Occurrence of Diurnal Raptors across a Wind Energy Landscape in Northeastern South Dakota

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Abstract - Wind energy facilities can pose direct risks to raptors (*Accipitriformes*, *Falconiformes*, and *Strigiformes*), mainly through collisions with turbine blades. However, less is known about indirect impacts such as potential behavioral changes. During October 2020–July 2023, we evaluated indirect effects of wind energy development on raptors occupying areas encompassing 2 adjoining wind energy facilities in northeastern South Dakota. Our objectives were to document trends in raptor occurrence, determine landscape and wind energy infrastructure covariates associated with raptor occurrence, and use the covariates to develop a spatial model to predict raptor occurrence across the study area. During the 2.8-year study, 713 individuals of 12 raptor species were observed during monthly, 20-minute surveys. Overall raptor occurrence declined ($P < 0.01$) but this change could not be linked to presence of wind energy infrastructure. Raptor occurrence was positively associated with the proportion of grassland ($P = 0.06$) and water ($P = 0.001$) within 1 km. No relationship was detected between raptor occurrence and presence of wind energy infrastructure. Overall, our spatial models suggested that raptor occurrence was greatest throughout the central portion of the study area, coinciding with greater grassland and water abundance. Our findings lend insight into raptor occurrence in grassland landscapes with wind energy infrastructure, but more research including fatality monitoring is needed to better understand influences of wind energy development on raptors in the region.

Introduction

North America's Great Plains region has a long history of human development. Since the early 1900's, agriculture has been the main source of anthropogenic change (Samson et al. 2004). However, recent decades have seen an increase in energy development, including wind energy, across the region. Influenced by the Great Plains Low-level Jet Stream, the Great Plains has some of the highest quality wind resources in the USA, with sustained wind speeds of >30 km/h (National Renewable Energy Laboratory 2017). While wind energy represents a critical source of renewable energy generation and may bolster rural economies (Mills 2018), understanding how its development affects wildlife has been of great conservation interest over recent decades (Allison et al. 2019).

The Great Plains is characterized by grasslands and wetlands that host >400 bird species, including true migrants, partial migrants, and year-round residents (Johnsgard 2012). At least 20 raptor species occur in the region, including resident and seasonally migratory species (Johnsgard 2009). For example, in much of the Northern Great Plains, *Bubo virginianus* Gmelin (Great-horned Owl) is found year-round, whereas *Circus hudsonius* Linnaeus (Northern Harrier) breeds in the Northern Great Plains but overwinters in the Southern Great Plains and adjoining areas. *Cathartes aura* Linnaeus (Turkey Vulture) is commonly observed throughout the Great Plains during the spring and summer breeding season but is

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absent in winter (Cornell Lab of Ornithology 2019). Understanding how raptors, as widespread apex predators, respond to anthropogenic change has important implications for habitat conservation, particularly due to notable and recent declines in populations of some raptor species (McClure and Rolek 2020).

Commercial wind energy infrastructure can pose direct and indirect risks to raptors (Allison and Butryn 2019, Garvin et al. 2011), including collision with wind turbine blades (direct impacts) and displacement from otherwise suitable habitat (indirect impacts; Dohm et al. 2019, Watson et al. 2018a). Less is known about behavioral changes of raptors that may result from habitat loss or fragmentation potentially caused by wind energy facilities. Several studies have documented avoidance of wind turbines by raptors (Marques et al. 2020, Pearce-Higgins et al. 2009, Watson et al. 2018b). The raptors may alter their use of habitat or change flight behaviors (Garvin et al. 2011, Johnston et al. 2014). Additional research is needed to better understand how such behavior may lead to indirect effects of wind development on raptors at the population level (Marques et al. 2021). In the Northern Great Plains most information about the effects of wind energy development on raptors is drawn from post-construction mortality monitoring, which accounts only for direct impacts (Conkling et al. 2022). Indirect impacts, such as avoidance of areas that otherwise would have been used by raptors (i.e., displacement), have been more difficult to quantify and, to our knowledge, have not been evaluated in this region. To better understand raptor distribution in relation to wind energy infrastructure and the encompassing landscape, we evaluated the occurrence of raptors near 2 wind energy facilities in South Dakota. Specifically, our objectives were to (1) quantify raptor occurrence relative to characteristic landscape features and distances from or densities of wind energy infrastructure during the first 3 years after construction, and (2) create a spatial model to predict raptor occurrence based on habitat and wind energy infrastructure covariates.

Materials and Methods

Our study area was composed of lands within 3 km of the Crowned Ridge I and Crowned Ridge II wind energy project boundaries in Grant, Codington, and Deuel counties, northeastern South Dakota (Fig. 1). Crowned Ridge I began operation in 2019 and contained 87 2.3-MW turbines. Crowned Ridge II contained 88 2.3-MW turbines that were constructed during July and August 2020 and became operational in November 2020. Hereafter we refer to these projects jointly as the Crowned Ridge wind project. Roads in the study area were mostly gravel except for several paved roads including Interstate 29 in the western portion of the study area. Human population centers in the area included the city of Watertown (pop. 22,655) and 7 towns with <200 people each (US Census Bureau 2020).

Lands in the study area were privately owned except for several 16- to 150-ha state and federally owned Wildlife Management Areas and Waterfowl Production Areas. Land cover was primarily cropland (51.7%) and grassland (38.7%). Croplands were used for growing *Medicago sativa* Linnaeus (dryland Alfalfa), *Zea mays* Linnaeus (Corn), and *Glycine max* Linnaeus (Soybean), and were typically bordered by 1 to several rows of trees to serve as windbreaks. Grasslands were mostly composed of grass-dominated herbaceous cover established under the Conservation Reserve Program, but some tracts were native tallgrass prairies (i.e., *Andropogon gerardii* Vitman, *Sorghastrum nutans* [L.] Nash), invaded by introduced grass species used for cattle grazing and hay harvests. Wetlands and waterbodies made up 2.9% and 1.8% of the study area, respectively (Multi-resolution Land Characteristics [MRLC] 2023). Wetlands were defined as areas where soils are periodically saturated with or covered by water, while waterbodies (per-

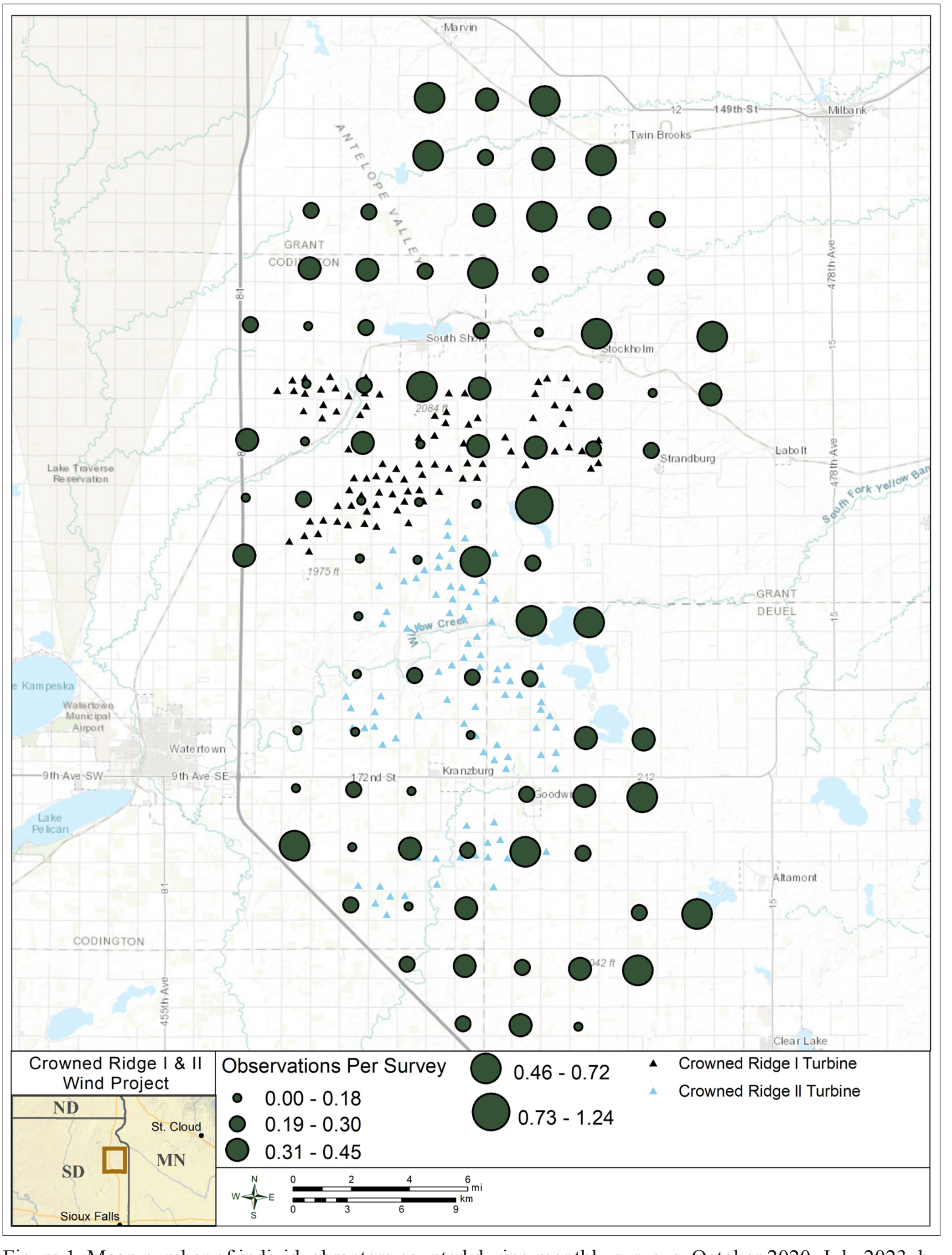

Figure 1. Mean number of individual raptors counted during monthly surveys, October 2020–July 2023, by survey plot location (green circles) near the Crowned Ridge I and II wind energy projects in northeastern South Dakota. Larger circles correspond to a greater number of individuals counted during each survey, on average.

manently flooded lakes and ponds) were defined as open water, typically with less than 25% cover comprised of vegetation or soil (MRLC 2023). Topography was characteristic of the Prairie Coteau Ecoregion with rolling hills and wetlands (Johnson and Larson 2007). Elevation ranged from 294–634 m (US Geological Survey [USGS] 2023). Annual precipitation during the study period ranged from 49.3–68.1 cm (NOAA 2025). Raptors known to breed within the study area included *Haliaeetus leucocephalus* Linnaeus (Bald Eagle), Great-horned Owl, Northern Harrier, *Buteo jamaicensis* Gmelin (Red-tailed Hawk), and *Buteo swainsoni* Bonaparte (Swainson's Hawk; South Dakota Game, Fish, and Parks 2012).

Field methods

Our surveys occurred during October 2020–July 2023. We randomly selected 90 survey plots from a 3.2-km × 3.2-km grid within 3 km of the Crowned Ridge wind project. We assigned each grid cell to 1 of 3 panels based on a spatially balanced sampling algorithm (Robertson et al. 2013) to evenly distribute survey efforts across the study area. Panel 1 (n = 30 grid cells) contained survey plots that were surveyed monthly, and Panels 2 and 3 (n = 30 grid cells each) contained survey plots that were surveyed in alternating months. Within each selected grid cell, a 0.8-km radius survey plot was established; a spatially balanced set of 60 grid cells (66% of the 90-grid cell sample frame) was surveyed monthly. We micro-sited each survey plot in the field to ensure an unobstructed view of the survey area from publicly accessible roads. If a survey location was considered inaccessible (e.g., in a pasture or along a private road), the location was adjusted to the nearest public road while avoiding overlap with adjacent survey plots.

A surveyor at the center of a given survey plot used binoculars to scan the area for 20 minutes and record all raptors within the plot regardless of flight height. We defined raptors as any species of the order *Accipitriformes*, *Falconiformes*, or *Strigiformes*. We used rangefinders and GPS units to determine whether raptors were within survey plot boundaries. We conducted surveys from 0.5 hour after sunrise to 0.5 hour before sunset. During summer the maximum number of surveys conducted daily by a surveyor was 32, while in winter the maximum was 18, due to fewer daylight hours. We tried to randomize the time of day when a given location was surveyed. We conducted surveys when wind speeds were <32 km/hour and absent moderate to heavy precipitation (Ralph et al. 1997, Coates et al. 2016, Smith et al. 2017). In addition, we counted vehicles within 0.8 km during the last 10 minutes of each survey to document traffic volume as a landscape feature.

Spatial Predictors

We considered habitat and anthropogenic covariates potentially relevant to raptor occurrence in the study area (Table S1 is available online at https://www.eaglehill.us/PRNAonline2/suppl-files/prna-58-kelly-s1.pdf). Spatial covariates were assessed based on their values in relation to survey points. We used land cover data from the US Department of Agriculture (2023) to quantify proportions of grassland, cropland (alfalfa, corn, and soybeans), and water across the study area. Wetlands and waterbodies were grouped into a single variable, "water." We used a 30-m digital elevation model (USGS 2023) to create a Terrain Roughness Index (TRI) and an index of orographic updraft. TRI was calculated as the mean elevation difference between each raster cell and its eight neighboring cells (Wilson et al. 2007). Orographic updraft was calculated for each raster cell as:

$$\text{orographic updraft} = v * C_a$$

where the updraft coefficient (C_a) = Sin(Slope°) * Cos (wind direction° – aspect angle°). Orographic updraft calculations followed Hanssen et al. (2020), with 1 exception. We set wind velocity (v) equal to 1 so that orographic updraft was relative across the study area. We obtained average wind direction from the Watertown Municipal Airport ~ 8.5 km west of the study area. Predominant wind direction was from the west, north, and south during 1 November–31 January, 1 February–30 April, and 1 May–31 October, respectively. Variables describing grassland, total crop cover, water, TRI, and orographic updraft were averaged across 1.0-km radii windows to represent the area slightly larger than our 0.8-km radii survey plots.

We calculated the distance from each survey plot to public roads by using spatial data from the South Dakota Department of Transportation (2022), and we manually digitized wind turbine service roads. We developed a relative traffic volume index by averaging the total vehicle count at each survey point and survey period. We then interpolated across the study area by using inverse distance weighting (Shepard 1968), and rescaled values between 0 and 1, with values of 1 corresponding to greater mean vehicular traffic.

Wind turbine and power line covariates included distance (from survey plot center) to turbine (km), distance to power line (km), turbine count (number of turbines), and length of power lines (km; termed power line density). We assessed wind turbine and power line density at 3 scales: 1.0, 3.2, and 5.0 km from plot centers. These distances have been used by others to assess raptor space use (Garvin et al. 2011, Pearce-Higgins et al. 2009, Squires et al. 2020). We obtained locations of turbines from the USGS US Wind Turbine database (Hoen et al. 2018). We obtained power line data from the Department of Homeland Security (2022). Power line voltage ranged from 69–345 kV and did not include distribution lines.

Analysis

We used a generalized linear mixed-effects model (GLMM) to assess raptor occurrence during the 3 years after completion of the Crowned Ridge wind project, while accounting for spatial and temporal variation and evaluating relationships with landscape covariates. We used a random forest classification model (Cutler et al. 2007, Kubosova et al. 2010) to generate a predictive spatial model for raptor occurrence and compare variables of importance to outputs of the GLMM. Random forest models predict binary outcomes, such as raptor occurrence from survey data, to identify variables of importance and can be used to predict landscape surfaces even when covariates are highly correlated (Cutler et al. 2007, Kubosova et al. 2010). While detection probability is important to consider in understanding changes in estimates of raptor occupancy and abundance (Murn and Holloway 2016), we did not attain sufficient replication within a given season to avoid violating the assumption of closure (Mackenzie et al. 2018). Therefore, instead of increased temporal replicates to maximize detection probability, our inference relied on broader spatial patterns in raptor occurrence, which stemmed from an increase in survey plot locations from our rotating panel sampling design.

Trend in raptor spatial and temporal occurrence. To determine spatial and temporal relationships, we fit binary (i.e., detected or not) raptor occurrence data from our surveys to predictor variables. Due to relatively small sample sizes for some individual species, we developed models only for *Buteo* spp. (hereafter, buteos), Northern Harriers, Turkey Vultures, and all raptors combined although the model for Turkey Vultures was not retained due to poor model convergence. We fit a binomial GLMM to raptor occurrence data to account for spatial and temporal variation associated with seasonality and annual variation in surveys. We fit the model by using package *glmm*TMB (Brooks et al. 2017) and assessed residual diagnostics with package *DHARMa* (Hartig 2022) in R version 4.1.3 (R Development Core Team 2022). Model development and inference followed practices highlighted in Bolker et al. (2009), including procedures for specifying fixed and random effects, selection of error distribution and link function, residual checking, and use of restricted maximum likelihood for inference. The fixed-effects structure included the survey year (defined as a 1 October–30 September period that overlapped 2 consecutive calendar years) for assessing trends, season, and spatial predictors related to the landscape and wind energy development. We identified 4 seasons based on the annual cycle of chief raptor activity, including spring migration (March–April), breeding (May–August), fall migration (September–November), and overwintering (December–February). Prior to modeling, we assessed the correlation between fixed effect covariates using the package *corrplot* (Wei and Simko 2024). We found that 2 covariates, the proportion of grassland and that of cropland within 1 km, were inversely correlated ($r = -0.96$), so we omitted cropland and retained grassland because of its biological significance to raptor space use in this region (Wiggins et al. 2014).

The random-effects structure included separate terms for year and survey location, plus an interaction term between survey location and year, to account for spatial and temporal variation related to survey effort and sampling design. We selected this random-effect structure based on study design and residual diagnostic plots after fitting the full model, using restricted maximum likelihood estimation (Bolker et al. 2009). In the Northern Harrier occurrence model, our random-effect structure only included year, due to overfitting with the inclusion of survey location. We developed marginal effects plots (Lüdecke 2018) to display biologically meaningful and statistically significant ($\alpha = 0.05$) spatial predictors for raptor occurrence.

Random forest analysis. We fit a random forest model for each species subgroup (all raptors, buteos, and Northern Harrier) to generate a predictive spatial model for habitat and infrastructure covariates and to determine variables of importance for each. We classified each survey based on binary occurrence, as described above. Random forest models require training and validation before being applied to novel datasets. Our random forest model for each raptor species subgroup was built and tuned to maximize accuracy via the R package *caret* (Kuhn 2008) and was trained and validated by using *randomForest* (Liaw and Wiener 2002). Through model training, we determined the optimum number of covariates allowed at each node (*mtry*), the number of trees, and the maximum number of nodes (*max nodes*) by comparing accuracy of the model with varying values of *mtry*, numbers of trees, and *max nodes*. For final model evaluation we reported the area under the curve, accuracy (overall percentage correctly classified), sensitivity (proportion of presence correctly classified), specificity (the proportion of absence correctly classified), and kappa (a measure of agreement between predicted presences and absences). We used the package *Boruta* to further validate variables deemed important in randomForest (Kursa and Rudnicki 2010). We used the random forest model for each species subgroup to develop spatially explicit predictions across the study area. For display, we binned predictions into 5 equal-area intervals corresponding with low to high relative raptor occurrence.

Results

During surveys conducted 18 October 2020–23 July 2023, we recorded 687 individual raptors comprising 12 species. Red-tailed Hawk accumulated the most observations, followed by Northern Harrier, Turkey Vulture, Bald Eagle, and *Buteo lagopus* Pontoppidan (Rough-legged Hawk); Table 1). Swainson's Hawk, *Falco sparverius* Linnaeus (American Kestrel), *Falco peregrinus* Tunstall (Peregrine Falcon), *Astur cooperii* Bonaparte (Cooper's Hawk), *Falco columbarius* Linnaeus (Merlin), *Aquila chrysaetos* Linnaeus (Golden Eagle), and *Buteo platypterus* Vielliot (Broad-winged Hawk) were observed less frequently. We also observed 18 unidentified buteos and 5 unidentified eagles. The mean number of individual raptors observed per 20-minute survey per plot during the 2.8-year study period ranged from 0 to 1.24 (Fig. 1). Overall raptor occurrence declined during the period ($P < 0.01$, Table 1, Fig. 2). We observed most individuals during spring migration and breeding (March–August) and fewest during overwintering (December–February).

In general, fewer total individuals were observed in the final 7 months of the study (January 2023–July 2023) compared to the same period in 2021 and 2020 (Table 1). Traffic surveys yielded a total of 10,650 vehicles observed. Traffic volume was relatively consistent throughout the study period, with most observations recorded at survey locations near a major interstate highway along the western edge of the study area.

Raptor occurrence was positively associated with the proportion of water within 1 km of survey plots ($P < 0.01$) and with that of grassland (Fig. 3a and 3b). No significant relationship was apparent for spatial predictors related to topography or wind energy infrastructure, although turbine count appeared weakly inversely related ($P = 0.11$; Fig. 3c, Table 2). Models for buteos and Northern Harrier exhibited positive associations with water ($P = 0.002$ and $P = 0.015$, respectively) as did the all-raptor occurrence model (Tables 3 and 4). The buteo model also indicated a significant positive relationship with grassland within 1 km (P = 0.023), but the relationship was weaker for Northern Harrier ($P = 0.114$). However, we detected a positive relationship between distance to road and Northern Harrier occurrence ($P = 0.012$; Table 4).

In the random forest analysis, classification accuracy was 77.9%, suggesting the model had moderate utility in predicting overall raptor spatial occurrence across the study area (Fig. 4). The model performed well at correctly predicting areas where raptors occurred (true-positive detection rate; sensitivity = 0.99) but struggled to accurately predict where raptors were absent (true-negative detection rate; specificity = 0.04; Table S2 and S3 are available online at https://www.eaglehill.us/prnaonline/suppl-files/prna-054-kelly-s1.pdf). Variable importance, in a random forest and Boruta model context, is determined by the decrease in prediction accuracy if that variable is removed. Therefore, variables deemed important ultimately improve the predictive

Table 1. Total counts of individual raptors per year and the total of each species observed during surveys conducted at the Crowned Ridge I and Crowned Ridge II wind energy projects from October 2020 to July 2023[1].

	Counts of individuals			
Species	**Year 1**	**Year 2**	**Year 3**	**Total**
American Kestrel	10	9	0	19
Bald Eagle	19	28	4	51
Broad-winged Hawk	0	1	0	1
Cooper's Hawk	4	2	0	6
Golden Eagle	0	1	0	1
Merlin	1	0	0	1
Northern Harrier	77	47	10	134
Peregrine Falcon	0	5	1	6
Rough-legged Hawk	24	16	2	42
Red-tailed Hawk	115	118	18	251
Swainson's Hawk	12	19	0	31
Turkey Vulture	52	68	1	121
Unidentified buteo	15	2	1	18
Unidentified eagle	4	1	0	5
TOTAL	333	317	37	687

[1]Year 1 = 18 October 2020–31 December 2020; Year 2 = 18 January 2021–31 December 2021; Year 3 = 10 January 2022–23 July 2023

capacity of the model. In both the random forest and Boruta models variables of importance in predicting raptor occurrence included year, season, proportion of water, proportion of grassland, and topographic ruggedness. In contrast to GLMM model, the Boruta model deemed distance from the nearest turbine as important for predicting raptor occurrence.

Discussion

We assessed the relationship between raptor occurrence and habitat including wind energy infrastructure in a Northern Great Plains landscape primarily to further understanding of influences of wind energy development on wildlife. We found that, collectively, 12 species of raptors exhibited decreased occurrence within 3 km of the Crowned Ridge wind project during a 2.8-year period after the project became operational. However, neither our GLMMs nor random forest analyses indicated an association between wind energy infrastructure and raptor occurrence that could explain the observed decline. The largest drivers of greater occurrence were increasing proportions of grassland and water features across the landscape. Similarly, Garvin et al. (2011) reported a decrease in raptor abundance after the development of a wind energy facility. However, the relatively short study period prevents us from determining whether our results indicate a long-term trend or from speculating about potential causes of the decline. Given these results, the decrease in overall raptor occurrence during the 2.8-year study period requires a broader consideration beyond variables included in our models. While we aimed to maximize survey coverage of the study area, life histories and population dynamics of long-lived raptor species (mostly

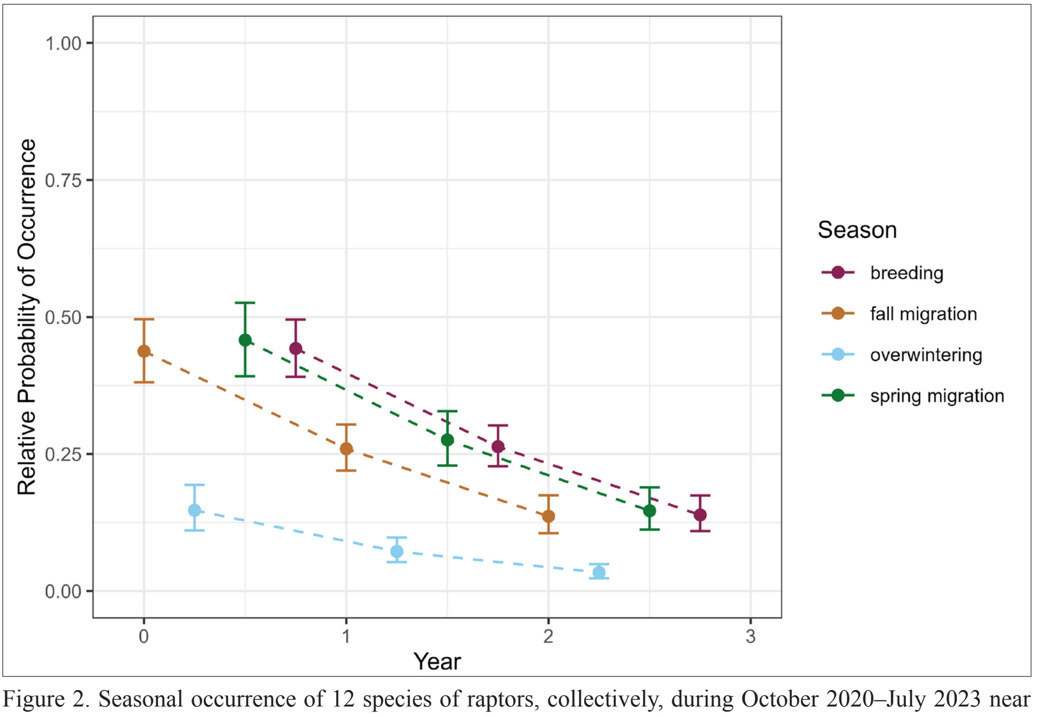

Figure 2. Seasonal occurrence of 12 species of raptors, collectively, during October 2020–July 2023 near the Crowned Ridge I and II wind energy projects, northeastern South Dakota. Vertical bars around points represent 95% confidence intervals surrounding the model adjusted marginal mean estimated using *ggeffects*. Seasons were defined as fall migration (September–November), overwintering (December–February), spring migration (March–April), and breeding (May–August).

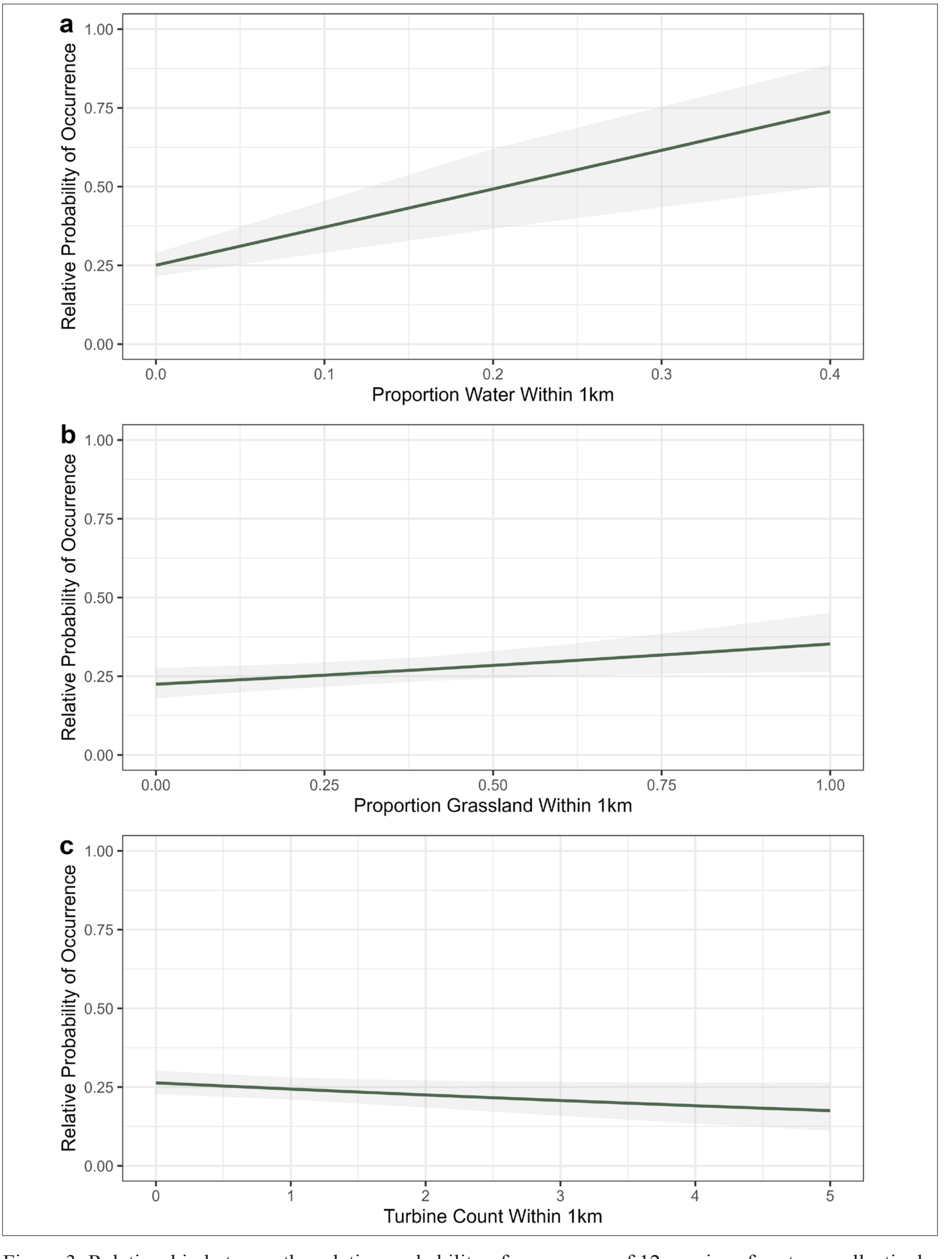

Figure 3. Relationship between the relative probability of occurrence of 12 species of raptors, collectively, and the proportion of land cover within 1 km comprised by water (a), grassland (b), or turbine count (c) within 1 km of the Crowned Ridge I and II wind energy facilities in northeastern South Dakota during October 2020–July 2023. Shaded regions encompassing trend lines represent 95% confidence intervals surrounding the model-adjusted marginal mean estimate, using *ggeffects*.

10+ years) operate on longer time horizons. The observed decline could be caused by natural fluctuations in species' abundances, mirroring rhythmic predator-prey dynamics (White 1994), or reflect annual changes in species distributions (Paprocki et al. 2014). In some studies, abundances of certain raptor species declined following construction and initial operation of wind projects, but returned to pre-construction levels after about 5 years (Estellés-Domingo and López-López 2024). More years of data are needed to better understand the apparent decline in overall raptor occurrence on our study area; this could be bolstered by post-construction mortality data collected within the study area.

In general, flight behavior and size of many raptor species may put them at increased risk for collision compared to most other bird species (Wulff et al. 2016, Garvin et al. 2011, Watson et

Table 2. Coefficients and model results from modeling raptor occurrence relationships with habitat covariates and wind facility infrastructure. Significant P-values (α ≤ 0.05) are presented in bold.

Variable	Coefficient	Standard error	Z value	*P*
Fixed effects (Intercept)	−1.663	0.82	−2.027	0.043
Year	−1.066	0.202	−5.29	**<0.001**
Grassland	0.682	0.361	1.891	0.059
TRI	−0.024	0.033	−0.727	0.467
Water	5.435	1.693	3.21	**0.001**
Season: fall migration	0.27	0.187	1.444	0.149
Season: overwintering	−1.37	0.193	−7.106	**<0.001**
Season: spring migration	0.123	0.16	0.77	0.441
Turbine density	−0.109	0.068	−1.597	0.11
Orographic uplift	4.645	3.529	1.316	0.188
Traffic volume	0.125	0.379	0.33	0.742

Table 3. Coefficients and model results from modeling buteo occurrence relationships with habitat covariates and wind facility infrastructure. Significant P-values (α = 0.05) are presented in bold.

Variable	Coefficient	Standard error	Z value	*P*
Fixed effects (Intercept)	−2.748	0.913	-3.01	0.003
Year	−0.849	0.226	-3.749	**<0.001**
Grassland	0.944	0.416	2.271	**0.023**
TRI	−0.053	0.038	-1.372	0.17
Water	5.578	1.835	3.039	**0.002**
Season: fall migration	0.278	0.211	1.322	0.186
Season: overwintering	-1.104	0.23	-4.798	**<0.001**
Season: spring migration	0.172	0.184	0.931	0.352
Turbine density	-0.056	0.081	-0.7	0.484
Orographic uplift	6.234	4.15	1.502	0.133
Traffic volume	0.328	0.429	0.764	0.445

al. 2018a, WEST 2023), and avoidance is a documented adaptation to wind energy infrastructure (Watson et al. 2018b, Marques et al. 2020). Avoidance behavior and collision events associated with wind energy developments have contributed to local declines in raptor abundance (Estellés-Domingo and López-López 2024), but this may be species-dependent (Garvin et al. 2011). While avoidance may reduce direct mortality, indirect impacts may include decreased migratory connectivity (Cabrera-Cruz and Villegas-Patraca 2016) and functional habitat loss (Marques et al. 2020). We did not detect a relationship between raptor occurrence and wind energy infrastructure, but we also did not directly document raptor behavior. Direct observations or telemetry data collected before, during, and after (i.e., during initial years of project operation) construction of a wind energy project would be needed to detect direct evidence of avoidance (Estellés-Domingo and López-López 2024).

While we did not detect evidence of a relationship between raptor occurrence and wind energy infrastructure, we found increased occurrence of raptors in areas with relatively high proportions of water features and grassland. We suspect that wetlands in our study area—ranging from basins of permanent open water to those that could become seasonally dry and densely vegetated—served as key sources of prey (Pauzé 2001, Murphy 1997 and 2010), providing foraging opportunities that were enhanced by nearby trees for perching. The observed positive association with grasslands is consistent with the findings that raptors in the Great Plains use grassland patches for hunting, as they generally harbor relatively abundant prey resources (e.g., small mammals, and passerine and galliform birds; Jones et al. 1983, Shaffer et al. 2019a and 2019b). They also offer nesting opportunities for ground-nesting raptors such as Northern Harrier in our study (Shaffer et al. 2019b). Wind turbines in our study area were generally sited away from water sources and primarily located in cropland. Only 15.5% of wind turbines (27 of 175) were sited in areas where grassland comprised >50% of land cover. This suggests that siting wind turbines in areas with less grassland is a strategy to avoid areas of higher raptor occupancy.

High site fidelity to breeding territories may increase exposure and risk of collision for raptors in wind energy landscapes (Watson et al. 2018b, 2024) and warrants careful consideration when siting wind energy infrastructure to minimize loss of functional habitat. Furthermore, to minimize

Table 4. Coefficients and model results from modeling Northern Harrier occurrence relationships with habitat covariates and wind facility infrastructure. Significant P-values (α = 0.05) are presented in bold.

Variable	**Coefficient**	**Standard error**	**Z value**	***P***
Fixed effects (Intercept)	−2.82	1.004	−2.811	0.005
Year	−0.732	0.286	−2.563	**0.01**
Grassland	0.746	0.472	1.581	0.114
TRI	<0.001	0.042	0.002	0.999
Distance to turbine	<0.001	<0.001	0.606	0.545
Distance to road	0.001	<0.001	2.522	**0.012**
Water	4.631	1.897	2.441	**0.015**
Season: fall migration	0.283	0.271	1.041	0.298
Season: spring migration	0.206	0.249	0.827	0.408
Turbine density	0.039	0.105	0.368	0.713
Orographic uplift	−1.669	4.589	−0.364	0.716
Traffic volume	−0.154	0.582	−0.264	0.792

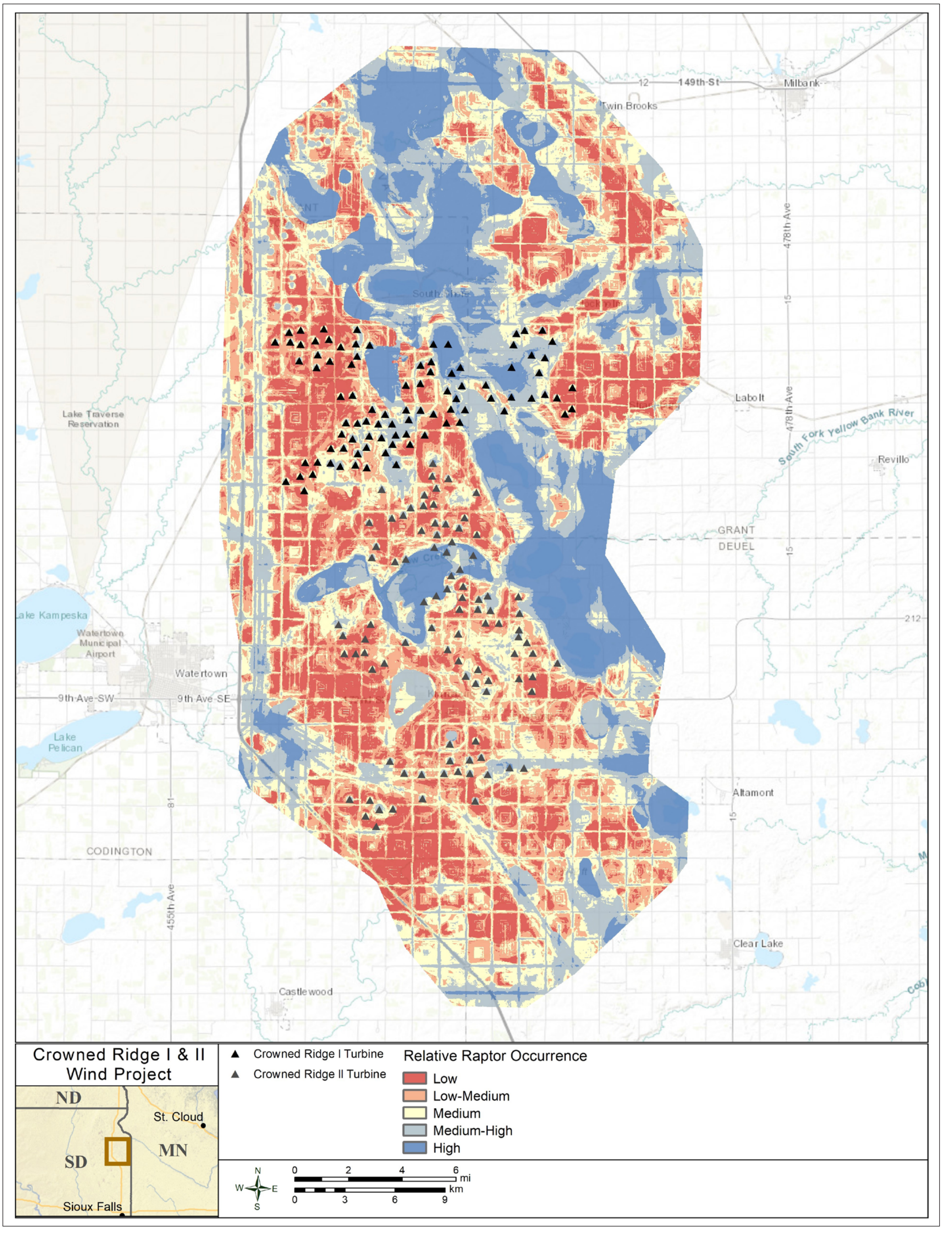

Figure 4. Predicted relative probability of raptor occurrence in the landscape encompassing the Crowned Ridge I and II wind energy projects in northeastern South Dakota during October 2020–July 2023. Predictions were developed using random forest models and were based on monthly surveys at 90 survey plots.

impacts to wildlife, the U.S. Fish and Wildlife Service recommends siting wind turbines away from intact habitats to reduce fragmentation such as that of relatively large, contiguous tracts of grassland (USFWS 2012). Our study of broad habitat relationships of raptors in a Northern Great Plains wind energy landscape contributes to knowledge that may benefit land managers and conservation agencies involved in the siting of wind energy projects in this region. However, this study is one of few such studies; more in-depth research is needed to assess how raptors will respond to future wind energy development at various temporal and spatial scales in the region.

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