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Research article

Lesser prairie-chicken habitat selection and survival relative to a wind energy facility located in a fragmented landscape

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The overlap of renewable wind energy with the range of lesser prairie-chickens *Tympanuchus pallidicinctus* raises concern of population declines and habitat loss. Lesser prairie-chickens are adversely affected by landscape change; however, it is unclear how this species may respond to wind energy development. Therefore, managers and wind energy developers are currently tasked with making management or siting recommendations of future wind energy facilities based on lesser prairie-chicken behavioral responses to other forms of anthropogenic development or responses of other grouse species to wind energy development. The current strategy of siting wind turbines in cultivated cropland within lesser prairie-chicken range has not been evaluated for its effectiveness at minimizing potential adverse impacts. We captured 60 female and 66 male lesser prairie-chickens from leks located along a gradient from wind turbines in southern Kansas, USA from 2017–2021. Over the study period, we collected lesser prairie-chicken location data and demographic information to evaluate resource selection, movement, and demography relative to environmental predictors and metrics associated with the wind energy facility. Lesser prairie-chickens used habitats in close proximity to wind turbines, provided that turbine density was low; however, avoidance associated with cultivated cropland appeared to be more predictive than the presence of wind turbines. We observed movement between turbines suggesting that wind turbines did not act as a barrier to local movements. We did not detect an influence of wind turbines on nest success or individual survival during breeding or non-breeding periods, a relationship that is consistent among multiple grouse species using habitats near wind energy infrastructure. Additional research is necessary to evaluate impacts associated with wind energy development in intact lesser prairie-chicken habitats, but placing wind turbines in cultivated croplands or other fragmented landscapes appears to be an important siting measure when considering wind energy facility siting across the lesser prairie-chicken range.

Keywords: grouse, lesser prairie-chicken, movement, renewable energy, resource selection, survival, *Tympanuchus pallidicinctus*, wind energy development

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Introduction

Declines in lesser prairie-chicken *Tympanuchus pallidicinctus* populations have been linked to widespread modification of native grasslands in the Southern Plains of the United States (Rodgers 2016, US Fish and Wildlife Service (USFWS) 2021a). Today, this prairie-grouse species occupies 10 to 20% of its historic range and is now limited to five US states including Kansas, Oklahoma, Colorado, New Mexico, and Texas (Rodgers 2016, US Fish and Wildlife Service (USFWS) 2021a). The continued loss of habitat has resulted in the lesser prairie-chicken being recently listed as threatened (northern population) or endangered (southern population) under the Endangered Species Act of 1973 (ESA) by the USFWS (87 Federal Register [FR] 72674 [25 November 2022]). With this designation, there is heightened urgency to better understand factors that could affect conservation strategies associated with this prairie grouse species.

Wind energy development has been identified as a risk to lesser prairie-chicken populations (Van Pelt et al. 2013). The demand for renewable energy in the US has increased exponentially in recent years, with solar and wind energy accounting for 21% of electricity generation in 2020 (US Energy Information Administration 2021). Much of the nation's wind production occurs in the Southern Plains (WINDExchange 2022) – also home to the remaining lesser prairie-chicken populations. The number of wind turbines operating within the range of lesser prairie-chicken increased from 1282 in 2012 to 4699 in 2022 (US Fish and Wildlife Service (USFWS) 2021a, US Geological Survey (USGS) 2022). Maintaining large, grassland dominated landscapes is essential to conserve lesser prairie-chicken populations (Ross et al. 2016, Sullins et al. 2019). However, it is unclear how, if, or to what degree habitat loss and fragmentation associated with wind energy development affects lesser prairie-chicken habitat, behavior, and demography.

The current method to predict and mitigate potential impacts to lesser prairie-chickens, in the absence of studies evaluating this species' response to wind energy development, are to draw inference from 1) studies that involve other forms of disturbance and 2) studies of wind energy development on other grouse species. Research on lesser prairie-chickens suggest that oil and gas development, roads, transmission lines, and buildings can result in displacement or avoidance of otherwise suitable habitats (Pitman et al. 2005, Hagen et al. 2011, Sullins et al. 2019). Studies evaluating transmission lines suggest that lesser prairie-chicken populations are impacted through avoidance and reduced survival (Wolfe et al. 2007, Hagen et al. 2011, Plumb et al. 2019, Peterson et al. 2020, Lawrence et al. 2021). Studies evaluating the effects of wind energy development on other grouse species have been conducted in Idaho, Kansas, Nebraska, and Wyoming, and include greater prairie-chicken *Tympanuchus cupido*, sharp-tailed grouse *Tympanuchus phasianellus*, and greater sage-grouse *Centrocercus urophasianus*. Results from these studies generally suggest that nest site selection, nest survival, and female survival are not negatively affected by the presence of a wind energy facility (McNew et al. 2014, Winder et al. 2014a, Harrison et al. 2017, LeBeau et al. 2017a, Smith et al. 2017, Proett et al. 2019). However, there is evidence that wind turbines may displace grouse during the general breeding season outside of the nesting period (Winder et al. 2014b, LeBeau et al. 2017a). Winder et al. (2015) observed increased greater prairie-chicken lek abandonment near turbines when leks were less than 8 km from turbines. However, Winder et al. (2015) did not find a relationship between distance to turbine and the rate of change in number of males at active leks. Similarly, LeBeau et al. (2017b) found no differences in the number of male greater sage-grouse attending leks pre- to post-wind energy development.

Based on how other grouse species respond to wind energy development and how lesser prairie-chicken respond to linear features like transmission lines, it is plausible that wind energy development could have negative effects on lesser prairie-chicken habitat use and population viability. However, there is a clear need to directly evaluate wind energy development impacts on lesser prairie-chicken populations. Current conservation strategies for lesser prairie-chickens assume that wind energy infrastructure, such as wind turbines, has a greater impact on lesser prairie-chicken populations than other forms of anthropogenic disturbances. For example, current strategies assume that lesser prairie-chicken habitat within 667–1800 m of a wind turbine is impacted, compared to a 200–300 m impact associated with an oil or gas well (Van Pelt et al. 2013, US Fish and Wildlife Service (USFWS) 2021a, b).

Given potential fragmentation effects, current wind energy siting practices prioritize development outside of intact grassland habitats (US Fish and Wildlife Service (USFWS) 2012). Currently, 88% of operating wind turbines within the lesser prairie-chicken range are located outside of habitat classified as potentially suitable (e.g. grassland or shrubland; National Land Cover Database (NLCD) 2019, US Geological Survey (USGS) 2022). An understanding of the effectiveness of siting wind energy outside of intact grassland provides important consideration for lesser prairie-chicken conservation and siting of future wind energy facilities. Identifying how lesser prairie-chickens respond to wind energy development in fragmented habitat may be difficult as there are many other factors that may be influencing space use and demography (Walters et al. 2014, Smith and Dwyer 2016). Nonetheless, quantifying behavioral responses in altered landscapes may be useful to understand the effects of current practices of siting wind energy facilities in previously altered habitats. Ultimately, studies focused on lesser prairie-chickens, rather than other grouse species, are needed to evaluate behavioral and demographic effects of wind energy development and provide managers with information to effectively avoid, minimize, and mitigate potential impacts from future wind energy projects (Ross et al. 2018).

We designed a five year study that evaluated behavioral and demographic metrics of a lesser prairie-chicken population occurring near a wind energy facility that was sited in cultivated croplands. All turbines were located in cultivated croplands, thus, any effect of the facility on lesser prairie-chicken may be confounded by avoidance behaviors relative to high levels of fragmentation associated with cultivated cropland (Harryman et al. 2019). We designed our study in an attempt to account for this potentially confounding issue by targeting captures at multiple leks across a suite of habitats ranging from intact grasslands to areas fragmented by cultivated cropland near and far from turbines**.** We used a weight of evidence approach to evaluate multiple parameters that included 1) resource selection to assess avoidance associated with wind energy facility infrastructure, 2) movements and potential barrier effects relative to wind turbines, and 3) nest success and individual survival associated with wind energy infrastructure from radio-marked lesser prairie-chickens. Our research provides the first direct measure of lesser prairie-chicken response to wind energy development, and a broad assessment of siting wind energy infrastructure in fragmented habitats adjacent to large blocks of native grassland.

Material and methods

Study area

The study area was located in the Central Great Plains and the Southwestern Tablelands Level III Ecoregion in Clark County, Kansas (US Environmental Protection Agency 2017; Fig. 1). Cultivated crops represented approximately 29% of the land cover within the region encompassing all lesser prairie-chicken global positioning system (GPS) locations (described below). Common crops include wheat (*Triticum* spp.) and grain sorghum (milo; *Sorghum bicolor*). Cultivated crops were situated on plateaus interspersed with native

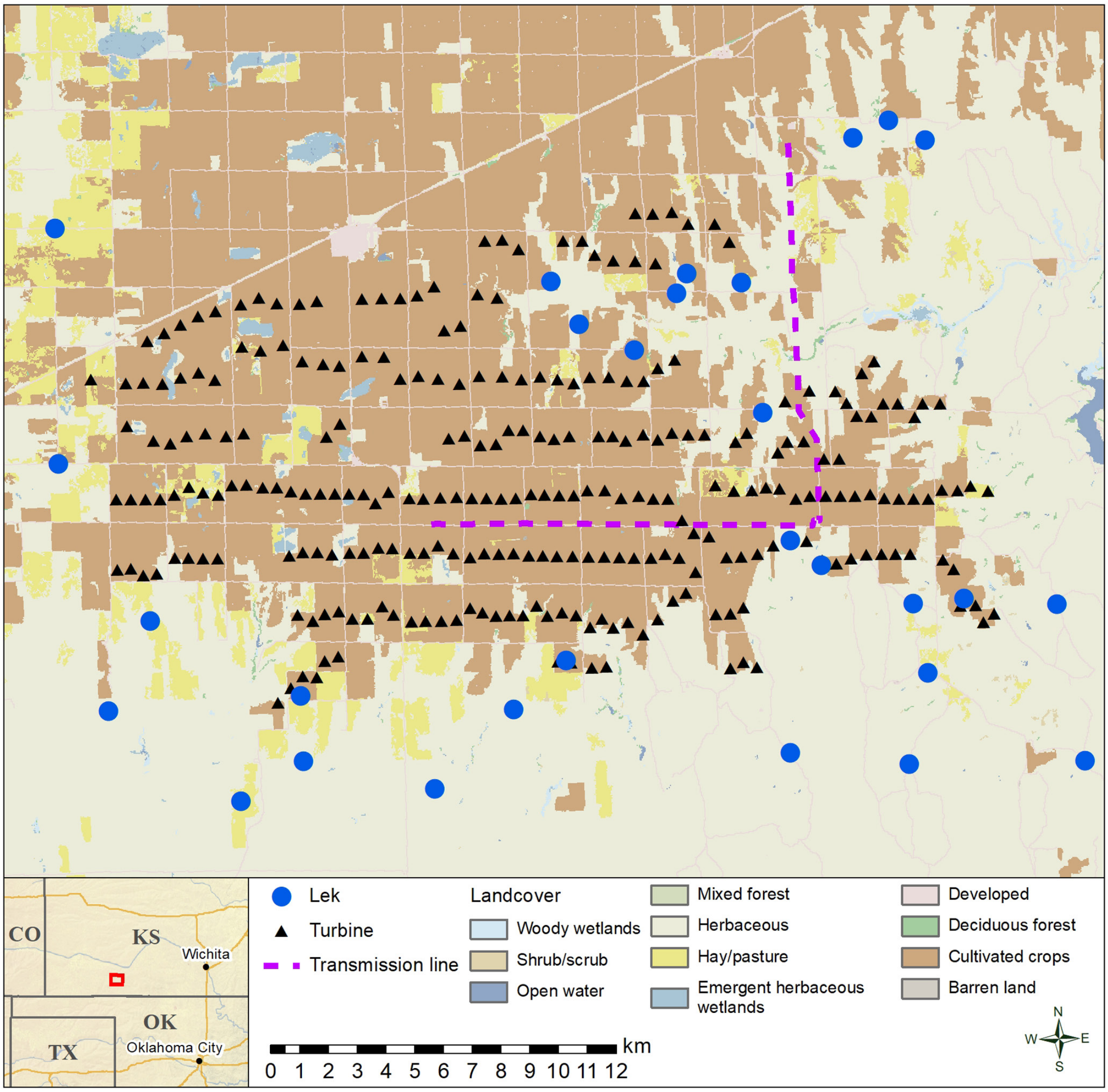

Figure 1. Study area depicting land cover, locations of lesser prairie-chicken leks, and the Cimarron Bend Wind Energy Facility wind turbines in Clark County, Kansas, from 2017–2021.

mixed grass drainages in the northern and eastern portion of the study area. The southern portion of the region consisted of mostly intact mixed grass prairie with gently rolling hills and numerous small drainages. Low-density residential development was centered in the town of Minneola, Kansas, in the northern part of the study area.

On 7 March 2017, the Starbuck Fire burned more than 202 000 ha in northwestern Oklahoma and quickly traveled north into Clark County, Kansas, burning a portion of the study area. The vegetation appeared to recover during the 2017 growing season as we did not detect considerable differences in grass cover between burned and unburned areas. However, a concurrent study approximately 15 km south noted that visual obstruction was lower up to 2.5 years after the fire (Parker et al. 2022).

The Cimarron Bend Wind Energy Facility (Facility) operated by Enel Green Power North America, Inc., has 200 wind turbines (2 MW) that became operational in March 2017 following construction that began in April 2016. The turbines are primarily accessed along existing county roads, but some new roads were developed off county roads to provide access to turbines. A substation, along with 21.6 km of new 345 kilovolt transmission line, also was constructed to transmit power to a previously established line approximately 10.0 km to the north. Construction of an additional 74 wind turbines directly north of the existing 200 turbines began in June 2020 and became operational in December 2020. All turbines were located in cultivated croplands.

Data collection

We conducted aerial lek surveys twice during the 2016 lekking season to document lek locations within 4.8 km of proposed wind turbines (Rintz and Kosciuch 2016). This distance was selected because the majority of lesser prairie-chicken habitat use occurs within 4.8 km of a lek (Taylor and Guthery 1980, Giesen 1994, Pirius et al. 2013), and is consistent with lesser prairie-chicken lek survey methodologies (US Fish and Wildlife Service (USFWS) 2016). During subsequent study years, surveys included visiting leks identified in 2016 to determine activity, and searching for previously undocumented leks by aerial surveys and driving publicly accessible roads. Leks identified during surveys near and along a gradient from the Facility were the focal point of our study. Female and male lesser prairie-chickens were captured on leks using walk-in drift traps and drop nets during the spring lekking period from late-March through April, 2017–2021 (Haukos et al. 1990). We attempted to maintain a sample of 30 lesser prairie-chickens each year and focused on capturing as many females as possible to maximize the number of nests available for monitoring. Captured lesser prairie-chickens were sexed, aged (Copelin 1963), and fitted with a GPS solar-powered telemetry units with a modified rump-mount harness (Bedrosian and Craighead 2007). In 2017, we used CTT 1000 BT3 Series GPS units (Cellular Tracking Technologies, Rio Grande, NJ, USA). In subsequent years, we used Harrier GPS-ultra high frequency units (Ecotone, Poland). Units were 18 gm in mass (< 3% body weight), programmed to collect locations every 30 min retrieved via ultra high frequency technology, and solar powered that lasted the life of the bird. Transmitters also had very high frequency capability, allowing for retrieval of units in the event of mortality. We removed locations collected from each individual for two days following capture, and we assumed that individuals acclimated to rump-mounted transmitters following this period. All capture and handling procedures were approved by the Kansas Department of Wildlife, Parks, and Tourism under a scientific collection permit (SC-036-2017).

All marked individuals were tracked regularly to download location data. Once GPS fixes became localized during the nesting period (late March through June), indicating a female potentially incubating on a nest, we confirmed the nest location and flushed the female during early incubation to determine clutch size. No other disturbances from the researchers occurred during the incubation period. We returned to the nest site to determine nest fate once GPS locations indicated the female departed the nest location. We considered a nest successful if at least one egg hatched (Rotella et al. 2004). We continued monitoring individuals throughout the summer, fall, and winter periods. In the event that movements became localized for more than 24 h, which indicated likely mortality, we confirmed a mortality event and retrieved the GPS transmitter.

Habitat covariates

We developed environmental and anthropogenic covariates to evaluate the response of lesser prairie-chicken behavior to the Facility during multiple seasons and at multiple scales (Table 1). Environmental covariates consisted of a combination of vegetation and landscape features. Vegetation layers including grass and shrub cover were developed from 1-m resolution National Agricultural Imagery Program image mosaics acquired in 2017 and 2021. We used Emi-automated object oriented analysis procedures developed by Image Spatial Consulting (Laramie, WY, USA) to generate separate grass and shrub cover habitat maps in the ERDAS Imagine software (LeBeau et al. 2017a). Grass and shrub cover were mapped in 5% cover class increments (i.e. 0–5, >5–10, …, >95–100%). Because vegetation estimates were categorized into 5% increments, we reclassified cover of each vegetation class by assigning each pixel to the mid-point value of each percentage increment. We performed a standard accuracy assessment protocol for remote sensing based thematic mapping using field vegetation data that we collected in 2017 and 2021 (Stehman and Czaplewski 1998). The procedure provides an overall accuracy, and omission and commission rate for each map class. The accuracy for the 2017 and 2021 classification was 76 and 71% for the shrub and 80 and 83% for the grass cover layers, respectively.

To incorporate changes in vegetation over the study period, we attributed location data recorded from 2017 through 2019 to vegetation layers developed from 2017 imagery. Location data recorded during 2020 and 2021 were associated with

Table 1. Environmental and anthropogenic covariates used in modeling lesser prairie-chicken resource selection, survival, and movements at the Cimarron Bend Wind Energy Facility in Clark County, Kansas, from 2017–2021. Variables were estimated within multiple buffers based on lesser prairie-chicken movements.

Covariate[a]	Description
Grass cover (Grass)	Percent grass cover developed from 1 m resolution National Agricultural Imagery Program (NAIP).
Proportion of grass (PropGrass)	Proportion of grassland land cover within each moving window derived from the National Land Cover Database (National Land Cover Database (NLCD) 2019).
Shrub cover (Shrub)	Percent shrub cover developed from 1-m resolution NAIP.
Proportion of shrub (PropShrub)	Proportion of shrubland land cover within each moving window derived from the National Land Cover Database (NLCD) (2019).
Patch size (Patch)	Average contagion index (range 0–100; O'Neill et al. 1988) within each moving window. Values near 0 equal high patchiness (i.e. each cell is a different patch type) and values near 100 represent landscapes containing a single patch. Contagion index was calculated using agriculture, bare ground, grass cover, trees, urban areas, major roads, and wind turbine pads.
Tree density (TreeDens)	Proportion of cells within each moving window containing trees.
Distance to tree (TreeDist)	Euclidean distance to trees (km).
Water (WaterProp)	Proportion of cells within each moving window containing water.
Distance to water (WaterDist)	Euclidean distance to water (km).
Distance to active lek (DistLek)	Euclidean distance to active lesser prairie-chicken lek (km).
TPI	Topographic position index within each moving window calculated as variability in mean elevation.
Elevation (Digital elevation models)	Altitude above ground level (m).
Agriculture (PropAg)	Proportion of cells within each moving window containing agriculture.
Distance to agriculture (AgDist)	Euclidean distance to agriculture (km).
Distance to urban areas (UrbanDist)	Euclidean distance to urban areas (km).
Distance to major roads (RoadDist)	Euclidean distance to state and federal highways (km).
Distance to transmission lines (TlineDist)	Euclidean distance to 345 kilovolt transmission line (km).
All surface disturbance (AllDisturb)	Percent of cells within each moving window where vegetation has been removed, excluding agriculture.
Wind facility surface disturbance (WindDisturb)	Percent of cells within each moving window where vegetation has been removed as a result of the wind energy facility (e.g. wind turbine access roads, wind turbine pads).
Wind turbine density (TurbCount)	Count of wind turbines within each moving window.
Distance to wind turbines (TurbDist)	Euclidean distance to wind turbines (km).
Turbine intersect (TurbInt)	Predictor used in step selection analyses to indicate whether used or available steps crossed between two turbines.

[a] Non-Euclidean distance covariates were estimated with 0.05, 0.46, 1.0, 2.2 and 5.0 km moving windows.

2021 imagery. Because our vegetation layers are not readily available across the species range, we also extracted grassland (classes 'Grassland/Herbaceous'), shrubland (classes 'Shrub/Scrub'), and cultivated cropland from the National Land Cover Database (Dewitz 2021). Distance to trees and water were measured as the Euclidean distance to each feature. Tree and water density was calculated as the proportion of cells that contained trees or water (Lautenbach et al. 2017). Trees and waterbodies were digitized using aerial imagery.

We considered the distance to active leks (km) as an additional covariate to account for the spatial relationship with individuals captured from a particular lek (as summarized in Haukos and Zavaleta 2016). Elevation and topographic position index (TPI) were calculated from a 10 m National Elevation Dataset (Digital Elevation Models [DEM]) as topographical features (US Geological Survey (USGS) 2015). TPI compared the elevation of each cell to the mean elevation within a specified neighborhood around that cell. Positive TPI values represent locations that are higher than the average of their surroundings as defined by the neighborhood and negative TPI values represent locations that are lower than their surroundings (Guisan et al. 1999).

We included Euclidean distance (in km) to major roads, transmission lines, wind turbines, cultivated cropland, and urban areas. Density metrics included all surface disturbance resulting in vegetation removal, surface disturbance from the wind energy infrastructure, and count of wind turbines. In addition, we developed a metric for movement analyses (TurbInt) that evaluated whether individuals moved across a theoretical straight line between two adjacent wind turbines. We included US and State highways as major roads. Major roads, turbine pads, and access roads were digitized using aerial satellite imagery in ArcMap 10 (Esri 2022). Turbine locations and overhead transmission lines were obtained from Enel Clean Energy. Wind energy facility covariates (turbine pads and access roads) were time-stamped to reflect their construction and operation dates given turbines were added to the landscape in 2020. Time-stamping was done to match covariates describing wind energy infrastructure presence to when lesser prairie-chicken locations were recorded. We estimated habitat patchiness using a contagion index (O'Neill et al. 1988) calculated using cultivated cropland, bare ground, grass cover, trees, urban areas, water, major roads, and wind turbine pads.

We assessed non-distance based covariates across five moving windows: 0.05, 0.46, 1.0, 2.2 and 5.0 km radii. The 0.05 km scale was chosen to represent conditions at a used location. The three intermediate moving windows approximated average lesser prairie chicken daily (0.46 km), double the average daily (1.0 km), and maximum daily (2.2 km) movements observed in this study. We assumed these moving window sizes were relevant to how lesser prairie-chicken perceive their environment during the breeding, nesting, summer, and winter periods. The 5.0 km radii moving window was based on a scale with relevance to lesser prairie-chicken resource selection (Sullins et al. 2019).

Analysis methods

We evaluated how the presence of the Facility influenced lesser prairie-chicken behavior and demography by assessing resource selection, movement, and nest and individual survival. In all analyses, we related lesser prairie-chicken locations to spatially explicit covariates measured on the landscape. More specifically, we used second-order Akaike's information criterion (AIC_c) to assess model support for all models (Burnham and Anderson 2002). All variables were centered and Z-transformed (Becker et al. 1988) to facilitate model convergence. Prior to developing any model, we performed initial variable screening procedures. We first ran univariate models and only retained variables when AIC_c scores indicated more parsimonious model fit than random intercept only models. For variables assessed across multiple moving windows, we selected the variable scale that had the lowest AIC_c score. We used a variable subsetting approach to develop nested candidate models and to determine the most parsimonious model (Arnold 2010). We first explored all variable combinations of six or fewer covariates that were retained following initial screening, except those describing wind energy infrastructure, and did not allow variables in the same model when $|r| > 0.6$. We bound models to a maximum of six covariates to limit the potential for model overfitting (Burnham and Anderson 2002). We used AIC_c to rank models and considered the most parsimonious model to be the base model for comparison with models containing wind energy facility infrastructure covariates.

We used a similar screening procedure for wind energy facility covariates. We then compared the base model to models including base model covariates plus all combinations of uncorrelated ($|r| > 0.6$) wind energy facility infrastructure covariates. Wind energy facility covariates included distance to wind turbines, distance to transmission lines, wind turbine density, surface disturbance associated with wind energy facility infrastructure, and all surface disturbance, which included wind energy facility surface disturbance. Candidate models were fitted with package MuMIn in R (www.r-project.org, Barton 2020). We allowed each model to compete and considered candidate models within four AIC_c from the top model to be competitive (Burnham and Anderson 2004).

Resource selection

We estimated lesser prairie-chicken resource selection at seasonal home range (second-order) and within seasonal home range scales (third-order) with resource selection functions (RSFs; Johnson 1980). Our intent was to develop yearlong resource selection models that could be used to inform management. However, we also developed resource selection models for nest site selection, and breeding (15 March to 1 August) and non-breeding (2 August to 14 March) seasons to assess variation in selection by seasons. We randomly selected 10 locations per individual for each day during breeding and non-breeding seasons to minimize spatial autocorrelation (Valcu and Kempenaers 2010).

Nest site selection was restricted to individuals that had a known nest. We generated 25 available nest locations for each nest. Available nest locations were restricted to a buffer around the lek of capture for each individual with a radius equal to the maximum distance from their lek of capture the individual traveled during the period from capture (or 15 March if captured in previous years) to nest initiation. For yearlong, breeding, and non-breeding resource selection models, available locations were generated at a rate of 25 times the number of used locations and were constrained to a 95% fixed kernel surrounding all individual locations at the seasonal home range scale and within individual 95% fixed kernels at the within seasonal home range scale (default bivariate kernel smoothing parameter; Worton 1989). We performed a post hoc assessment of the final yearlong models by using 5, 10, 15, 20 and 25 available locations per used location and determined that 25 available locations per used location were adequate for coefficient convergence (Northrup et al. 2013). We used conditional logistic regression with the survival package in R (www.r-project.org, Therneau 2021) to evaluate nest site selection, where each nest and its 25 paired available points were assigned to a strata. To estimate yearlong, breeding, and non-breeding season RSFs, we used binomial generalized mixed models with package *lme4* in R (www.r-project.org, Bates et al. 2015). We used an individual grouse intercept term nested within year to account for individual variation and possible variation in individuals across years (Gillies et al. 2006). The RSFs took the form:

$$w(x) = \exp(\beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_n x_n)$$

where $w(x)$ was proportional to the probability of selection, and $\beta_{n's}$ were coefficient estimates for each covariate. The model building process followed the methods above, and were implemented in yearlong, breeding, non-breeding, and nesting models at each scale of selection.

We used fivefold cross validation to evaluate the most-supported yearlong home range scale RSF model by randomly partitioning data by individual. We estimated predictions based on four of five groups (training data) and compared them to the withheld group, and repeated this until five withheld groups were evaluated (Johnson et al. 2006). We binned predictions into five equal-area (quartile) intervals (Wiens et al. 2008). Validations were performed by running simple linear regression models on the number of observed locations from test groups compared to expected locations generated from each RSF bin (Johnson et al. 2006). We considered models to be good predictors when linear regression models had high coefficients of determination ($r^2 > 0.9$) and 95% confidence intervals of slope estimates excluded 0 and included 1 (Howlin et al. 2004). We mapped the most predictive RSF model across the study area by using coefficients from the top model and distributed predictions into five equal area bins corresponding with increasing relative probability of selection.

Movements

We used step-selection functions (SSF; Fortin et al. 2005) to determine if the wind turbine configuration at the Facility acted as a barrier to movements. SSFs characterize selection of an individual as it traverses between consecutive locations (Thurfjell et al. 2014) and represents local-scale selection with a focus on resource selection while moving within a home range (third-order resource selection; Johnson 1980). We performed separate analyses for male and female lesser prairie-chickens during breeding and non-breeding seasons because we expected that males and females exhibited different movement behaviors during these time periods (Borsdorf 2013). We paired each location used by an individual with five available locations. We chose five available locations per used location to balance computational time with coefficient estimate accuracy as recommended by Thurfjell et al. (2014). We generated available locations from a distribution of step length and turning angles based on observations of used locations (Fortin et al. 2005, Thurfjell et al. 2014). This allowed us to determine covariates associated with each used or available location for each step. In addition, we evaluated paths along used and available steps to determine whether they intersected with theoretical lines connecting two wind turbines to assess whether individuals moved between turbines, given their availability. We used conditional logistic regression, where we assigned each used point and its five paired available points to a stratum. Individuals were assigned to a unique cluster to calculate standard errors (SE) and 95% confidence intervals and account for non-independence within an individual's movements (Craiu et al. 2008) using the *survival* package in R (www.r-project.org, Therneau 2021). Model selection was consistent with previous analyses and the methods presented above.

Nest and individual survival

To evaluate potential fitness consequences associated with wind energy infrastructure, we used cox proportional hazard models to relate nest failure and hazard of death to habitat covariates with the *coxme* packages in R (www.r-project.org, Cox 1972, Therneau 2020). Year was included as a random effect in all models. We assessed nest survival using time to event models over a 26-day incubation period during 2017–2021 nesting seasons (incubation period of 25–29 days; Hagen and Giesen 2005, Grisham et al. 2014). We assigned the nest's date of initiation and end date based on movement patterns identified from GPS location data and field observer visits to the nest site. Nests that contained at least one hatched egg at the end of the 26-day incubation period were considered successful (Rotella et al. 2004).

We used the Andersen–Gill (A–G) formulation of the Cox proportional hazard model to estimate individual survival because of its ability to use time-varying covariates (Anderson and Gill 1982). We modeled daily male and female lesser prairie-chicken survival from 15 March to 1 September (breeding season) and 2 September to 14 March (non-breeding season) separately. We allowed individuals to enter and leave the study with left and right censoring (Winterstein et al. 2001). Individuals that died within two days of capture were not included in survival analysis because we could not rule out the possibility of capture-related mortality (Blomberg et al. 2018). We assigned the date of mortality by reviewing the GPS movement data and confirmed mortality with field observations.

Results

Twenty-five active lesser prairie-chicken leks were identified during pre-construction aerial lek surveys within 4.8 km of proposed turbines during spring 2016 (10 March through 1 May; Rintz and Kosciuch 2016). An additional five leks were discovered during ground surveys during subsequent study years. The average maximum number of individuals attending leks ranged from 6.5 in 2017, 4.4 in 2019, and 4.6 in 2021 (total number of individuals counted at all known leks ranged from 101 to 138 during the study period). We captured 60 female and 66 male lesser prairie-chickens over the study period at 17 leks that averaged 3.3 km from a wind turbine (range: 0.4–6.6 km). We used approximately 226 000 locations from 84 individuals (37 females and 47 males) in subsequent analyses. We were unable to collect data from 29 individuals due to land access constraints or GPS transmitter failure over the study period. An additional 13 individuals were masked because they died within two days of capture.

Resource selection

More than half of all locations used by lesser prairie-chickens were in areas within 2.2 km of a wind turbine, with no cultivated cropland within 0.46 km, and with a proportion of grassland within 5.0 km exceeding 0.7 (Fig. 2). The base home range model evaluating yearlong resource selection included proportion of cultivated cropland within 0.46 km, elevation, distance to active leks, TPI within 2.2 km, tree density within 0.46 km, and proportion of water within 5.0 km. In general, lesser prairie-chickens selected higher elevation areas in more rugged terrain that occurred closer to active leks with less cropland and tree density, and higher proportion of water (Table 2). All models containing wind energy infrastructure covariates were more informative than the base home range model (Supporting information). Coefficients describing wind energy infrastructure suggested that lesser prairie-chickens avoided surface disturbance within 2.2 km ($\beta = -0.60$, 95% CI $= -0.61$ to -0.58; Table 2), selected areas with fewer wind turbines within 0.46 km ($\beta = -0.34$, 95% CI $= -0.36$ to -0.33), but selected areas near wind turbines ($\beta = -0.36$, 95% CI $= -0.38$ to -0.35), compared to what was available.

The spatial prediction of the RSF was a strong predictor of lesser prairie-chicken yearlong habitat selection (Fig. 3). When we partitioned validation testing and training groups by individual, average $r^2 = 0.99 \pm <0.001$ (SE), and confidence intervals of slope estimates included 1 and excluded 0 in all folds.

The within home range base model evaluating yearlong selection included percent shrub cover within 0.46 km, suggesting that lesser prairie-chickens selected areas with relatively low shrub cover (Table 2). All models containing wind energy facility covariates were more informative than the within home range base model (Supporting information). Lesser prairie-chickens selected greater surface disturbance associated with the wind energy facility ($\beta = 0.10$, 95% CI $= 0.09$–0.10; Table 2) at the 5.0 km scale.

For each seasonal model and scale that we assessed, models containing wind energy facility covariates were more informative than base models (Supporting information). At the

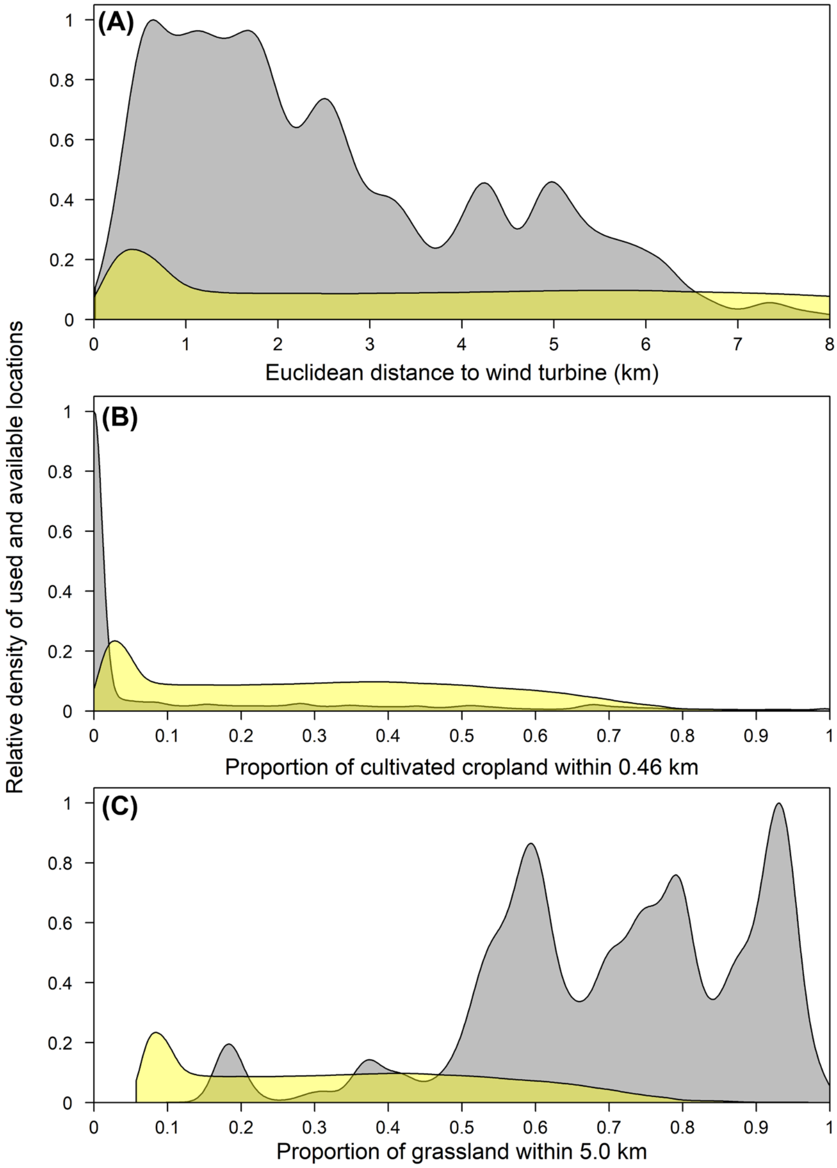

Figure 2. Density of locations used by lesser prairie-chicken (gray) and what was available across the study area (yellow) relative to (A) distance to wind turbines, (B) proportion of cropland within 0.46 km, and (C) proportion of grassland within 5.0 km near the Cimarron Bend Wind Energy Facility in Clark County, Kansas, from 2017–2021. Density plots were relativized by dividing values by their maximum.

Table 2. Coefficient estimates and 95% confidence intervals (CI) for covariates used in modeling lesser prairie-chicken yearlong resource selection at the Cimarron Bend Wind Energy Facility, in Clark County, Kansas, from 2017–2021. An asterisk (*) denotes covariates that were significant at the 95% confidence level.

		95% CI	
Parameter	Estimate	Lower	Upper
Home range scale[a]			
$\text{PropAg}_{0.46\ \text{km}}$	−1.20*	−1.21	−1.18
DEM	2.20*	2.18	2.22
DistLeks	−1.02*	−1.03	−1.01
$\text{TPI}_{2.2\ \text{km}}$	0.52*	0.51	0.53
$\text{TreeDens}_{0.46\ \text{km}}$	−2.19*	−2.24	−2.14
$\text{PropWater}_{5.0\ \text{km}}$	0.54*	0.53	0.55
$\text{AllDisturb}_{2.2\ \text{km}}$	−0.60*	−0.61	−0.58
$\text{TurbCount}_{0.46\ \text{km}}$	−0.34*	−0.36	−0.33
TurbDist	−0.36*	−0.38	−0.35
Within home range scale[b]			
$\text{Shrub}_{0.46\ \text{km}}$	−0.15*	−0.16	−0.14
$\text{WindDisturb}_{5.0\ \text{km}}$	0.10*	0.09	0.10

[a] Parameters include proportion of cropland within 0.46 km ($\text{PropAg}_{0.46\ \text{km}}$), elevation (DEM), distance to active leks (DistLeks), TPI within 2.2 km ($\text{TPI}_{2.2\ \text{km}}$), proportion of trees within 0.46 km ($\text{TreeDens}_{0.46\ \text{km}}$), proportion of water within 5.0 km ($\text{PropWater}_{5.0\ \text{km}}$), all surface disturbance within 2.2 km ($\text{AllDisturb}_{2.2\ \text{km}}$), count of wind turbines within 0.46 km ($\text{TurbCount}_{0.46\ \text{km}}$), and Euclidean distance to wind turbines (TurbDist). [b] Parameters include percent shrub cover within 0.46 km ($\text{Shrub}_{0.46\ \text{km}}$) and wind facility surface disturbance within 5.0 km ($\text{WindDisturb}_{5.0\ \text{km}}$).

home range scale, lesser prairie-chickens generally avoided surface disturbance within 2.2 km, avoided wind facility surface disturbance within either 2.2 or 5.0 km, selected areas with fewer wind turbines within 0.46 km, selected areas closer to wind turbines, and selected areas farther from transmission lines in breeding and non-breeding seasons (Supporting information). Within the home range, resource selection was associated with greater wind facility surface disturbance within 5.0 km during the breeding and non-breeding seasons (Supporting information). Lesser prairie-chickens selected areas farther from wind turbines during the non-breeding season (Supporting information).

Movement

All SSF models that included wind energy facility covariates were more informative than base models (Supporting information). During the breeding season, females selected grassland habitats interspersed with other vegetation communities, void of trees, and in areas with greater topographic ruggedness (Table 3). The most predictive model suggested that females selected areas with greater surface disturbance within 0.05 km (β = 0.03, 95% CI = 0.00 to 0.06), and areas near wind turbines (β = −0.41, 95% CI = −0.62 to −0.20), but selected areas with fewer wind turbines within 0.46 km (β = −0.08, 95% CI = −0.13 to −0.03). Females also avoided crossing between wind turbines (β = −0.02, 95% CI = −0.11 to 0.07) during the breeding season; however, we considered this to be an uninformative predictor because 95% confidence intervals overlapped zero. We observed 1098 female steps that crossed between turbines during the breeding season. During the non-breeding season, females selected areas near active leks that contained less proportion of cropland, lower tree density, greater topographic ruggedness, and areas closer to water (Table 3). The most predictive model suggested that females selected areas closer to wind turbines (β = −0.36, 95% CI = −0.53 to −0.19). Forty-two steps crossed between two turbines during the non-breeding season.

Males selected rugged, higher elevation grassland habitats in areas closer to active leks during the breeding season (Table 3). The top model suggested that males selected areas with greater surface disturbance within 0.05 km (β = 0.04, 95% CI = −0.01 to 0.08), lower wind facility surface disturbance within 5.0 km (β = −0.56, 95% CI = −0.85 to −0.28), but did not avoid crossing between turbines (β = 0.05, 95% CI = 0.01–0.09). We considered surface disturbance an uninformative predictor because 95% confidence intervals overlapped zero. We observed 1185 male steps cross between turbines during the breeding season. During the non-breeding season, males selected rugged areas with diverse vegetation communities that were closer to active leks, but contained little cultivated cropland (Table 3). The top model suggested that males avoided surface disturbance within 2.2 km (β = −0.19, 95% CI = −0.32 to −0.07), but selected areas closer to wind turbines (β = −0.44, 95% CI = −0.75 to −0.13) and did not avoid crossing between turbines (β = 0.04, 95% CI = 0.03 to 0.06). We observed 2203 steps cross between turbines during the non-breeding period. During the breeding and non-breeding seasons, the average distance to a wind turbine for steps that crossed between turbines was 0.59 km (range 0.02–2.38 km), and 0.65 km (range 0.02–2.90 km), respectively, which represented an average turbine spacing of approximately 1.2 km. Visual inspection of movements between turbines during the breeding and non-breeding seasons indicated that these movements primarily occurred on the periphery of the wind energy facility (Fig. 4). Large-scale movements through the facility were not observed during our study.

Nest and individual survival

We observed 31 nests over the study period. The distance from all identified nest locations to the nearest turbine averaged 2.4 km and was similar across years (range 2.0–2.5 km yearly average). Two models containing wind energy infrastructure covariates were more supported than the base model (Supporting information). The most supported model suggested that nest survival was negatively correlated with percent grass cover within 1.0 km (β = 0.75, 95% CI = 0.24–1.25; Table 4), positively correlated with proportion of shrubland within 1.0 km (β = −0.34, 95% CI = −0.79 to 0.12), and positively correlated wind facility surface disturbance within 0.46 km (β = −6.60, 95% CI = −17673.47 to 17660.27). However, we considered proportion of shrubland and wind facility surface disturbance predictors uninformative because confidence intervals surrounding parameter estimates overlapped with zero.

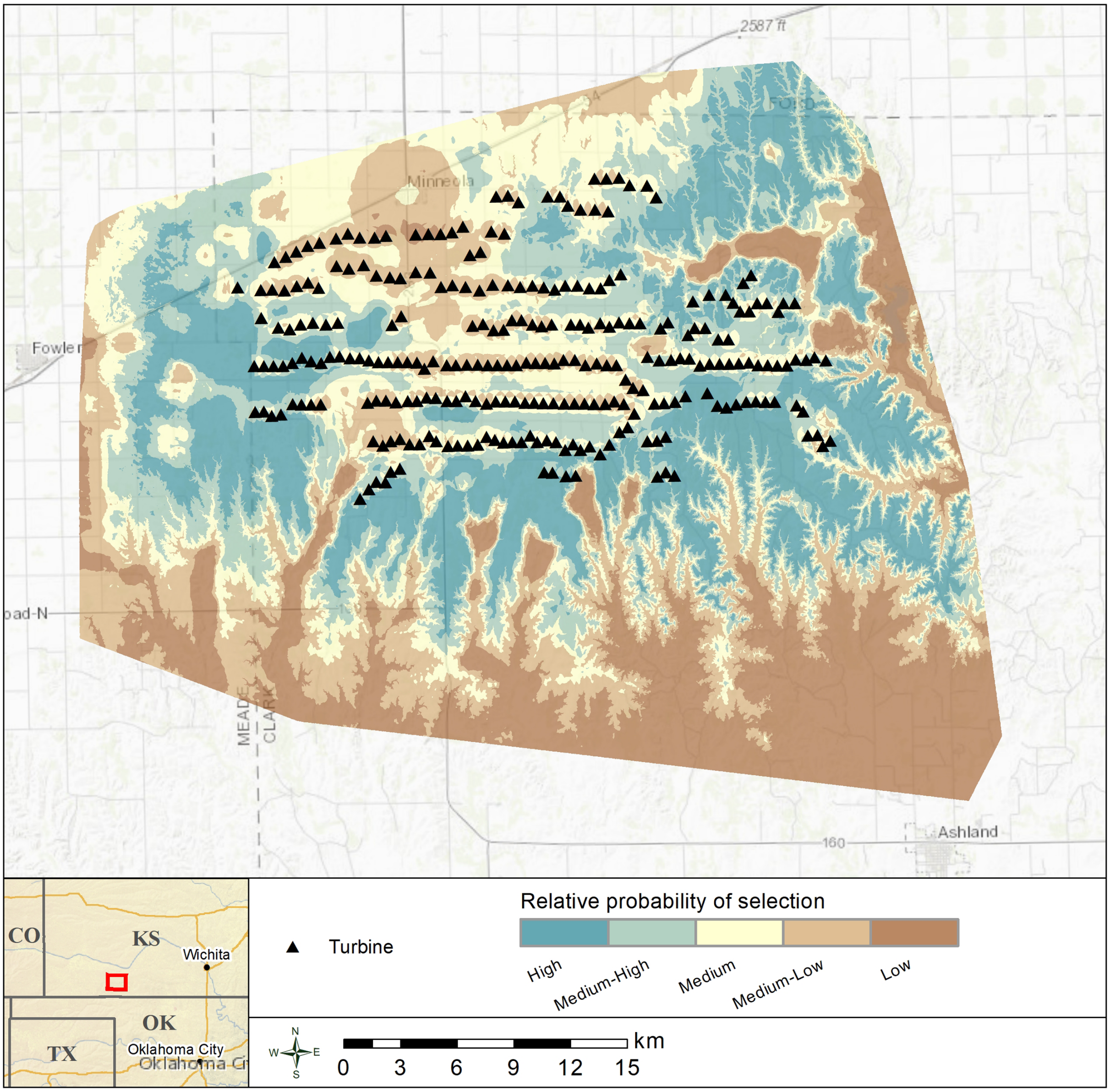

Figure 3. Relative probability of yearlong habitat selection by male and female lesser prairie-chickens at the home range scale near the Cimarron Bend Wind Energy Facility in Clark County, Kansas, from 2017–2021.

We did not observe a difference in survival between males and females during the breeding ($\beta = 0.05$, 95% CI $= -0.56$ to 0.65) or non-breeding seasons ($\beta = 20.61$, 95% CI $= -39448.57$ to 39489.78), so we combined all individuals and estimated overall survival rates. Kaplan–Meier (Kaplan and Meier 1958) survival estimates for both sexes during the breeding season was 43.4% during the study period (95% CI 33.4 to 56.2%), and fluctuated from 67.3% (95% CI 45.5 to 99.5%) in 2017, 21.9% (95% CI 9.3 to 51.7%) in 2019, and 66.1% (95% CI 45.8 to 95.4%) in 2021. Models containing wind energy facility covariates were more informative than base models in describing survival during the breeding season; however, all models were within four AIC_c of the base model (Supporting information). During the breeding season, lesser prairie-chicken survival was negatively correlated with the proportion of shrubland within 0.05 km ($\beta = 0.08$, 95% CI $= 0.02$–0.14), positively correlated with TPI within 0.05 km ($\beta = -0.22$, 95% CI $= -0.44$ to 0.01), negatively correlated with the proportion of tree cover within 0.46 km ($\beta = 0.15$, 95% CI $= 0.00$–0.30), and positively correlated with proportion of wind facility surface disturbance within 0.46 km ($\beta = -0.84$, 95% CI $= -1.97$ to 0.29; Table 4). However, confidence intervals surrounding the coefficient describing TPI and wind facility surface disturbance overlapped with zero. No models containing wind energy facility covariates were more informative than base models describing survival during the non-breeding season (Supporting information). During the non-breeding season survival was negatively associated with

Table 3. Coefficient estimates and 95% confidence intervals (CI) for variables in the most parsimonious models describing lesser prairie-chicken site-scale habitat selection and movements at the Cimarron Bend Wind Energy Facility, in Clark County, Kansas, from 2017–2021. An asterisk (*) denotes covariates that were significant at the 95% confidence level.

Parameter	Estimate	95% CI	
		Lower	Upper
Female–breeding season[a]			
Grass$_{0.05\text{ km}}$	0.28*	0.21	0.36
PropGrass$_{0.46\text{ km}}$	0.09*	0.01	0.17
Patch$_{0.05\text{ km}}$	−0.06*	−0.10	−0.01
TPI$_{2.2\text{ km}}$	0.43*	0.12	0.73
TreeDens$_{0.46\text{ km}}$	−0.23*	−0.34	−0.12
AllDisturb$_{0.05\text{ km}}$	0.03*	0.00	0.06
TurbCount$_{0.46\text{ km}}$	−0.08*	−0.13	−0.03
TurbDist	−0.41*	−0.62	−0.20
TurbInt	−0.02	−0.11	0.07
Female-non-breeding season[b]			
PropAg$_{1.0\text{ km}}$	−0.38*	−0.54	−0.22
DistLeks	−0.68*	−1.22	−0.14
TPI$_{1.0\text{ km}}$	0.61*	0.42	0.79
TreeDens$_{1.0\text{ km}}$	−0.34*	−0.46	−0.22
WaterDist	−0.23	−0.48	0.03
TurbDist	−0.36*	−0.53	−0.19
Male–breeding season[c]			
DistLeks	−1.50*	−2.09	−0.92
DEM	0.75*	0.41	1.10
RoadDist	−0.49	−0.97	0.00
PropGrass$_{1.0\text{ km}}$	0.61*	0.38	0.84
TPI$_{1.0\text{ km}}$	0.49*	0.32	0.67
AllDisturb$_{0.05\text{ km}}$	0.04	−0.01	0.08
WindDisturb$_{5.0\text{ km}}$	−0.56*	−0.85	−0.28
TurbInt	0.05*	0.01	0.09
Male–non-breeding season[d]			
PropAg$_{1.0\text{ km}}$	−0.44*	−0.74	−0.15
DistLeks	−0.84*	−1.23	−0.46
DEM	0.49*	0.24	0.75
Patch$_{0.05\text{ km}}$	−0.12*	−0.16	−0.08
TPI$_{1.0\text{ km}}$	0.39*	0.23	0.55
AllDisturb$_{2.2\text{ km}}$	−0.19*	−0.32	−0.07
WindDisturb$_{0.46\text{ km}}$	−0.06	−0.17	0.05
TurbDist	−0.44*	−0.75	−0.13
TurbInt	0.04*	0.03	0.06

[a] Parameters include percent grass cover within 0.05 km (Grass$_{0.05\text{ km}}$), proportion of grassland within 0.46 km (PropGrass$_{0.46\text{ km}}$), patch size contagion index within 0.05 km (Patch$_{0.05\text{ km}}$), TPI within 2.2 km (TPI$_{2.2\text{ km}}$), proportion of trees within 0.46 km (TreeDens$_{0.46\text{ km}}$), all surface disturbance within 0.05 km (AllDisturb$_{0.05\text{ km}}$), count of wind turbines within 0.46 km (TurbCount$_{0.46\text{ km}}$), Euclidean distance to wind turbines (TurbDist), and wind turbine intersection (TurbInt). [b] Parameters include proportion of cropland within 1.0 km (PropAg$_{1.0\text{ km}}$), Euclidean distance to active leks (DistLeks), TPI within 1.0 km (TPI$_{1.0\text{ km}}$), proportion of trees within 1.0 km (TreeDens$_{1.0\text{ km}}$), Euclidean distance to water (WaterDist), and Euclidean distance to wind turbines (TurbDist). [c] Parameters include Euclidean distance to active leks (DistLeks), elevation (DEM), Euclidean distance to major roads (RoadDist), proportion of grassland within 1.0 km (PropGrass$_{1.0\text{ km}}$), TPI within 1.0 km (TPI$_{1.0\text{ km}}$), all surface disturbance within 0.05 km (AllDisturb$_{0.05\text{ km}}$), wind facility surface disturbance within 5.0 km (WindDisturb$_{5.0\text{ km}}$), and wind turbine intersection (TurbInt). [d] Parameters include proportion of cropland within 1.0 km (PropAg$_{1.0\text{ km}}$), Euclidean distance to active leks (DistLeks), elevation (DEM), patch contagion index within 0.05 km (Patch$_{.05\text{ km}}$), TPI within 1.0 km (TPI$_{1.0\text{ km}}$), all surface disturbance within 2.2 km (AllDisturb$_{2.2\text{ km}}$), wind facility surface disturbance within 0.46 km (WindDisturb$_{0.46\text{ km}}$), Euclidean distance to wind turbine (TurbDist), and wind turbine intersection (TurbInt).

TPI within 0.05 km ($\beta = -1.65$, 95% CI $= -3.46$ to 0.15), although we considered this an uninformative parameter because confidence intervals overlapped with zero.

Discussion

Perceived responses to wind energy development by lesser prairie-chicken was previously based on measured responses to other anthropogenic features, and responses of other grouse species to wind energy development. Results from this study provide individuals and groups with a vested interest in species conservation, management, and energy development foundational information to understand lesser prairie-chicken behavioral and demographic responses to wind energy development. Siting measures that focus on placing turbines in cultivated croplands appear to be an important measure when considering potential impacts to lesser

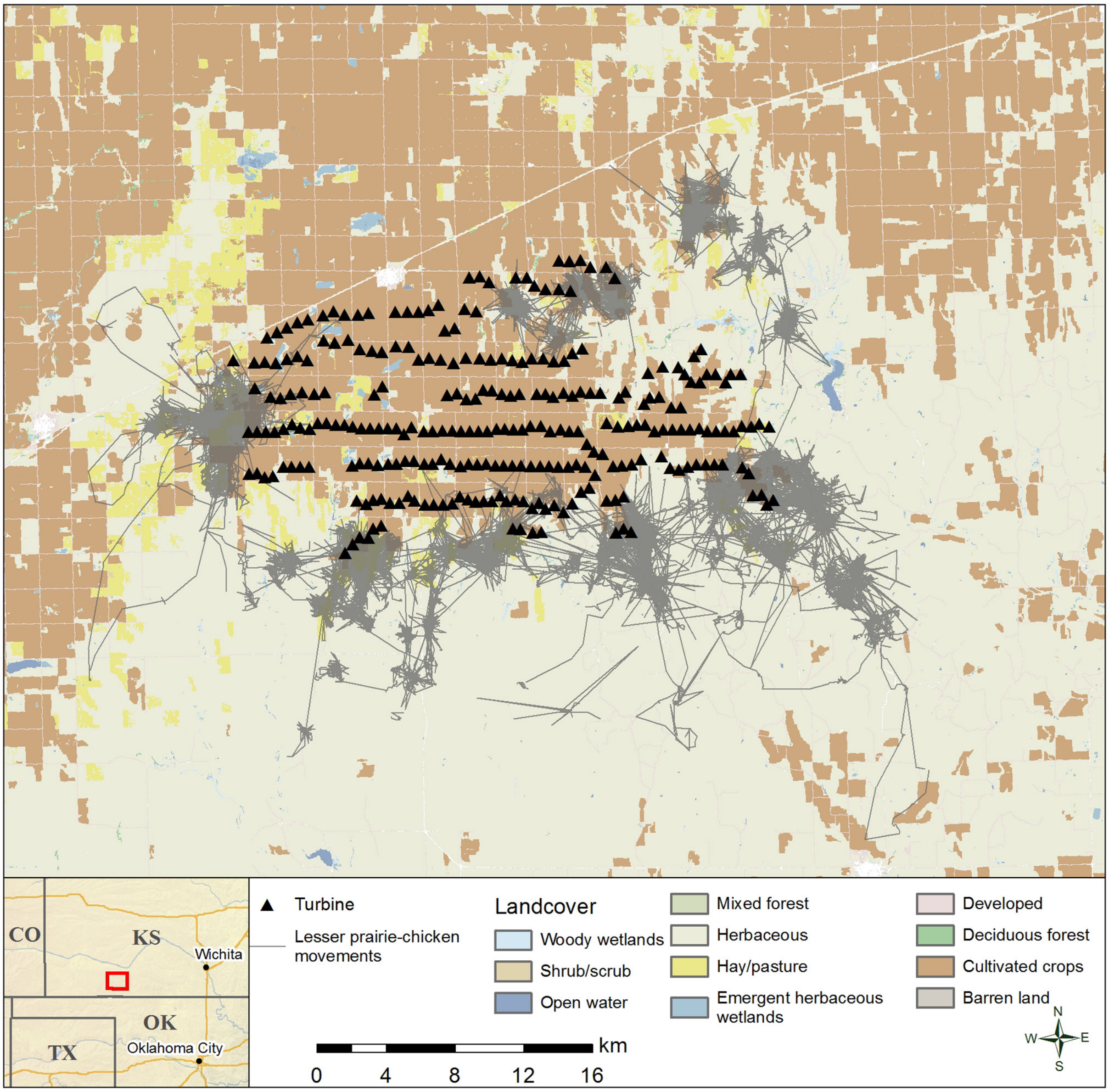

Figure 4. Lesser prairie-chicken locations connected by lines, indicating movements near the Cimarron Bend Wind Energy Facility in Clark County, Kansas, from 2017–2021.

prairie-chickens. During our study, we monitored multiple generations of lesser prairie-chickens along a gradient from wind turbines. Overall, we found limited evidence that lesser prairie-chickens avoided or experienced demographic consequences associated with a wind energy facility placed in cultivated croplands.

Resource selection by lesser prairie-chickens near the facility did not appear to vary by season. Lesser prairie-chickens avoided landscapes with large amounts of cultivated cropland containing a relatively high density of turbines or surface disturbances associated with wind energy infrastructure. Turbines were sited primarily in cultivated cropland; therefore, we cannot confidently determine if avoidance of the interior of the wind facility was a result of wind turbines or the extensive cultivated cropland at the facility. Nonetheless, the magnitude of effect associated with wind turbine density was less than the effect of cultivated cropland. For example, our yearlong model predicted a 54% reduction in relative probability of selection for areas where the proportion of cultivated cropland was 25% within 0.46 km. Areas with the same proportion of cultivated cropland plus the addition of one turbine within 0.46 km resulted in a 69% reduction in predicted relative probability of selection.

Displacement from otherwise suitable habitat has been documented in studies evaluating lesser prairie-chicken responses to oil and gas development, roads, and transmission lines (Pruett et al. 2009, Hagen et al. 2011, Plumb et al. 2019, Lawrence et al. 2021), and displacement caused by wind

Table 4. Coefficient estimates and 95% confidence intervals (CI) for covariates used in nest and adult survival modeling at the Cimarron Bend Wind Energy Facility, in Clark County, Kansas, from 2017–2021. An asterisk (*) denotes covariates that were significant at the 95% confidence level.

Parameter	Estimate	95% CI	
		Lower	Upper
Nest survival[a]			
Grass$_{1.0\ \mathrm{km}}$	0.75*	0.24	1.25
PropShrub$_{1.0\ \mathrm{km}}$	−0.34	−0.79	0.12
WindDisturb$_{0.46\ \mathrm{km}}$	−6.60	−17673.47	17660.27
Breeding season survival[b]			
PropShrub$_{0.05\ \mathrm{km}}$	0.08*	0.02	0.14
TPI$_{0.05\ \mathrm{km}}$	−0.22	−0.44	0.01
TreeDens$_{0.46\ \mathrm{km}}$	0.15*	0.00	0.30
RoadDist	0.33*	0.07	0.60
WindDisturb$_{0.46\ \mathrm{km}}$	−0.84	−1.97	0.29
Non-breeding season survival[c]			
TPI$_{0.05\ \mathrm{km}}$	−1.65	−3.46	0.15

[a] Parameters include percent grass cover within 1.0 km (Grass$_{1.0\ \mathrm{km}}$), proportion of shrubland within 0.46 km (PropShrub$_{1.0\ \mathrm{km}}$), and wind facility surface disturbance within 0.46 km (WindDisturb$_{0.46\ \mathrm{km}}$).
[b] Parameters proportion of shrubland within 0.05 km (PropShrub$_{0.05\ \mathrm{km}}$), TPI within 0.05 km (TPI$_{0.05\ \mathrm{km}}$), proportion of trees within 0.46 km (TreeDens$_{0.46\ \mathrm{km}}$), Euclidean distance to major roads (RoadDist)and wind facility surface disturbance within 0.46 km (WindDisturb$_{0.46\ \mathrm{km}}$).
[c] Parameters include TPI within 0.05 km (TPI$_{0.05\ \mathrm{km}}$).

energy development has been documented in a greater prairie-chicken and greater sage-grouse population (Winder et al. 2014b, LeBeau et al. 2017a). Another study found no evidence for displacement by greater prairie-chickens where most wind turbines were sited in pastureland (Harrison et al. 2017). While cultivated croplands interspersed within intact grassland may provide foraging opportunities (Sullins et al. 2018, Harryman et al. 2019, Tanner et al. 2021), lesser prairie-chicken abundance is negatively associated with cultivated cropland exceeding a landscape threshold (Fuhlendorf et al. 2002, Ross et al. 2016), suggesting that large tracts of cultivated croplands do not provide habitat to satisfy lesser prairie-chicken life history needs.

We observed movements of lesser prairie-chickens between turbines, suggesting that turbine spacing at the Facility did not result in a barrier to local movements in those areas which is in contrast to studies that suggest anthropogenic features including transmission lines, roads, and well pads may influence movements (Pruett et al. 2009, Peterson et al. 2020, Londe et al. 2022). In contrast to local movements, we did not detect longer movements through the wind energy facility (>5 km). Lesser prairie-chickens are known to make long-distance movements (>5 km) from their home range (Hagen and Gieson 2020, Peterson et al. 2020). We found that the maximum distance each individual moved from lek of capture averaged 5.1 km (range: 0.4–17.2 km), indicating that marked lesser prairie-chickens in this study were capable of making long-distance movements. At a landscape scale, wind energy has the potential to reduce connectivity between leks, and may impact population viability (Peterson et al. 2020, Schilder et al. 2022). However, as our results suggest, habitat connectivity is likely to be landscape context dependent, and given the extensive cultivated cropland in the interior of the facility, we cannot conclude that marked individuals would have moved through the area absent turbines. Future research addressing how a wind energy facility could impact connectivity at a larger scale would be beneficial for managers tasked with maintaining lesser prairie-chicken populations.

We failed to detect negative effects of the Facility on survival. Overall, apparent nest success in our study was low compared to those observed elsewhere in the region during the study period (Parker 2021), which could reflect small sample sizes, a lack of quality nesting habitat throughout our study area or existing anthropogenic features. Similarly, other studies did not detect negative effects on grouse nest success or survival relative to wind turbines (McNew et al. 2014, Winder et al. 2014b, Harrison et al. 2017, Smith et al. 2017, Proett et al. 2019, LeBeau et al. 2017a). Survival was also influenced by the amount of shrub and ground cover, suggesting that composition of various cover types may be more influential on survival than metrics associated with the wind energy facility (Robinson et al. 2018). Furthermore, lesser prairie-chicken survival rates observed during this study were within the range observed at other studies in the region (Hagen et al. 2010, Robinson et al. 2018).

Our study would be strengthened by using a before-after study design to compare lesser prairie-chicken responses before and after development of the wind energy facility. Unfortunately, a lack of pre-development data is a common weakness for studies evaluating potential impacts of anthropogenic development on wildlife species (Hebblewhite 2011, Conkling et al. 2021). Any displacement or survival consequences resulting from the wind energy facility were likely small given the strong avoidance of cultivated cropland where turbines were sited, and the relatively high use by lesser prairie-chickens near the facility after development. A before-after study design also would have allowed us to evaluate if the facility acted as a barrier to large-scale movements or if the large expanse of cultivated cropland limited this type of movement prior to the development of the facility.

As the demand for renewable energy increases, managers and energy developers will benefit from tools to avoid and minimize potential impacts to lesser prairie-chickens from future wind energy development. The USFWS predicts between 22 and 54 wind energy facilities will be built within the range of lesser prairie-chickens within the next 25–30 years (US Fish and Wildlife Service (USFWS) 2021a, LPC Conservation LLC 2021). The results of this study will have direct application to future wind energy facilities sited within the range of the lesser prairie-chicken. The perception that lesser prairie-chicken will respond to wind energy development similarly to other forms of anthropogenic development appears plausible. However, our results indicate that this response may be dependent on variability in habitat across the species' range, evidenced by other studies evaluating effects of other anthropogenic features on population metrics. A universal strategy for developing future wind energy projects in lesser prairie-chicken habitat may not be an effective measure to balance the demand for renewable energy with lesser prairie-chicken conservation. A conservative case-by-case approach to evaluating impacts associated with wind energy development may be beneficial to the lesser prairie-chicken given its current status, but consideration should be given when turbines are sited in cultivated croplands or other fragmented landscapes. More robust studies in various habitat types, including intact grassland, are critical to understanding how lesser prairie-chicken populations respond to wind energy development across the species' range and should be prioritized in the future, especially given the increased demand for renewable energy development.

Management implications

Based on the results of our study, siting wind turbines in cultivated croplands could be an important siting tool to minimize disturbance to remaining intact grasslands. Where possible, turbines should be placed in areas with a high proportion of cultivated cropland within 0.46 km to minimize impacts. Density of wind turbines within 0.46 km should also be minimized near suitable lesser prairie-chicken habitat. Based on documented movements between turbines, impacts may also be minimized by considering wind turbine spacing to allow movement between wind turbines. Results of this study allow us to begin to understand the effects of wind energy development located in cultivated cropland on lesser prairie-chickens, a siting measure that is currently being implemented across the species' range. Future research should be conducted in variable habitat types across the species' range to better understand how other populations of lesser prairie-chickens respond to wind energy development.

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Author contributions

Chad LeBeau: Conceptualization (equal), Data Curation (supporting); Formal Analysis (supporting); Funding Acquisition (equal), Investigation (lead), Methodology (equal), Project Administration (lead), Resources (equal), Software (supporting); Supervision (lead), Validation (equal), Visualization (equal), Writing – Original Draft Preparation (equal), Writing – Review and Editing, (equal). **Kurt Smith**: Conceptualization (supporting); Data Curation (lead), Formal Analysis (lead), Funding Acquisition (supporting); Investigation (supporting); Methodology (equal), Project Administration (supporting); Resources (supporting); Software (lead), Supervision (supporting); Validation (equal), Visualization (equal), Writing – Original Draft Preparation (equal), Writing – Review and Editing, (equal). **Karl Kosciuch**: Conceptualization (equal), Funding Acquisition (equal), Investigation (supporting); Methodology (supporting); Project Administration (supporting); Visualization (equal), Writing – Original Draft Preparation (equal), Writing – Review and Editing, (equal).

Transparent peer review

The peer review history for this article is available at https://publons.com/publon/10.1002/wlb3.01091.

Data availability statement

Restrictions apply to availability of wolverine den site information, as it is defined as classified information by the Swedish Environmental Protection Agency. Non-classified data are archived in the Dryad Digital Repository (https://doi.org/10.5061/dryad.b8gtht7hv, LeBeau et al. 2023). Den site data are available from the corresponding author conditional on permission from the Swedish Environmental Protection Agency.

Supporting information

The Supporting information associated with this article is available with the online version.

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