope was different from 0 but slightly less than 1 (0.834; 95% CI: 0.747, 0.920). Chi-square goodness-of-fit tests for all folds suggested acceptable model fit ($\chi^2 \geq 0.665$, $P \geq 0.119$). Compared with croplands, cranes showed strong selection of wetlands, similar selection of grasslands, and avoidance of developed lands and forested lands (Table 3). Cranes also selected areas closer to wetland basins; they were half as likely to select areas for every 1 km farther from these features. Coefficients for slope and disturbance index showed weak selection of gentle slopes (slopes close to 0) and areas with lower disturbance index values. Similarly, we found a modest effect of elevation; cranes selected areas of slightly higher elevation.

Wind towers were generally placed in locations not often selected by cranes in years when most towers had already been constructed (Figure 2). Eighty percent of crane use occurred in RSF categories where only 5% of wind towers were constructed. These towers were in habitats identified as wetland, cropland, or grassland, with distances <1 km from wetland basins, and thus were in locations predicted to be highly selected by cranes. Conversely, 88% of towers were placed in the 3 least-selected RSF categories; only 8% of crane locations occurred in locations with these characteristics (Figure 2). Within the 3 least-selected RSF categories, towers were located in forest (75%), cropland (17%), grassland (7%), and developed and other areas (<1%), with none in wetlands. The distance of towers to wetlands averaged 2.1 km, and the average slope around towers was 1.3°.

TABLE 3. Parameter estimates (β; logit scale), standard errors, and 95% confidence limits from the highest-ranked model (Table 2) estimating resource selection functions of wintering Sandhill Cranes on the Texas High Plains, 2011–2013.

Variable	β	SE	Lower 95% CL	Upper 95% CL
Intercept	−6.643	0.285	−7.202	−6.083
Land cover [a]				
Development	−1.216	0.135	−1.481	−0.951
Forest	−0.955	0.112	−1.174	−0.737
Grassland	−0.149	0.042	−0.238	−0.066
Wetland	3.808	0.055	3.700	3.917
Other	2.102	0.224	1.663	2.541
Distance to water	−0.673	0.027	−0.726	−0.619
Elevation	0.004	0.000	0.004	0.005
Slope	−0.310	0.026	−0.361	−0.258
Index of human activity	−0.007	0.002	−0.011	−0.003
Random effect (bird)	0.372	0.144	0.090	0.654

[a] Cropland land cover was used as the reference level.

DISCUSSION

The central and southern Great Plains in North America serve as the principal wintering area for the midcontinental population of Sandhill Cranes (Krapu et al. 2011, 2014, Gerber et al. 2014). This region and its wetland resources are critical for meeting the management goals of maintaining the current size and distribution of the midcontinental Sandhill Crane population (Central Flyway Webless Migratory Game Bird Technical Committee 2006). This regional significance provided the initial impetus to investigate the potential overlap of the midcontinental population with the thousands of wind towers constructed primarily in the 2000s, especially given that wintering migrants may be more affected by wind towers than resident species (Villegas-Patraca et al. 2012). Our assessment revealed a potentially limited threat of wind towers to midcontinental Sandhill Cranes due to modest spatial overlap regionally, brief or no exposure for >50% of the population wintering in the study region, and habitat associations that differed from where the majority of towers have been built.

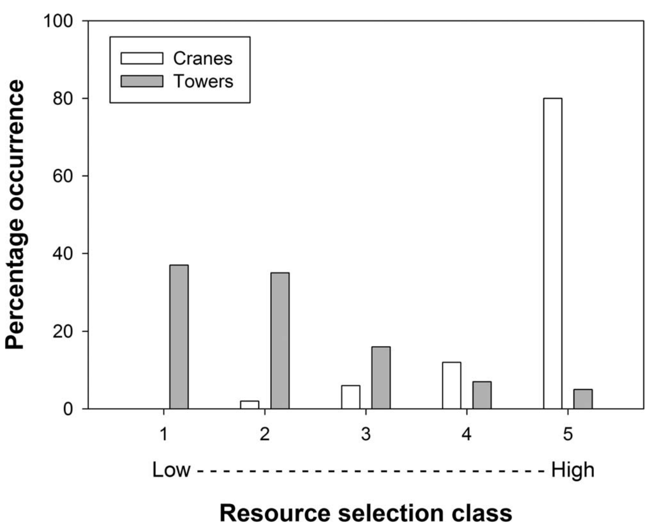

FIGURE 2. Percentage of GPS-marked Sandhill Cranes and wind towers constructed in 1999–2013 (Diffendorfer et al. 2014) in locations with characteristics indicative of low to high relative probability of crane use based on Sandhill Cranes wintering on the High Plains of Texas, 2011–2013.

Spatial overlap between tower locations and preconstruction observations of wintering cranes was relatively modest (7%). There were few instances in which high densities of cranes and high densities of towers coincided, sites which would likely be of the greatest risk to cranes. Although current overlap appears relatively low, future risks might increase if additional wind developments were to be constructed across a larger portion of the wintering area of the midcontinental population.

Sandhill Cranes use the central and southern Great Plains for ~4–6 mo (Krapu et al. 2011). Individual cranes varied in the amount of time that they were within 10 km of wind towers, with ~25% of potentially exposed cranes near wind towers for 1–4 days and ~15% for ≥1 mo. Individual risk is likely correlated with exposure time (Janss and Ferrer 2000); thus, only a portion of the birds would be exposed long enough to be considered potentially under significant risk from disturbance or collision mortality. Furthermore, based on observations of individually marked cranes during 2009–2013, we estimated that ~50% of the midcontinental population in the study area used locations that had wind towers nearby (<10 km). This level of population exposure, when compared with the modest spatial overlap, suggests that numerous individuals may be exposed to wind towers, but only in a limited number of locations. Thus, if desired, it may be possible to significantly reduce individual exposure by focusing on relatively few of the thousands of tower locations.

Our sample of GPS-marked cranes provided perspective on how cranes used landscapes containing existing wind towers. Crane locations ≤10 km from towers were at slightly greater distances than would be expected by chance. This result could be interpreted as evidence for avoidance of wind towers, which has been found for other species during various times during their life history (e.g., breeding; Pearce-Higgins et al. 2009, migration; Larsen and Madsen 2000, wintering; Fijn et al. 2012, Stevens et al. 2013). Wintering Sandhill Cranes formed smaller flocks at lower densities when they occurred <8 km from towers in Texas, a result viewed as indication of avoidance behavior (Narvarrete 2011). Reduced use of areas surrounding wind towers would result in displacement to other suitable areas if available. Foraging habitats primarily in cultivated fields are likely abundant elsewhere, but wetlands used as day and night roosts may be more limiting in this region and would be of greater conservation concern (Iverson et al. 1985, Krapu et al. 2011).

The results of our habitat selection modeling provided an alternative interpretation of distances between cranes and towers. We found that wintering cranes generally selected wetlands or upland areas near wetland basins. Past work in our study region has supported these basic habitat selection criteria. Iverson et al. (1985) found that the use of harvested grain sorghum fields and playa wetlands was greater than their availability, whereas the use of cotton fields and grasslands was less than availability. More recently, Navarrete (2011) determined that cranes selected for corn and grain sorghum fields diurnally. We found that nearly 90% of towers have been constructed in locations with characteristics not widely selected by Sandhill Cranes, mainly within forested and cropland areas >1 km from wetland basins. Thus, cranes may have used locations at distances greater from wind towers than expected by chance because sites were not equally likely to be selected by cranes; in particular, most wind towers occurred in locations with a low relative probability of use by wintering cranes.

Our work provides an initial assessment of estimates of overlap by comparing pre-establishment crane distribution with current placement of towers. Assessing the distribution of cranes before and after wind tower construction would have been a more direct assessment of potential displacement and allowed for stronger inference (Strickland et al. 2011). Furthermore, although the resource selection analysis provided an individual perspective on habitat selection, our sample of cranes was limited, as was the spatial extent over which they wintered in comparison with the entire midcontinental population. Any sampling bias that may have existed could have affected our inferences about habitat selection and the potential impacts of wind towers. Despite these caveats, we found selection for habitat characteristics that corresponded with past assessments (e.g., Iverson et al. 1985), indicating that our sample may have been a reasonable representation of wintering cranes in the region.

Our assessment provides both regional-scale information regarding overlap for a wildlife population with current wind energy development and local-scale information using habitat associations of a target species to assess risks associated with individual towers. We found minimal overlap between wind towers and wintering Sandhill Cranes, and discovered that most wind towers have been constructed in locations not often selected by wintering cranes. Thus, the current distribution of wind towers may have limited negative impacts on wintering cranes in the central and southern Great Plains region or on the midcontinental population overall. A continuation of this seeming compatibility of wintering cranes and wind energy development will depend upon the placement of future towers in locations not highly preferred by cranes.

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Author contributions: A.T.P., D.A.B., and G.L.K. conceived the idea and wrote the paper; D.A.B. collected the data; and A.T.P. analyzed the data.

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APPENDIX TABLE 4. 68% percentile of error magnitudes (m) as provided in the supplementary data of Douglas et al. (2012) for 7 location classes provided by Service Argos (http://www.argos-system.org/). We used these position errors to estimate the spatial distributions of wintering Sandhill Cranes following the methods of Tougaard et al. (2008).

Location class	*n* [a]	Error in longitude (m)	Error in latitude (m)
3	1,110	330	202
2	2,324	789	463
1	3,424	1,948	1,145
0	7,070	6,147	3,513
A	1,672	3,366	2,163
B	1,362	7,213	4,472
Z	540	5,627	1,608

[a] Number of locations used to determine percentiles.