



# Placement of Wind Energy Infrastructure Matters: A Quantitative Study Evaluating Response of Lesser Prairie-Chicken to a Wind Energy Facility

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Placement of Wind Energy Infrastructure Matters: A Quantitative Study Evaluating Response of Lesser Prairie-Chicken to a Wind Energy Facility

**Wind Wildlife Research Fund**  
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## Abstract

Increases in domestic energy demand have the potential to negatively affect wildlife populations that are particularly sensitive to landscape change. The negative effects of landscape change on lesser prairie-chicken populations have been well documented, but little is known about the effects of wind energy development on this species. To estimate the effects of wind energy development on various lesser prairie-chicken population metrics, we captured and monitored 43 male and 32 female lesser prairie-chickens over a three-year period following the development of a wind energy facility in southern Kansas. The purpose of this study was to investigate the effects of wind energy infrastructure on multiple lesser prairie-chicken population parameters to provide a basis for evaluating potential future population-level effects. We found that lesser prairie-chickens selected habitats regardless of the presence of wind energy infrastructure during the nesting, breeding, and non-breeding time periods. In addition, nest and annual male and female adult survival were not negatively affected by wind energy infrastructure during the study. However, while our study results suggest that habitat selection did not result in fitness consequences, such impacts may not have been fully realized due to the relatively short study period and the inherent site fidelity exhibited in lesser prairie-chicken populations. The wind energy infrastructure was placed in previously altered landscapes, and we hypothesize that the impacts of this alteration have likely already been realized on the parameters we analyzed in this study. Our results suggest that the current wind energy development practice of siting wind energy facilities in altered habitats and outside of intact habitats within the range of lesser prairie-chickens may be a useful impact minimization tool.

## Introduction

In the past 150 years, the Great Plains region has undergone large-scale landscape changes primarily due to Euro-American settlement, subsequent cultivation, and urban development (Samson et al. 2004, Engle et al. 2008, Drummond et al. 2011). More recently, energy development has become a source of landscape change in the Great Plains region and is expected to increase based on current energy demands (McDonald et al. 2009, Jones and Pejchar 2013, Allred et al. 2015, American Wind Energy Association [AWEA] 2019).

McDonald et al. (2009) estimated that approximately 46,821 square kilometers (km<sup>2</sup>) of temperate grasslands could be impacted by biofuel production by the year 2030. In addition, it is estimated that approximately 1,392 km<sup>2</sup> of land would be affected by renewable energy sources by 2030 and renewable energy usage is expected to increase by 25% between 2018 and 2040 (McDonald et al. 2009, International Energy Agency [IEA] 2018). At this rate of land conversion, whether from oil and gas, renewable energy, or other anthropogenic land use, previously intact grasslands are expected to become lost or fragmented, increasing the potential for negative impacts to wildlife populations that are sensitive to landscape change (Leu et al. 2008, McDonald et al. 2009, Jones and Pejchar 2013, Northrup et al. 2013).

One negative impact associated with landscape change and habitat fragmentation on wildlife populations is apparent population declines of grassland bird species within the Great Plains region (Brennan and Kuvlesky 2005, Sauer et al. 2017). One of these species is the lesser prairie-chicken (*Tympanuchus pallidicinctus*, hereafter "LEPC"). LEPC are endemic to the Great Plains and the effects of direct (e.g., death from crushing or collision and habitat removal) and indirect (e.g., behavioral avoidance) impacts of habitat loss have resulted in range-wide population declines (US Fish and Wildlife Service [USFWS] 2014, Garton et al. 2016, Nasman et al. 2018). LEPC are now estimated to occupy less than 15% of their historic distribution (USFWS 2014). Much of the recent habitat loss is due to energy development as well as other landscape changes (Woodward et al. 2001, Fuhlendorf et al. 2002, Evans and Li 2017).

The LEPC has been considered an umbrella species (i.e., conservation actions related to one species benefits others) for prairie conservation as they require large, intact tracts of prairie to complete their

annual cycle (Johnsgard 1983, Pruett et al. 2009b, Sandercock et al. 2011). Specifically, LEPC are thought to need in excess of 8,000 hectares of native grasslands and shrublands in which they exhibit high site fidelity to maintain self-sustaining populations (Campbell 1972, Bartuszevige and Daniels 2016, Van Pelt 2016). In addition, areas that contain 77% grassland within a five-km radius have a higher predicted level of LEPC use than areas with less grassland (Sullins et al. 2019). Due to loss of these large undisturbed areas and resulting population declines of LEPC throughout its range in the Great Plains, this species was designated “threatened” by the USFWS in 2014 (Van Pelt 2016). While that listing decision was later vacated in court (Van Pelt 2016), the USFWS remains concerned that anthropogenic activity may lead to further population declines (USFWS 2014).

Wind energy infrastructure (hereafter, WEI) has the potential to increase fragmentation within LEPC habitat generating a growing need to understand these impacts and identify potential mitigation for declining LEPC populations. However, because there are no studies to our knowledge that have directly evaluated LEPC ecology relative to WEI, there is a lack of understanding as to what effects wind energy development may have on LEPC populations. Because wind energy is an anthropogenic disturbance that can fragment the landscape, it is expected that LEPC will respond in ways observed in studies of other forms of anthropogenic development, but the extent and magnitude of this response may vary based on the different characteristics among the types of anthropogenic development (e.g., structure heights, amount of human activity; Bartuszevige and Daniels 2016, LeBeau et al. 2017a).

Research indicates that oil and gas development, roads, transmission lines, and buildings have negatively affected LEPC habitat use during specific time periods (Pitman et al. 2005, Hagen et al. 2011). Some existing studies suggest that LEPC respond similarly to anthropogenic influences as other North American grouse species including the greater prairie chicken (GRPC; *Tympanuchus cupido*) and sharp-tailed grouse (STGR; *T. phasianellus*; Hagen 2010, Hovick et al. 2014), but the intensity of these responses may be larger for LEPC because of their increased susceptibility to habitat alterations (Hagen 2010).

The uncertainties of whether WEI affects LEPC persist because no studies have been conducted that evaluate the effects on established populations (Walters et al. 2014). Thus, our inferences on potential impacts are derived from related North American grouse species where such studies have been conducted. Studies have occurred in Idaho, Kansas, Nebraska, and Wyoming and the species included GRPC, STGR, and greater sage-grouse (GRSG; *Centrocercus urophasianus*). These studies generally found that nest survival and nest site selection were not negatively affected by proximity to wind turbines (McNew et al. 2014, Harrison et al. 2017, LeBeau et al. 2017a, Proett et al. 2019) and that female survival was not negatively affected by the presence of a facility (Winder et al. 2014a, LeBeau et al. 2017a, Smith et al. 2017). Displacement effects during the non-nesting season were evaluated at two study sites, and the researchers found that the presence of wind turbines negatively affected GRPC space use and GRSG habitat selection during the general breeding periods (nesting through brooding; Winder et al. 2014b, LeBeau et al. 2017a). There is some evidence for increased lek abandonment in areas close to wind turbines, but the rates or trends in the number of individuals attending leks across a gradient from wind turbines did not change pre- to post-development (Winder et al. 2015, LeBeau et al. 2017b).

To gain species-specific information for management and conservation of LEPC populations, additional research needs to be conducted on LEPC. Given that wind energy development is expected to increase within the LEPC range (McDonald et al. 2009, AWEA 2019), an understanding of LEPC population-level effects from wind energy development is important. To start to develop this understanding, we must first understand the short- and long-term effects of displacement from habitats and the potential consequences of displacement on population fitness parameters including nest, brood, and adult survival. Results from well-designed studies focused on LEPC are necessary to evaluate LEPC population-level effects of wind energy development, as well as provide land managers with information necessary to make decisions that will minimize and mitigate impacts on LEPC from future wind energy projects when development occurs in LEPC habitats (Ross et al. 2018).



Current wind energy project siting practices often prioritize development outside of intact grassland habitats, but this prioritization may shift into less fragmented landscapes as the demand for renewable energy increases (Leu et al. 2008, USFWS 2012, Jones and Pejchar 2013, AWEA 2019). Identifying WEI impacts to LEPC in unfragmented habitat may not be possible from studies in altered landscapes because the fragmentation effects on population parameters could already be realized, resulting in little additional effect of WEI. In addition, other local anthropogenic land use practices may collectively impact LEPC populations. Thus, it is difficult to evaluate specific impacts associated with WEI as there are many potentially confounding factors that exist on the landscape (Walters et al. 2014, Smith and Dwyer 2016). However, quantifying this effect in altered landscapes can provide useful siting tools that minimize impacts to LEPC populations for future wind projects in similar landscape types.

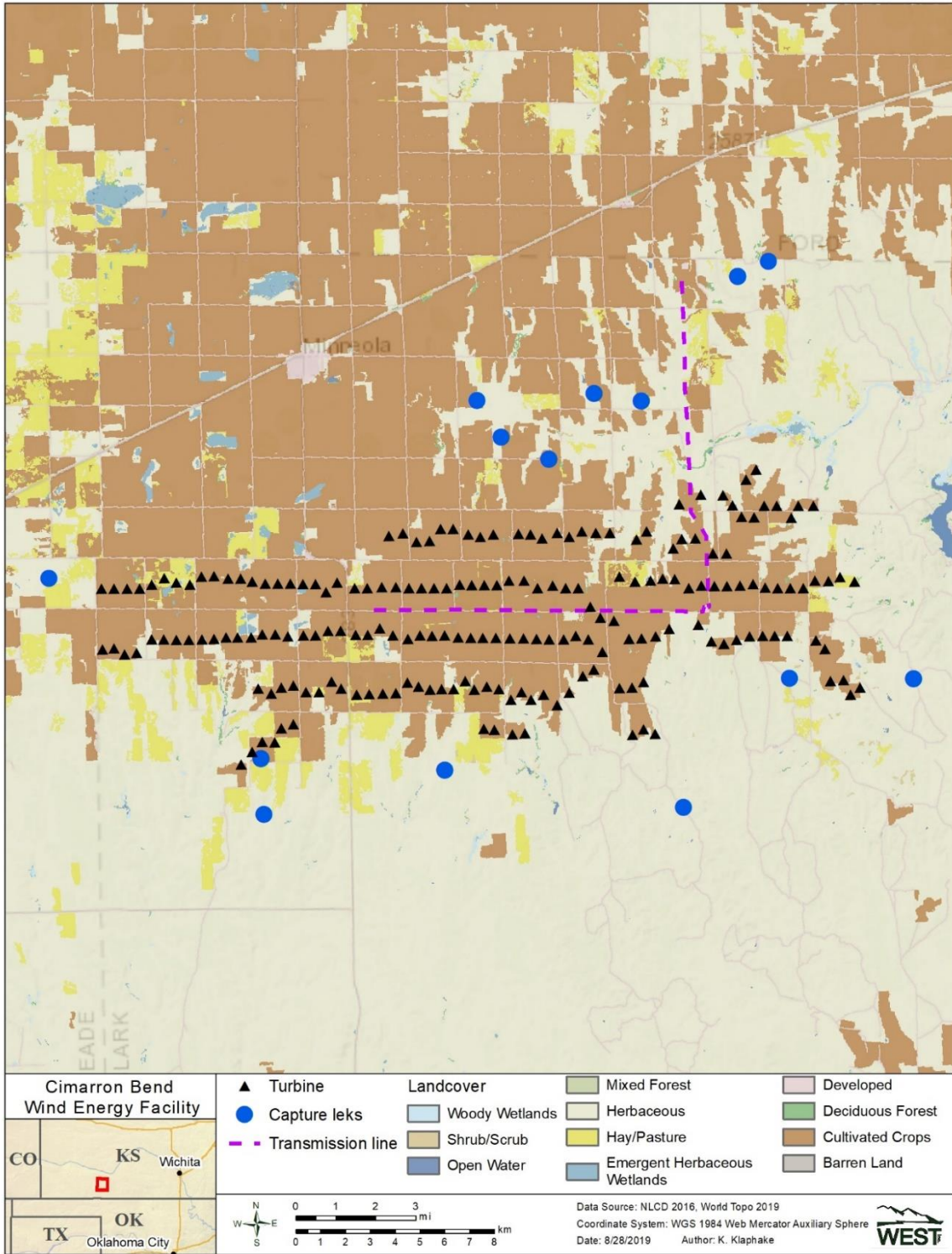
We designed a three-year study that accounts for confounding factors that exist on the landscape in order to investigate the effects of WEI on multiple LEPC population parameters. Our overall objective was to obtain data that could be used to inform population-level effects by evaluating the responses of LEPCs to WEI in all life stages three years following WEI development. Specifically, our objectives were to 1) identify whether LEPC were being displaced from seasonal habitats at multiple scales of habitat selection by WEI; 2) identify the effects of WEI on nest and individual survival; and 3) identify whether wind turbines acted as a barrier to movements. We predicted that LEPC would respond similarly to WEI as other prairie grouse species, but the spatial extent and intensity of observed effects may be greater due to the presumed heightened sensitivity of LEPC to land use change and energy development.

## Study Area

The study area is located in the Central Great Plains and the Southwestern Tablelands Level III Ecoregion in Clark County, Kansas (US Environmental Protection Agency 2017). The majority of the study area is fragmented by agricultural production (livestock grazing and row crop). Common crops observed within the study area are wheat (*Triticum* spp.) and grain sorghum (milo [*Sorghum bicolor*]). Agricultural lands are situated on plateaus interspersed with native mixed grass drainages in the northern and eastern portion of the study area. This landscape then shifts toward more extensive croplands towards the central and western portions of the study area. The southern portion of the study area is mostly intact mixed grass prairie with gently rolling hills that facilitate numerous drainages. Low-density residential development is centered on the town of Minneola, Kansas just outside the north central boundary of the study area. At the center of the study area is the Cimarron Bend Wind Energy Facility (CBWEF) operated by Enel Green Power North America, Inc., which has 200 2-megawatt (MW) wind turbines that became operational March 2017. 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 (13.4 miles [mi]) of new 345-kilovolt (kV) transmission line was also constructed to transmit power to a previously established line approximately 10.0 km (6.2 mi) to the North (Figure 1).

LEPC lek locations were the main sampling unit in our study. LEPC lek locations positioned near the CBWEF were the focus within our study area but our focus also extended beyond the CBWEF in all directions to capture LEPC on leks located along a gradient from the CBWEF. All of the turbines were located in croplands in the central portion of the study area. Thus, any effect of the CBWEF on the local LEPC population is likely confounded by the established avoidance behavior relative to high levels of fragmentation associated with cropland (Harryman et al. 2019, Sullins et al. 2019). We designed our study in an attempt to account for this potential confounding issue by 1) targeting multiple leks (e.g., capturing 2-3 individuals at each lek each year); 2) targeting leks that were located in close proximity to turbines; 3) targeting leks that were located within intact grassland habitats; and 4) targeting leks located in the northeast corner of the Project where the effect of cropland could be differentiated from that of WEI.





**Figure 1.** Location of lesser prairie-chicken leks targeted for capturing relative to the Cimarron Bend Wind Energy Facility in Clark County, Kansas from 2017-2019.

## Methods

### Field Methods

Aerial lek surveys were conducted twice during the 2016 lekking season within 4.8 km (3.0 mi) of proposed wind turbines (Rintz and Kosciuch 2016). For the subsequent study years, surveys included visiting leks identified in 2016 to determine activity, and searching for new leks by aerial surveys and driving publically accessible roads. These survey protocols were consistent with survey methodology within the region, and the results of these surveys were the basis of our sampling scheme (USFWS 2016).

Female and male LEPC were captured on leks using walk-in drift traps and drop nets during the spring lekking period; March to mid-May from 2017 through 2019 (Haukos et al. 1990). We attempted to maintain a sample size of 30 LEPC per year focusing on capturing as many females as possible. All LEPC were sexed, aged (Copelin 1963), and fitted with a Global Positioning System (GPS) solar-powered telemetry unit with a modified rump-mounting harness (Bedrosian and Craighead 2007). During the first year we used CTT 1000 BT3 Series GPS units from Cellular Tracking Technologies (Rio Grande, New Jersey, USA). For subsequent years we used Harrier GPS-ultra high frequency (UHF) units from Ecotone (Poland). These units were 18 grams in mass (<3% body weight), programed to collect locations every 30-minutes and equipped with solar power batteries to last the life of the bird. In addition, these units had very high frequency (VHF) capability, facilitating retrieval of units in case of mortality. All capture and handling procedures were approved by the Kansas Department of Wildlife, Parks, and Tourism (KDWPT) under a scientific collection permit.

All marked individuals were tracked regularly to download UHF data. Once GPS fixes became localized during the nesting period (late March through June), indicating a female incubating on a nest, we visited the potential nest or re-nest location and flushed the female in early incubation to determine clutch size and stage of incubation. No other disturbances from the researcher occurred during the incubation period. We returned to the nest site to determine nesting success once GPS locations indicated the female departed the nest location. We considered a nest successful if at least one egg hatched. We continued to monitor individuals throughout the summer, fall, and winter periods. We conducted weekly brood flushes for females with successful nests until the chicks fledged around 28 days post-hatch. In the event movements became localized for more than 24 hours, which indicated likely mortality, we retrieved the GPS units via VHF telemetry.

### Habitat Covariates

We developed a suite of anthropogenic and environmental covariates to estimate habitat selection and survival for LEPC during multiple seasons and at multiple scales (Table 1). We included the minimum distance from LEPC location to major roads (km), transmission lines (km), wind turbines (km), agriculture (km), urban areas (km), and CBWEF facility disturbance as metrics for anthropogenic disturbances (Table 1). We quantified the percentage of CBWEF facility disturbance and number of wind turbines associated with the CBWEF infrastructure within multiple spatial scales (Table 1). CBWEF facility metrics included digitized turbine pads and access roads. In addition, we considered a covariate (turbine intersect) that identified whether a used or available step intersected an imaginary line between two adjacent wind turbines in the movement analysis. Covariates that included infrastructure associated with CBWEF were collectively referred to as WEI covariates. We included US and State highways as major roads. Major roads and access roads were digitized using aerial satellite imagery and ArcMap 10 (ESRI 2011). Turbine locations and overhead transmission lines were obtained from Enel Clean Energy, the operators of the CBWEF.

We considered elevation and topographic position index (TPI), both of which were calculated from a 10-meter (m) National Elevation Dataset (Digital Elevation Models [DEM]) as topographical features (US

Geological Survey [USGS] 2015). TPI compared the elevation of each cell in a DEM to the mean elevation of a specified neighborhood around that cell (Table 1). Positive TPI values represent locations that are higher than the average of their surroundings as defined by the neighborhood (ridges) and negative TPI values represent locations that are lower than their surroundings (valleys; Table 1; Guisan et al. 1999). This covariate was included to capture the variability of drainage features across the landscape.

Environmental covariates consisted of a combination of vegetation and landscape features (Table 1). The distance to tree and water were measured as the Euclidean distance to each feature and tree and water density was the proportion of cells within multiple scales that contained water or trees (Lautenbach et al. 2017). We considered the distance to active leks (km) as an additional covariate to control for the spatial dependency that inherently exist from individuals captured from a particular lek (as summarized in Haukos and Zavaleta 2016). The landscape within the study area is highly fragmented, resulting in a large distribution of patch sizes. We attempted to capture potential selection of this variety of patch types and sizes using an average contagion index calculated using cropland, bare ground, grass cover, trees, urban areas, water, major roads, and wind turbine pads (O'Neill et al. 1988).

Vegetation layers used in the analysis were remotely sensed vegetation products developed from 1-m resolution National Agricultural Imagery Program (NAIP) image mosaics acquired in 2017. Semi-automated object oriented analysis procedure developed by Image Spatial Consulting was used to generate grass, shrub, bare ground, and ground cover habitat maps in the ERDAS Imagine software (Table 1, Figure 2; LeBeau et al. 2017a). Grass and shrub cover were mapped at 5% increments through 50% and above. Once shrub and herbaceous cover were plotted across the study area, percentage of ground cover was computed pixel by pixel. For each pixel, percent ground cover was derived as the sum of the shrub and grass cover percentages. Bare ground equated to 0% grass and shrub cover. Because vegetation estimates were categorized into 5% increments, we calculated the proportion of pixels within each buffer that contained cover classes greater than the respective cover class. For example, the proportion of grass cover greater than 10% within 460 m was calculated as the proportion of pixels within 460 m of a point that contained grass cover class greater or equal to 10% (e.g., grass\_g10\_460). We repeated this process for each vegetation index and cover class. Trees were digitized using aerial imagery with heads up manual interpretation.

We performed a standard accuracy assessment protocol for remote sensing based thematic mapping using field vegetation data that were collected in 2017 (Stehman and Czaplewski 1998). The accuracy procedure provides an overall accuracy, omission and commission accuracy for each map class. The accuracy for the 2017 classification was 76% for the shrub and 80% for the grass cover layer.

**Table 1.** Environmental and anthropogenic covariates used in modeling lesser prairie-chicken resource selection, survival, and movements at the Cimarron Bend Wind Energy Facility (CBWEF) study area, Clark County Kansas, 2017–2019. Variables were estimated within multiple buffers based on lesser prairie-chicken movement.

Covariates <sup>1</sup>	Variable Description
<b>Environmental Covariates</b>	
Grass Cover (categorical; Grass)	Percent grass cover (1-50%) binned into 5% cover class intervals (e.g., 1-5%). For each grass cover class, we calculated the proportion of cells within each moving window that contained grass cover greater than the respective cover class (e.g., Grass_g5_50 represented the proportion of cells within 50-meter (m) that contained grass cover greater than 5%).
Grass Cover (continuous; Grass_cont)	Percent grass cover (1-50%) where cells were assigned to the midpoint of cover class values.
Shrub cover (Shrub)	Percent shrub cover (1-50%) binned into 5% cover class intervals. For each shrub cover class, we calculated the proportion of cells within each moving window that contained shrub cover greater than the respective cover class (e.g., Shrub_g40_1045 represented the proportion of cells within 1,045-m that contained shrub cover greater than 40%).
Bare ground (Bare)	Percent bare ground (1-50%) binned into 5% cover class intervals. For each bare ground class, we calculated the proportion of cells within each moving window that contained bare ground greater than the respective cover class (e.g., Bare_g25_2200 represented the proportion of cells within 2,200-m that contained bare ground greater than 25%).
Ground cover (Ground)	Percent ground cover (grass and shrub; 1-95%) binned into 5% cover class intervals. For each cover class, we calculated the proportion of cells within each moving window that contained ground cover greater than the respective cover class (e.g., Ground_g10_460 represented the proportion of cells within 460-m that contained ground cover greater than 10%)
Patch size (Patch)	Average contagion index (range 0-100; O'Neill et al. 1988) within each moving window. Values near 0 high patchiness (e.g., 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, water, major roads, and wind turbine pads.
Tree density (Tree_d)	Proportion of cells within each moving window containing trees.
Distance to tree (Tree_dist)	Euclidean distance to trees (kilometer [km])
Water (Water_prop)	Proportion of cells within each moving window containing water.

Distance to water (Water_dist)	Euclidean distance to water (km)
Distance to active lek (Dist_leks_active)	Euclidean distance to active lesser prairie chicken lek

**Topographical Covariates**

TPI	Topographic position index (TPI) within each moving window calculated as variability in mean elevation.
Elevation (Dem)	Altitude above ground level (m)

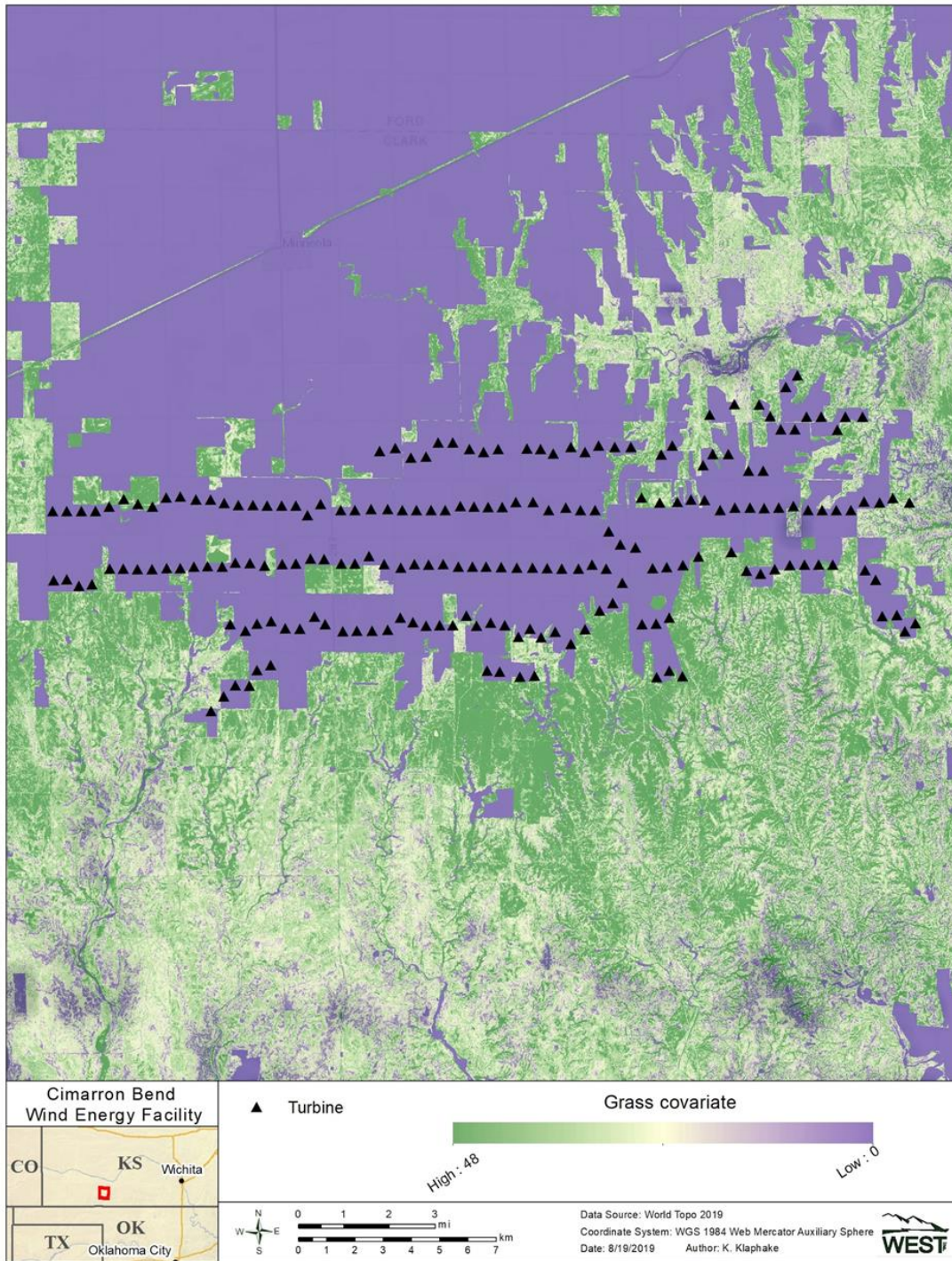
**Anthropogenic Covariates**

Cropland (Ag_prop)	Proportion of cells within each moving window containing cropland
Distance to agriculture (Ag_dist)	Euclidean distance to agriculture (km).
Distance to urban areas (Urban_dist)	Euclidean distance to urban areas (km)
Distance to major roads (Majroad_dist)	Euclidean distance to state and federal highways
Distance to transmission lines (Tline_dist)	Euclidean distance to 345 kilovolt (kV) transmission line constructed by the CBWEF (km)

**Wind Energy Infrastructure Covariates (WEI)**

Wind facility disturbance (Durb_prop)	Proportion of cells within each moving window where vegetation has been removed as a result of CBWEF (e.g., wind turbine access roads that included county roads and pads)
Wind turbine density (Turb_count)	Count of wind turbines within each moving window.
Distance to wind turbines (Turb_dist)	Euclidean distance to CBWEF wind turbines (km)
Distance to wind facility disturbance (Roadpad_dist)	Euclidean distance to CBWEF wind turbines and access roads that included county dirt roads (km)
Turbine Intersect (Turb_intersect)	Indicates whether used or available steps cross between two turbines.





**Figure 2.** Percent grass cover at the 50 m by 50 m pixel level developed by Image Spatial Consultants using remotely sensed National Agricultural Imagery Program image mosaics acquired in 2017, and used to evaluate lesser prairie-chicken habitat selection and survival relative to the Cimarron Bend Wind Energy Facility in Clark County, Kansas from 2017-2019.

## Analysis Methods

LEPC response to WEI was evaluated using three different metrics: displacement, survival, and movement. In all analyses, we related these metrics to various habitat covariates measured on the landscape (Table 1). While the overall analysis methods differed among these three metrics, the methods used to develop covariates, select models, and evaluate model covariates were similar.

## Covariate Analysis

We evaluated movements from individuals captured in 2017 and 2018 across multiple temporal scales to inform biologically relevant moving windows (circular buffers) for assessment of predictor covariates. We removed locations from each individual that preceded two days post capture and evaluated movements until being censored (mortality or censoring). We assumed that individuals acclimated to rump-mounted transmitters following two days post capture. Movements were estimated as the Euclidean distance between relocations across times we assessed. We summarized each individual and then averaged individual movements to estimate population-level (e.g., all monitored individuals) movement properties. First, we estimated movement between 30-minute relocation intervals for all individuals. We then estimated daily movement by filtering data to one location per day for each individual by selecting the location nearest to 12:00 for each individual to standardize locations to a 24-hour interval. For females that nested, we estimated daily movement from two days post capture to the time of nest initiation and also estimated the maximum distance between the nest and off-nest foraging locations. Finally, we estimated daily movements for all individuals during the breeding (two days post capture to August 1) and non-breeding (August 1 to March 15) seasons separately. The resulting average movements or buffer sizes roughly approximate LEPC movements across different temporal scales, which we assume may be relevant to how LEPC perceive their environment. That is, habitat selection by LEPC may depend on local features, but also surrounding habitats at these circular buffers around locations. Numerous movement metrics were calculated to provide a range of possible buffer sizes and we selected three that represented a range of movements of increasing magnitude. We also included a smaller 50-m window to assess whether the responses we measured were more related to habitat within the local surroundings.

## Model Selection

The model development process for the population-level model was consistent among response metrics evaluated during multiple time periods and at different scales. We first pooled all individuals into a single dataset to determine the most predictive buffer size of each covariate by using a univariate screening process. This screening process revealed the most predictive buffer size for each covariate by selecting the most parsimonious buffer size using  $AIC_c$  (Akaike 1974, Burnham and Anderson 2002). We then considered all possible combinations of five or fewer screened covariates and all possible WEI metrics, not allowing more than one WEI metric to be included in any model. We limited models to five covariates to limit the potential of overfitting models (Burnham and Anderson 2002). We used  $AIC_c$  to rank models and considered the most parsimonious model to be the population-level model with the lowest number of covariates that had the lowest  $AIC_c$  within two  $AIC_c$  values of the top model (Akaike 1974, Burnham and Anderson 2002, Arnold 2010). The population-level model was then evaluated for multicollinearity through evaluation of variance inflation factors (Kutner et al. 2004). In addition, we retained all population-level models with the lowest  $AIC_c$  that contained a WEI covariate for comparison purposes.

Once a final population-level model was determined, we fit models for each individual with at least 25 used locations by forcing the same covariates included in the population-level model. This approach ensured consistent comparisons among individuals and allowed for a population-level interpretation of combined individual bird effects absent the influence of varying levels of used points for the different birds. We bootstrapped coefficients by sampling coefficients for each individual to generate mean coefficient values that represented the population-level coefficients. We repeated this 1,000 times to generate median and confidence interval estimates (5<sup>th</sup> and 95<sup>th</sup> quantiles; Manly et al. 2002). Only



population-level models were used to assess survival and connectivity as the properties of these models (described below) preclude the ability to assess covariates at the individual level. Specific details about each metric, period, and scale are presented below.

## Displacement

One of our objectives was to identify if LEPC were being displaced from habitats that would have been otherwise occupied if the WEI was not present. For this objective, we used habitat selection modeling to compare habitats used by LEPC to habitats that were available during different seasons and at multiple scales (Manly et al. 2002). Evaluation at multiple scales allows for a more comprehensive understanding of the nested nature of habitat selection (Haukos and Zavaleta 2016). For instance, selection of habitat within a home range (3<sup>rd</sup> order selection; Johnson 1980) is conditional on selection of a home range (2<sup>nd</sup> order selection; Johnson 1980). If habitat features are selected or avoided at a larger scale, detection of these effects may not be apparent by only evaluating habitat selection at a smaller scale (e.g., DeCesare et al. 2012).

## General Analysis Framework

We estimated LEPC habitat selection during nesting, breeding, and non-breeding seasons at seasonal home range (home range scale) and within seasonal home range scales (local scale) with traditional resource selection functions (RSFs). Seasonal home range and local scale RSFs represented 2<sup>nd</sup> and 3<sup>rd</sup> order habitat selection, respectively (Johnson 1980). We extracted covariate values associated with used and available locations to evaluate the variability in habitat selection across the study area. We used generalized linear models to maximize the use-available likelihoods with an exponential link function (McDonald 2013). Models took the following form:

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

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 during each period and at each scale of selection.

Following model development, predictions of relative probability of habitat selection were generated within a minimum convex polygon of all LEPC locations to visually represent habitat selection relative to WEI. Predictions were made using five equal quantile bins using covariates from the top model and the model that included WEI to inspect changes in habitat selection with and without the influence of WEI. In addition, we compared the average binned prediction within 0.5 km increments from distance to wind turbine to further inspect the differences in habitat selection with and without a WEI effect.

## Nesting

We estimated RSFs during the pre-nesting period for females at the home range and local scales to determine what landscape features influenced the extent of habitats used during the pre-nesting period. The pre-nesting period is an important time period when females make decisions on where to place their nest, which could be influenced by the presence of the WEI as it further fragments the landscape (Hagen and Giesen 2005, Wolfe et al. 2016). This decision making happens at multiple scales (Haukos and Zavaleta 2016) and is dependent on the lek location at which that female bred. In this case, we used lek of capture as a proxy for the lek at which a female bred (Giesen 1994, Hagen et al. 2013, Haukos and Zavaleta 2016). The home range scale evaluated habitats within individual seasonal home ranges compared to habitats surrounding their lek of capture prior to nest initiation. The local scale evaluated habitats used compared to available habitats within the seasonal home range that individual selected following capture and prior to nest initiation. Finally, the last decision making process is where the

individual decides to place its nest within its home range, which was the site-specific nest site selection scale (or 4<sup>th</sup> order scale; Johnson 1980).

We restricted data to female LEPC from two days post capture until nest initiation for pre-nesting habitat selection at the home range and local scale and the nest location for the site-specific nest site habitat selection scale. For females that did not initiate a nest, we assigned a pseudo-nest initiation date based on the average initiation dates for nesting females during each year (5 May 2017, 20 May 2018, and 2 June 2019). Used habitats for the seasonal home range scale were defined for each individual by generating 95% fixed kernels around each individual's location (default bivariate kernel smoothing parameter; Worton 1989). Available habitats at the home range scale were defined for each individual by generating a buffer around lek of capture with a radius equal to the maximum distance of the female from lek of capture prior to nest initiation (Figure 3). We sampled available habitats within these areas using points that were uniformly distributed within each extent at a density of one point per 100 x 100 m cell. At the local scale, used habitats were defined as locations used by individual LEPC and available habitats were defined for each individual by generating 95% fixed kernels around used locations (default bivariate kernel smoothing parameter; Worton 1989). Available habitats at the local scale were sampled using points that were uniformly distributed within each available extent at a density of one point per 100 x 100 m cell (Figure 3). Nest site selection was restricted to individuals that had a known nest. We generated 25 available nesting locations for each nest. Available nesting locations were restricted to a buffer around 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 two days post-capture to nest initiation (Figure 3).

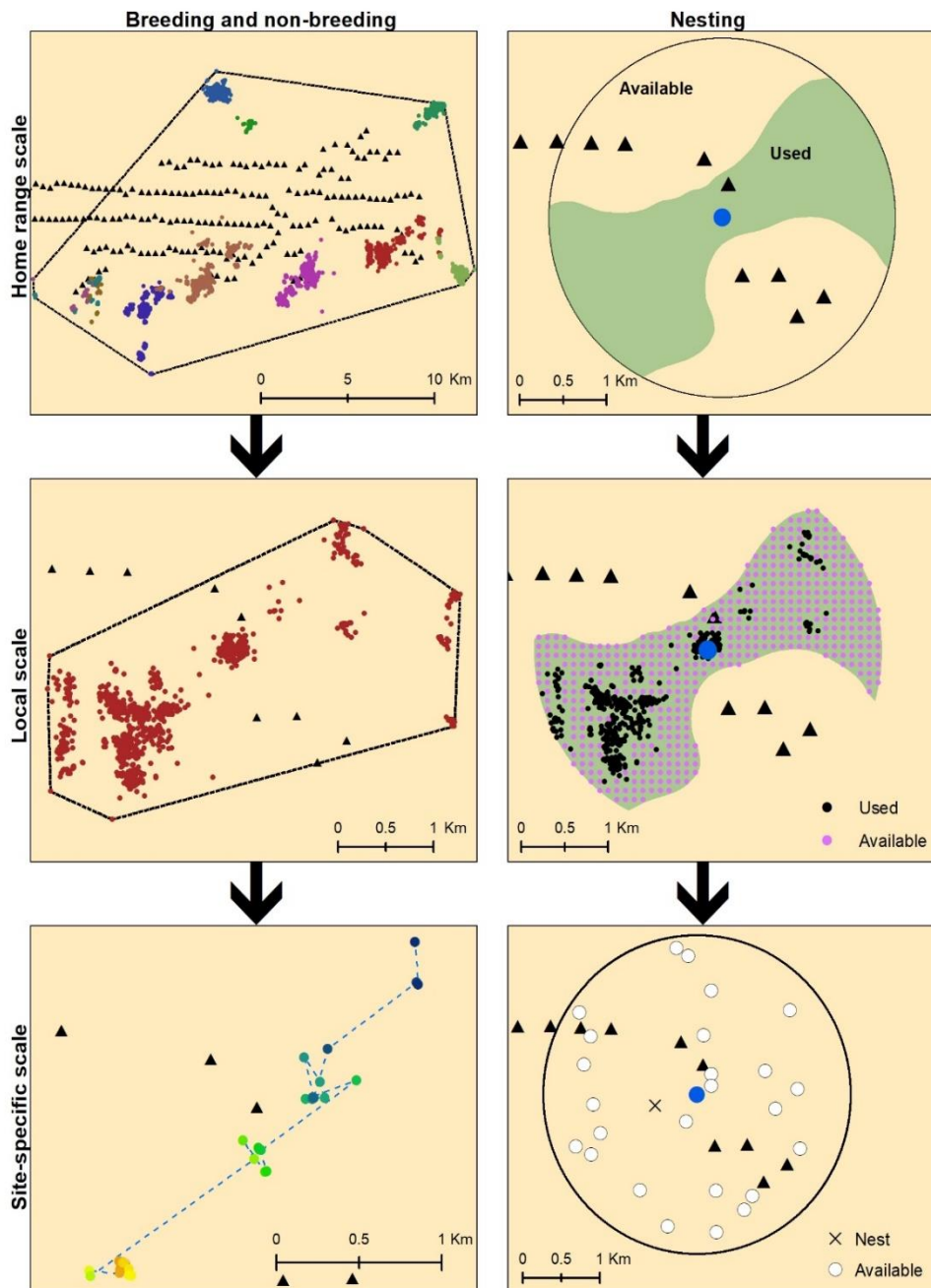
## Breeding

The breeding season (~March 15 to August 1) is an important time period when males and females congregate to breed, females nest and raise broods all in an effort to recruit new individuals into the local population. The male breeding season is shorter than females but the inclusion of males increased our sample size and assumed males selected similar habitats as females at this scale (Hagen et al. 2004, Boggie et al. 2017). Similar to the nesting period, LEPC make a series of decisions during this time period based on available habitats and these decisions could be influenced by the presence of WEI (Haukos and Zavaleta 2016). The seasonal home range scale evaluated used and available habitats by the entire sample of radio-marked LEPC while the local scale evaluated habitats used by individuals within their respective breeding season home ranges (Figure 3).

We restricted the locations of individuals from two days post-capture to August 1 each year. We randomly selected 10 locations per individual for each day to minimize spatial autocorrelation (Valcu and Kempenaers 2010). Available locations were generated at a rate of 25 times the number of used locations and were constrained to a 100% fixed kernel surrounding all individual locations at the seasonal home range scale and within each LEPC 95% fixed kernel at the within seasonal home range scale (default bivariate kernel smoothing parameter; Figure 3; Worton 1989).

## Non-Breeding

While the nesting and breeding season may be important for population recruitment, the non-breeding period is an important survival period for LEPC to ensure new individuals are recruited into the breeding population and contribute to multiple generations (Hagen 2004, Pirius et al. 2013). The habitats that individuals select relative to turbines during this time period may impact survival, which could impact population viability. Similar to the breeding period, the home range scale evaluated selection within the extent of all locations from the sampled population and the local scale evaluated selection within each individual's home range (Figure 3). We restricted the locations of individuals from August 1 to March 15 each year but all other methods were identical to the breeding season specific scales.



**Figure 3.** Examples of the extent of used and available lesser prairie-chicken locations used to develop resource and step habitat selection functions during multiple time periods and at multiple scales at the Cimarron Bend Wind Energy Facility, Clark County, Kansas from 2017-2019. The blue circle in the nesting panels are example lek locations and the black triangles in all figures are wind turbines. The colored dots in the breeding and non-breeding panel represent lesser prairie-chicken locations.

## Survival

We evaluated displacement during multiple seasons using RSFs described above. If LEPC are being displaced by the WEI, we would expect individuals to be forced to select lower quality habitats which in turn could have negative consequences to individual fitness. On the other hand, if individuals are not being displaced there is potential for the habitats that they occupy to act as ecological traps where the habitat may seem of high quality but have lower survival, which leads to individual fitness consequences (Aldridge and Boyce 2007, Hale and Swearer 2016). To evaluate for the potential negative consequences to fitness, we used survival modeling to determine the effects of WEI on nest and individual survival (Cox 1972, Anderson and Gill 1982). Model development followed the methods outlined above.

We estimated Cox models to relate hazard of death to habitat covariates, which in turn estimated survival within the study area using the `coxph` function in the R survival package (Therneau and Grambsch 2000). Cox models (Cox 1972) estimate the relationship between multiple explanatory variables and the instantaneous probability of death (called 'hazard'; Therneau and Grambsch 2000). Cox models provide risk ratios or hazard ratios that can be used to compare the effects of different levels of a particular covariate of interest (e.g., distance to nearest turbine) on the risk of failure (e.g., nest or individual death). We used the Andersen-Gill (A-G) formulation of the Cox model to estimate individual survival because of its ability to use time-varying covariates as covariates changed throughout the survival period (Anderson and Gill 1982).

We assessed nest survival for a 26-day incubation period during 2017–2019 nesting seasons (incubation period lasts 25–29 days; Hagen and Giesen 2005, Grisham et al. 2014). Nests from second attempts following failed nests for each individual might not be independent of first nests, and were excluded from survival analyses as they could potentially bias our results. Failures occurred when a female's nest was predated. We assigned the nest's date of initiation and failure date based on movement patterns identified from the GPS collected information and field observer visits to the nest site or mortality location. Nests that contained at least one egg at the end of the 26-day incubation period were considered successful (Rotella et al. 2004).

We modeled female and male LEPC annual survival from time of capture (or March 15 to March 14) during all study years. We assumed that year was independent when there were multiple years of survival data for a single LEPC. Mortality events were recorded only when we confirmed mortality visually via telemetry. We assigned the date of mortality by reviewing the GPS movement data. We evaluated the differences in survival between males and females. If differences were not detected, we combined all individuals and estimated population-level survival rates. We used 30-minute intervals to capture the point in time closest to an individual's mortality event, which provided the most accurate habitat conditions at the time of the event.

## Movements

Evidence suggests LEPC avoid tall structures such as transmission lines and trees which can also act as a barrier to movements between key habitats (e.g., nesting, breeding, and non-breeding habitats; Pruett et al. 2009a, Hagen et al. 2011, Bartuszevige and Daniels 2016, Lautenbach et al. 2017). Wind turbines are (really) tall structures and if LEPC respond similarly to wind turbines as other tall structures, there is potential that the configuration of turbines on the landscape may reduce connectivity between key habitats. We used step-selection functions (SSF; Fortin and Dale 2005) to determine if the turbine configuration on the landscape acted as a barrier to movements between key habitats. Model selection was consistent with previous analyses and the methods presented above. In addition, the extent of used data included in each seasonal SSF were identical to the breeding and non-breeding displacement analyses above. We performed separate analyses for male and female LEPC during both seasonal periods because males and females are likely exhibiting different behaviors and movements during these time periods.

Our previous habitat selection models used a more traditional RSF to evaluate selection at the home range, local, and site-specific scale (e.g., nest site selection). However, we used SSF models to evaluate site-specific habitat selection that focused on movement patterns during the breeding and non-breeding period (Figure 3). SSFs characterize selection of an individual as it navigates the landscape by consecutive locations (Thurfjell et al. 2014). SSFs represent site-specific scale selection with a focus on movement patterns within an individual's home range (3<sup>rd</sup> order resource selection; Johnson 1980), which may not be captured with more traditional RSFs, similar to the ones used in this study (Figure 3). We paired each location used by an individual with five available locations. 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 (where the individual moved to [used] compared to location available to move to [available]). In addition, we evaluated paths along used and available steps to determine whether they intersected with features of interest (e.g., theoretical lines connecting two wind turbines) to assess whether individuals crossed or moved between two features, given their availability, providing insight about features that may influence habitat connectivity. We performed four separate analyses to evaluate connectivity for female and male LEPC during the breeding and non-breeding seasons.

## Results

Twenty-five active LEPC leks were identified during pre-construction aerial lek surveys within 4.8 km of proposed turbines during spring 2016 (March 10 through May 1; Rintz and Kosciuch 2016). The number of individuals observed ranged from five to 18 (median = 9) and the distance from each lek to the nearest proposed turbine ranged from 0.13 km to 6.6 km (median = 2.6 km). Of the leks within 2.5 km of proposed turbines, the number of individuals attending those leks ranged from seven to 18 (median = 13) compared to a range of five to 16 (median = 8) individuals attending leks more than 2.5 km from proposed turbines.

The Starbuck fire started March 7, 2017, in northwest Oklahoma and quickly traveled north into Clark County, Kansas and through a portion of the study area (Figure 4). The vegetation appeared to recover during the 2017 growing season as we did not detect considerable differences in grass cover between the burned and unburned areas (see Figure 3 and 4). Nineteen of the leks identified in 2016 were located within the perimeter of the fire. We were able to visit four of these leks prior to the fire and counted six to 14 individuals attending these leks. Following the fire, we did not detect any lekking activity at any of these leks (inactive post fire), with the exception that we observed two individuals at one lek (1.3 km from the nearest proposed turbine location; Figure 4). We counted individuals attending eight leks located outside of the fire perimeter. The total number of individuals attending those leks ranged from three to 18 (median = 12) and the distance to the nearest operating turbine ranged from 0.4 km to 6.2 km (median = 3.8 km). We captured nine males and 15 females at five of these leks as land access precluded capture efforts at three leks in 2017.

Two leks that were previously located within the fire perimeter became active again in spring 2018 (Figure 4). We counted 11 active leks in 2018 and the total number of individuals counted at those leks ranged from six to 19 (median = nine) and the distance to the nearest turbine ranged from 0.1 km to 6.6 km (median = 1.8 km). We captured 18 males and 11 females at eight of the 11 leks in 2018. We were not successful at capturing individuals at two leks, and one lek was inaccessible.

Lek activity was variable across the study area in 2019 compared to previous years (Figure 4). Nine leks that were inactive in 2018 were active in 2019 and the distance to the nearest turbine ranged from 0.2 km to 6.3 km (median = 3.1 km). Conversely, four leks that were active in 2018 were inactive in 2019 and the distance to the nearest turbine for those leks ranged from 0.7 km to 4.1 km (median = 2.1 km). Despite the increase in the number of leks from 2018 to 2019, the median number of individuals attending leks was 3-fold lower in 2019 than in 2018 due to nine leks containing three or fewer individuals. We captured

16 males and six females from six leks and the distance to the nearest turbine for these six leks ranged from 1.7 km to 6.2 km (median = 2.8 km) during the spring 2019.

Overall, we captured 43 males and 32 females over the 3-year study along a gradient within various habitat types (Figure 5). The distance to the nearest turbine from place of capture varied from a median of 1.8 km in 2018 to 2.8 km in 2019. Eighteen individuals were lost due to GPS failure primarily during the 1st year of study and not included in the analysis.

Based on the movement information collected from individual LEPC, we chose to evaluate predictor variables within 2200-m, 1045-m, and 460-m moving windows to assess LEPC resource selection, movements, and survival relative to WEI. The resulting buffer sizes roughly approximate LEPC movements across different temporal scales, which we assume may be relevant to how LEPC perceive their environment (Table 2).

**Table 2.** Summary of male and female lesser prairie-chicken movement (meters) across multiple temporal scales. Movement was estimated as Euclidean distances between relocations of each radio-marked LEPC captured in 2017 and 2018 at the Cimarron Bend Wind Energy Facility, Clark County, Kansas from 2017–2018.

TEMPORAL SCALE	MEAN	MAXIMUM <sup>1</sup>	MEDIAN
Distance between ~30-minute relocations	104.4	2,514.9	98.8
Daily movement	460.5	3,161.4	386.4
Daily movement nest initiation <sup>2</sup>	588.5	2,222.8	497.1
Distance-nest to off-nest foraging <sup>3</sup>	122.1	1,274.4	102.2
Daily movement breeding season <sup>4</sup>	415.6	2,831.8	352.6
Daily movement non-breeding season <sup>5</sup>	516.7	2,318.5	501.2

1 Calculated as the mean of the maximum movement for each individual

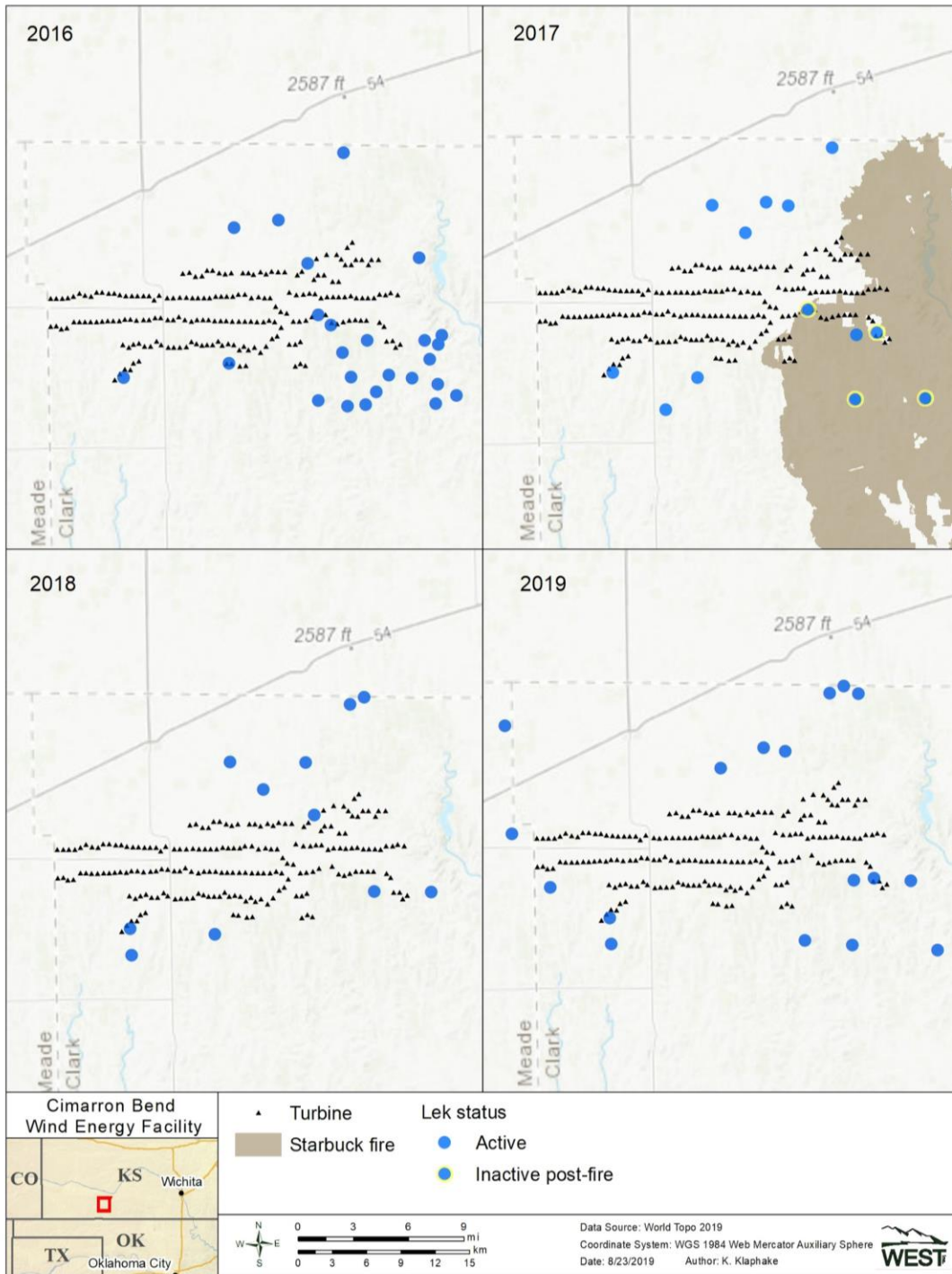
2 Daily movement from 2-day post capture to nest initiation

3 Maximum distance from nest location to off-nest foraging location

4 Daily movement from 2-day post capture to August 1

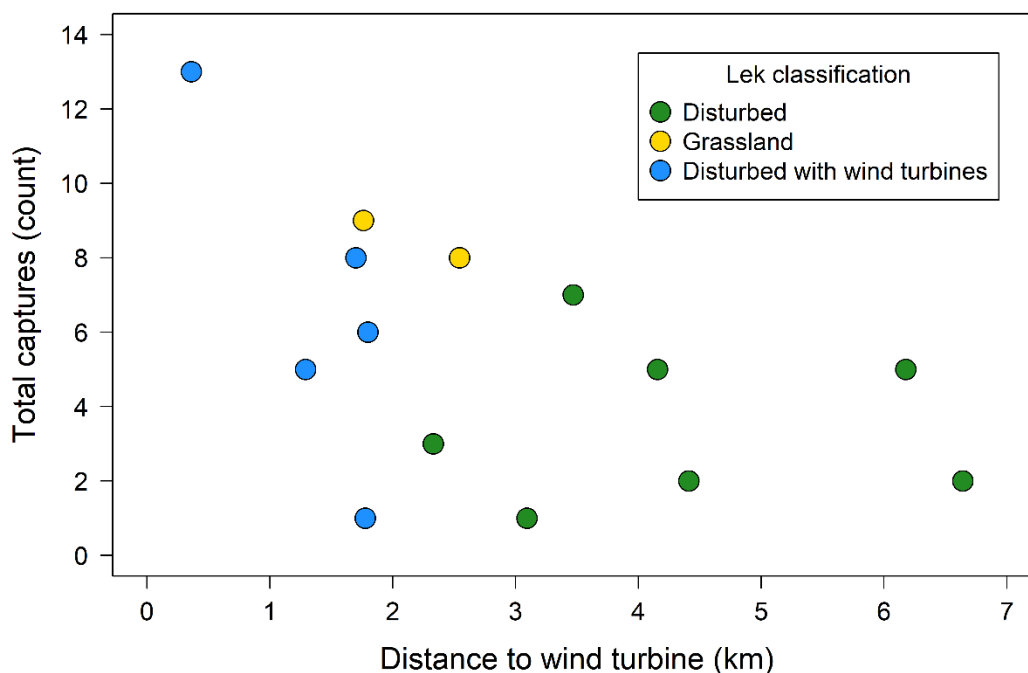
5 Daily movement from August 1–March 14





**Figure 4.** The spatial variation of active lesser prairie-chicken leks prior (2016) and post (2017-2019) development of the Cimarron Bend Wind Energy Facility, Clark County, Kansas





**Figure 5.** The spatial variation of active lesser prairie-chicken leks prior (2016) and post (2017-2019) development of the Cimarron Bend Wind Energy Facility, Clark County, Kansas

## Displacement

### Nesting

We captured 32 females over the study period, and 22 had enough data (either attributed to early fatalities or GPS malfunction) to be included in the home range and local scale habitat selection analyses. We observed 17 nests over the 3-year study ( $n = 8$  in 2017,  $n = 7$  in 2018, and  $n = 2$  in 2019). The distance to the nearest turbine ranged from 0.54 km to 7.26 km for all identified nest locations. We excluded two of the 17 nests from the nest site selection analysis because they failed shortly after laying, therefore generating a low number of used locations and subsequent available locations to accurately identify available habitat. We observed little evidence to suggest that WEI was displacing LEPC during the nesting period as no effects of WEI were included in the most parsimonious models at the home range or local scales (Appendix A1). However, the most parsimonious model for nest site selection at the site-specific scale did demonstrate potential avoidance of the wind facility disturbance, but this model was similar to the model that excluded the effect of WEI. The k-fold validation results indicated that each RSF model developed had good overall predictability (mean  $r_s$  home range = 0.69, mean  $r_s$  local = 0.74, and mean  $r_s$  nest site = 0.85).

Females selected nesting home ranges relatively closer to leks and in areas with less moderately dense shrub cover (Table 3, Figure 6). There was some evidence that suggested females selected home ranges that were closer to roads, higher in elevation, and farther from transmission lines, but there was some variability among individuals (Table 3). At this home range scale, the most competitive model that included a WEI covariate included distance to turbine ( $\beta = -0.99$ ; 90% CI: -2.65, 0.50); however, this model was 127.88 AIC<sub>c</sub> units from the most parsimonious model (Appendix A1).

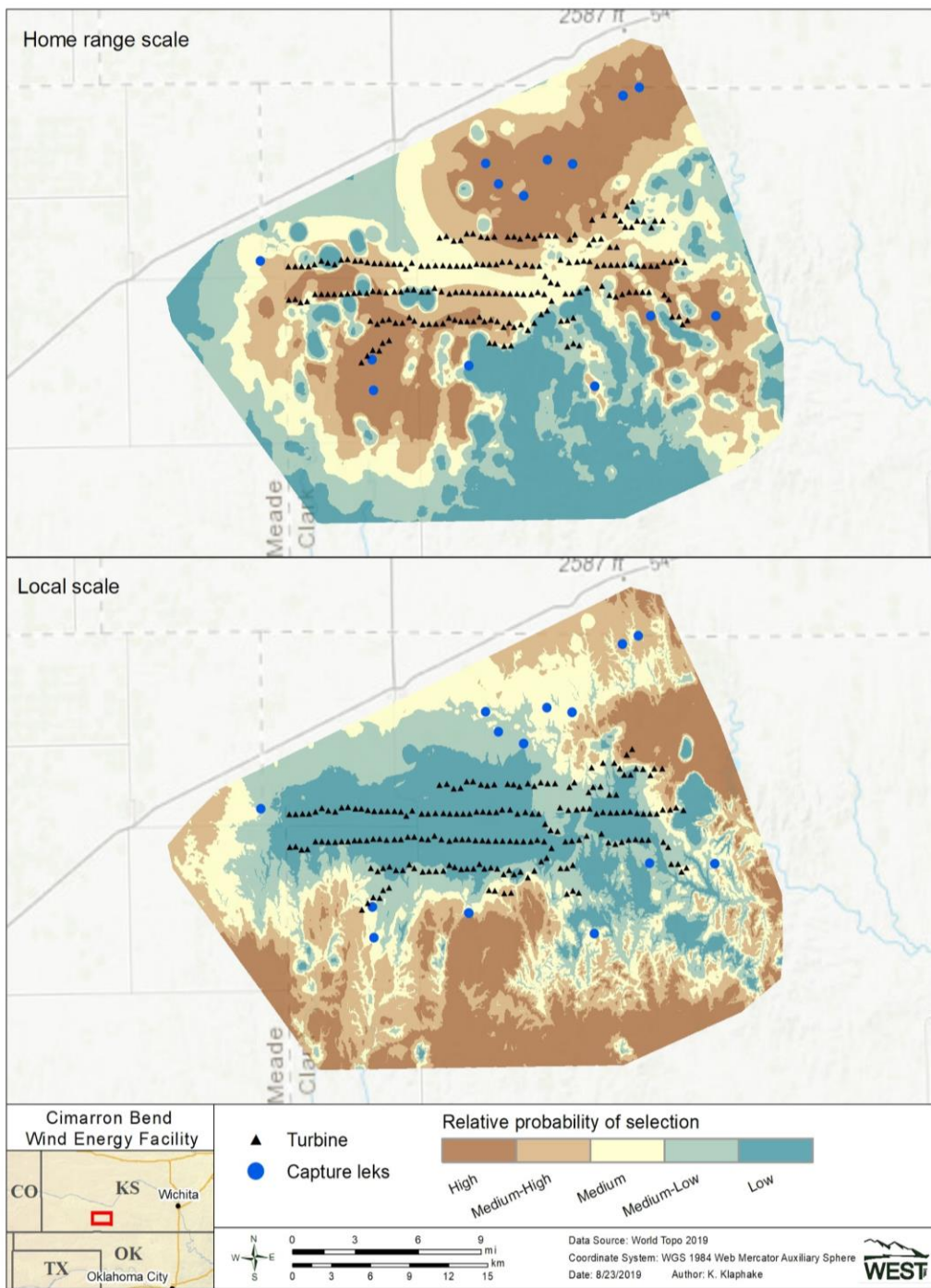
Within their home range at the local scale, LEPC selected areas with relatively higher grass cover, rugged areas, and farther from leks (Table 3). In addition, they selected areas with a higher percentage of trees within a 2.2 km buffer (Table 3). The most competitive WEI model included distance to the nearest road/pad ( $\beta = 0.54$ ; 90% CI: 0.06 - 1.08) but was 88.87 AIC<sub>c</sub> values from the most parsimonious model that excluded the effect of WEI. Inspection of the relative probability of selection across the study area indicated the lowest predicted levels of selection occurred within the CBEWF or areas with low grass cover (e.g., agricultural lands; Figure 6).

At the site-specific nest site selection scale, females selected nest sites with relatively greater grass and ground cover and in higher elevations. In addition, the relative probability of nest site selection increased by 65% for every one km increase in distance from wind facility disturbance indicating some level of displacement. Fifteen models were within two AIC<sub>c</sub> of the top model, with either distance to turbine or distance to wind facility disturbance included in all of the competing models. In addition, the best model lacking a WEI effect was 2.85 AIC<sub>c</sub> values from the model that included distance to wind facility disturbance. Comparison of prediction maps indicated that the habitat near turbines was of relatively low selection regardless of the presence of turbines (Appendix B1). Under both modeling scenarios, females selected nest site locations with a greater proportion of ground cover. This is characteristic of habitats farther from turbines (mean ground cover within 1-km of turbines was 48.7 and 84.5 beyond 1-km of turbines), further suggesting that habitat near turbines was of relatively low selection regardless of the presence of the turbines (Figure 7).

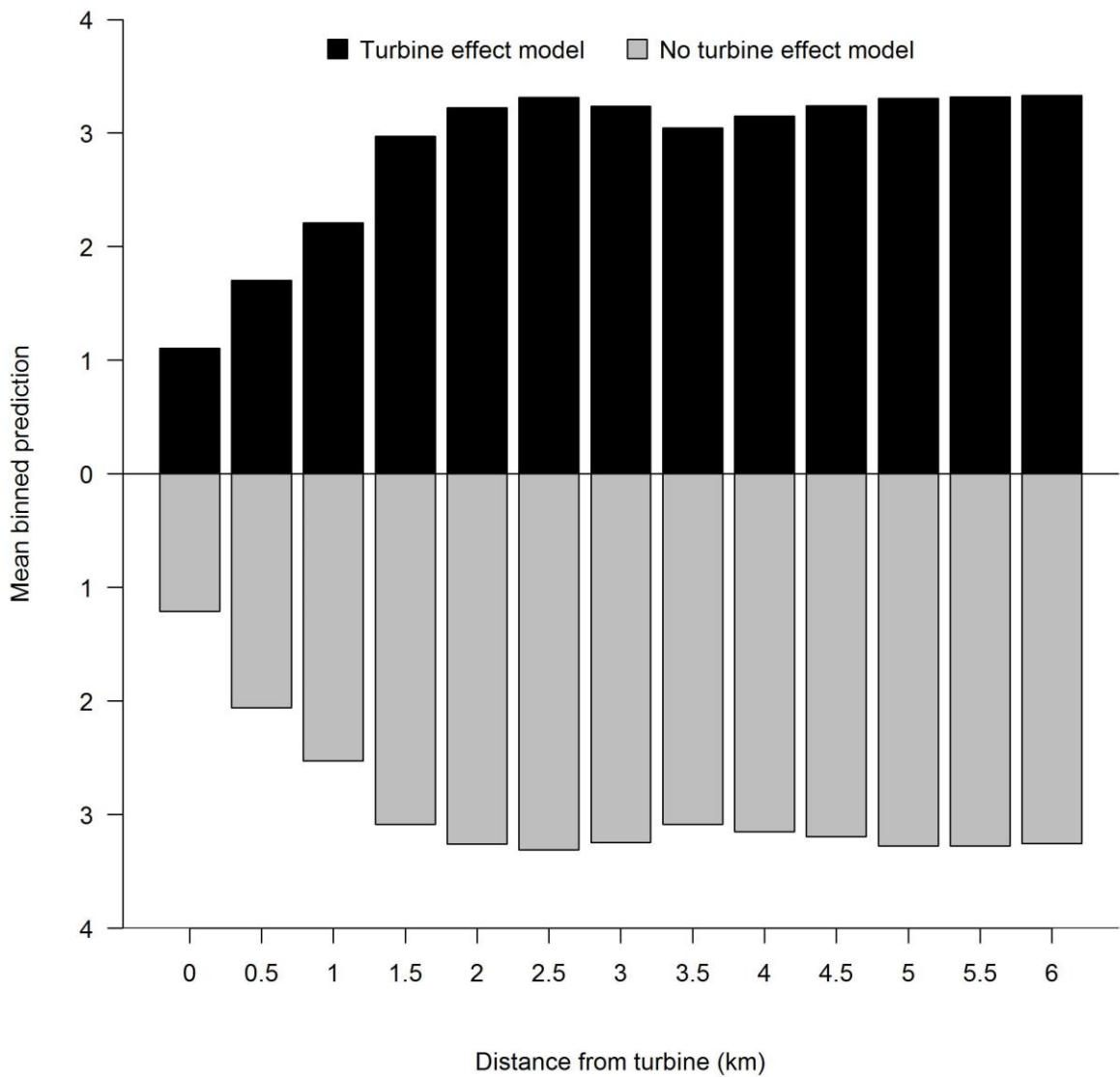
**Table 3.** Summary of male and female lesser prairie-chicken movement (meters) across multiple temporal scales. Movement was estimated as Euclidean distances between relocations of each radio-marked LEPC captured in 2017 and 2018 at the Cimarron Bend Wind Energy Facility, Clark County, Kansas from 2017–2018.

Parameter	Estimate	90 % CI	
		Lower	Upper
<b>Home range scale</b>			
Shrub_g35_460	-3.53*	-8.30	-0.48
Dem	0.004	-0.03	0.04
Dist_leks_active	-12.21*	-20.31	-6.97
Majroad_dist	-0.80	-3.34	1.73
Tline_dist	3.16	-2.68	12.12
<b>Local scale</b>			
Grass_cont	0.01*	0.003	0.02
Ground_g95_460	-0.21	-0.65	0.24
TPI_1045	0.10*	0.07	0.13
Tree_d_2200	154.33*	77.43	233.30
Dist_leks_active	0.67*	0.17	1.20
<b>Site-specific scale<sup>1</sup></b>			
Grass_g30_50	0.03*	0.01	0.06
Ground_g10_50	0.22*	0.03	0.88
Dem	0.06*	0.03	0.10
Roadpad_dist	0.49*	0.20	0.80

<sup>1</sup> Due to small individual sample sizes, bootstrapping was not conducted. Estimates and CI are reported from pooled model



**Figure 6.** Female lesser-prairie chicken relative probability of habitat selection at the home range and local scales during the nesting period at the Cimarron Bend Wind Energy Facility, Clark County Kansas from 2017-2019.



**Figure 7.** The average distribution of binned predictions for lesser prairie-chicken nest site selection at the site-specific scale with and without the effect of wind energy infrastructure within 0.5 km distance bands from wind turbines at the Cimarron Bend Wind Energy Facility, Clark County, Kansas from 2017-2019.

## Breeding

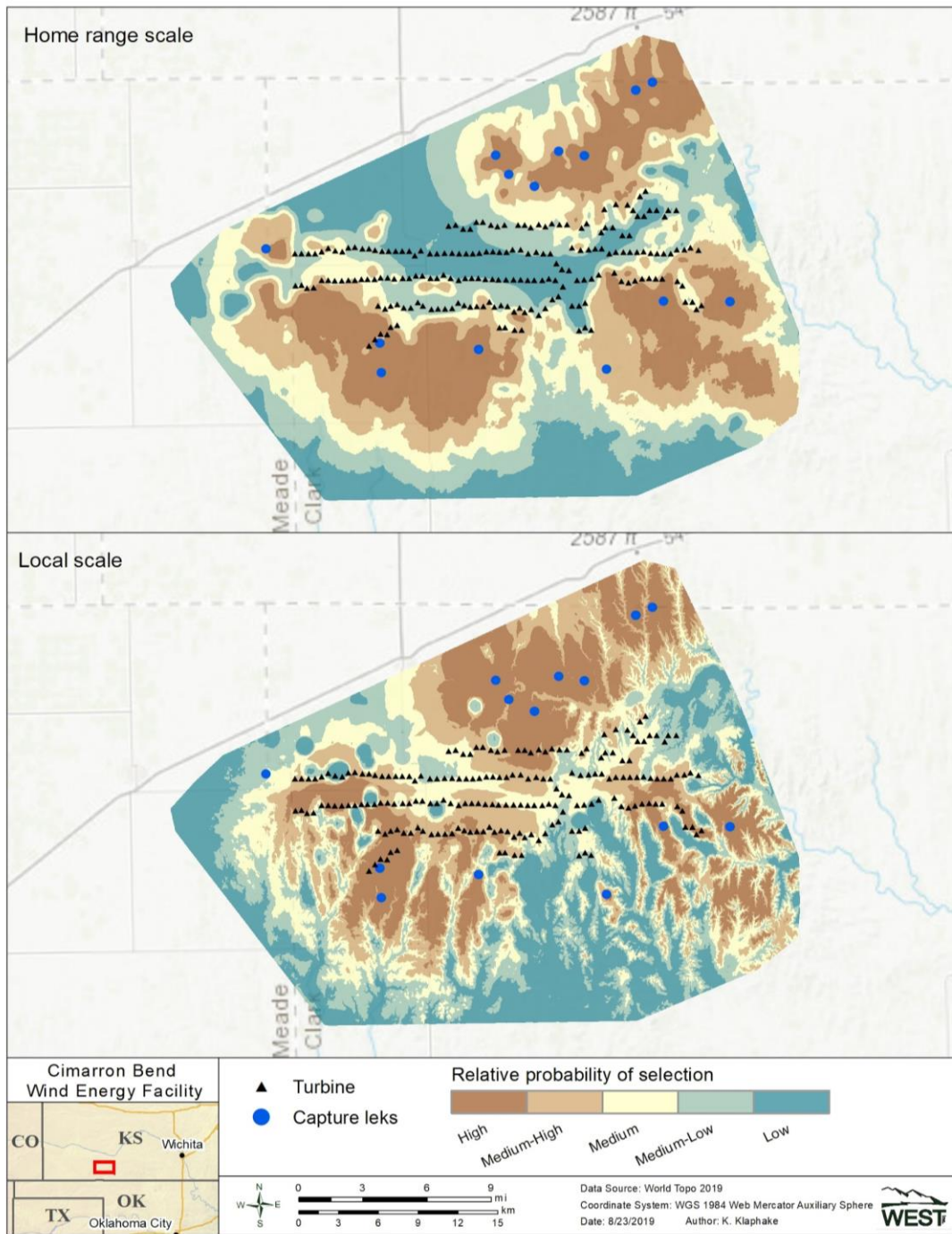
Twenty-two females and 33 males were included in the breeding habitat selection analyses except we excluded one female from the local scale analysis due to insufficient number of used locations to define a home range. We used 25,650 used locations to evaluate breeding habitat selection at the home range and local scales. We found no evidence that females and males were being displaced by the WEI as no WEI were included in the most parsimonious model for each scale nor did this effect differ among females and males. The k-fold validation results indicated that each RSF model developed had good overall predictability (mean  $r_s$  home range = 0.99 and mean  $r_s$  local = 0.71).

LEPC selected breeding home ranges relatively closer to leks, higher in elevation, and in areas with greater ground cover (Table 4; Figure 8). LEPC generally selected areas that were less rugged and more heterogeneous areas, but this pattern varied among individuals (Table 4). Distance to turbine ( $\beta = -1.20$ ; 90% CI: -2.58, -0.049) was included in the most competitive wind infrastructure models; however,  $AIC_c$  for this model was considerably higher than that of the most parsimonious model (Appendix A2).

Similar to the home range scale, LEPC selected habitats relatively closer to leks and in areas of more heterogeneous habitats at the local scale (Table 4, Figure 8). However, at this finer scale of selection LEPC selected more rugged habitats and there was some evidence that LEPC selected areas with less grass cover and less dense shrub cover (Table 4). The most competitive wind infrastructure model contained percentage of wind facility disturbance ( $\beta = -2.90$ ; 90% CI: -20.7, 7.67); however, as with the landscape scale model,  $AIC_c$  for this model was considerably higher than that of the most parsimonious model (Appendix A2).

**Table 4.** Coefficient estimates and 90% confidence intervals (CI) for covariates used in modeling lesser prairie-chicken breeding habitat selection. We obtained estimates by bootstrapping coefficients from models for each individual. An asterisk (\*) denotes covariates that were significant at the 90% confidence level.

Parameter	Estimate	90 % CI	
		Lower	Upper
<b>Home range scale</b>			
Ground_g20_460	0.39*	0.10	0.87
Patch_460	-0.05	-0.23	0.08
TPI_2200	-0.18	-0.56	0.09
Dem	0.30*	0.05	0.71
Dist_leks_active	-6.62*	-11.57	-3.45
<b>Local scale</b>			
Grass_cont	-0.01	-0.08	0.02
Patch_460	-0.04*	-0.06	-0.02
Shrub_g40_460	-1.05	-3.94	1.18
TPI_1045	0.16*	0.12	0.21
Dist_leks_active	-1.45*	-2.49	-0.70



**Figure 8.** Lesser prairie-chicken relative probability of habitat selection at the home range and local scales during the breeding period at the Cimarron Bend Wind Energy Facility, Clark County, Kansas from 2017-2019.



## Non-Breeding

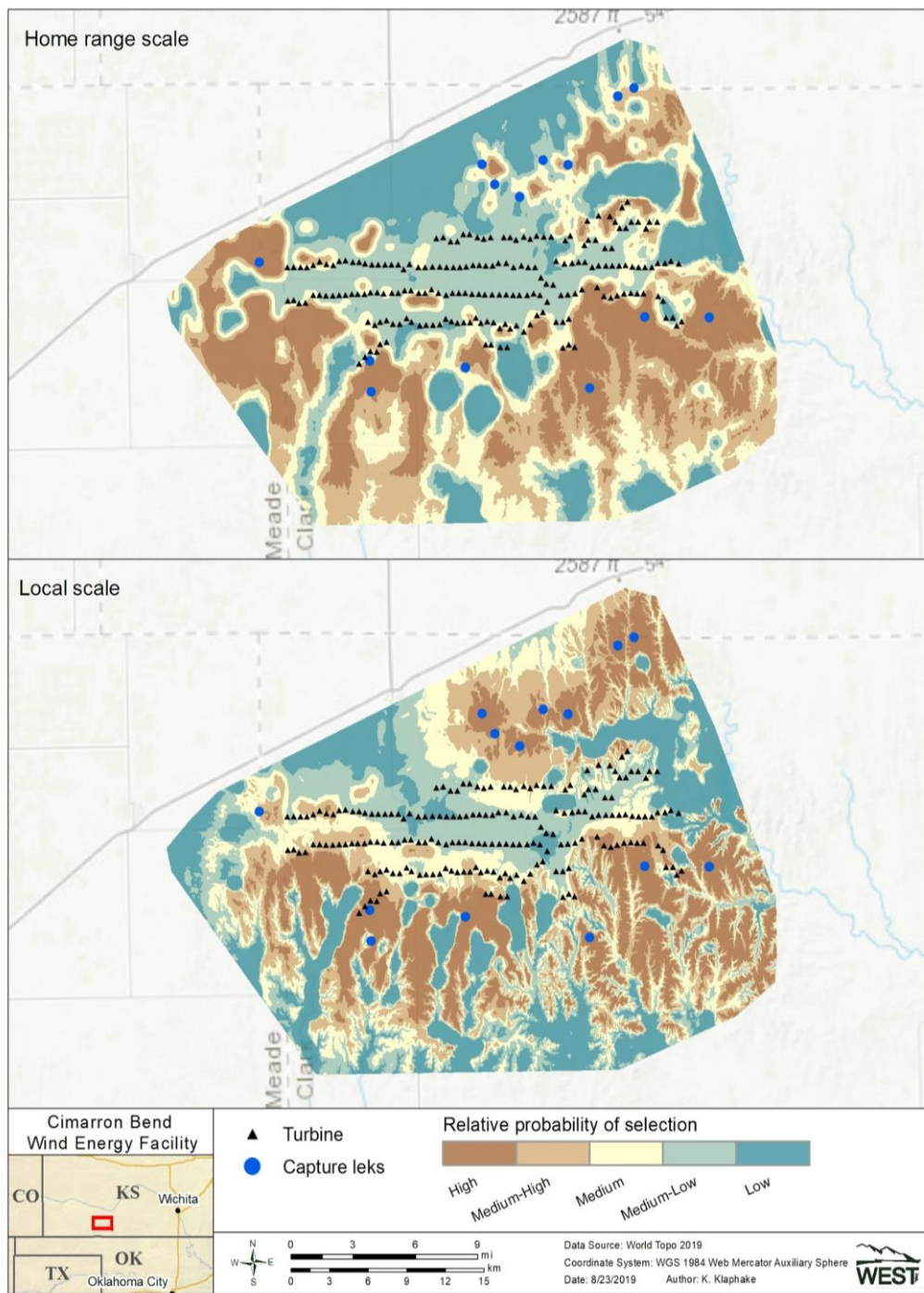
The number of females and males included in the non-breeding analysis was much lower than breeding season analyses because the majority of fatalities occurred during the breeding season. We used 16,970 locations from 3 females and 10 males in the non-breeding analyses. Similar to the other analyses, we found no evidence that LEPC were being displaced by the WEI as LEPC were selecting habitats closer to wind facility disturbance at the home range scale and WEI were not included in the most parsimonious model at the local scale. The k-fold validation results indicated that each RSF model developed had good overall predictability (mean  $r_s$  home range = 0.76 and mean  $r_s$  local = 0.71).

LEPC selected home ranges with relatively more ground cover, more rugged areas, areas with lower tree density, and areas that were closer to wind facility disturbance (Table 5, Figure 9, Appendix A3). The relative probability of home range selection decreased by 62% for every one km increase in distance to wind facility disturbance (Table 5). However, comparison of prediction maps that included and excluded the effect of wind facility disturbance indicated that habitat near turbines was of relatively low selection regardless of the presence of the turbines, suggesting the effect of the facility is likely a product of the larger scale of selection that we evaluated (Appendix B2). In addition, the average predictions were similar under both scenarios relative to distance to turbine, further suggesting that habitat near turbines was of relatively low selection regardless of the presence of the turbines (Figure 10). A similar effect was also observed in the nest site selection analysis.

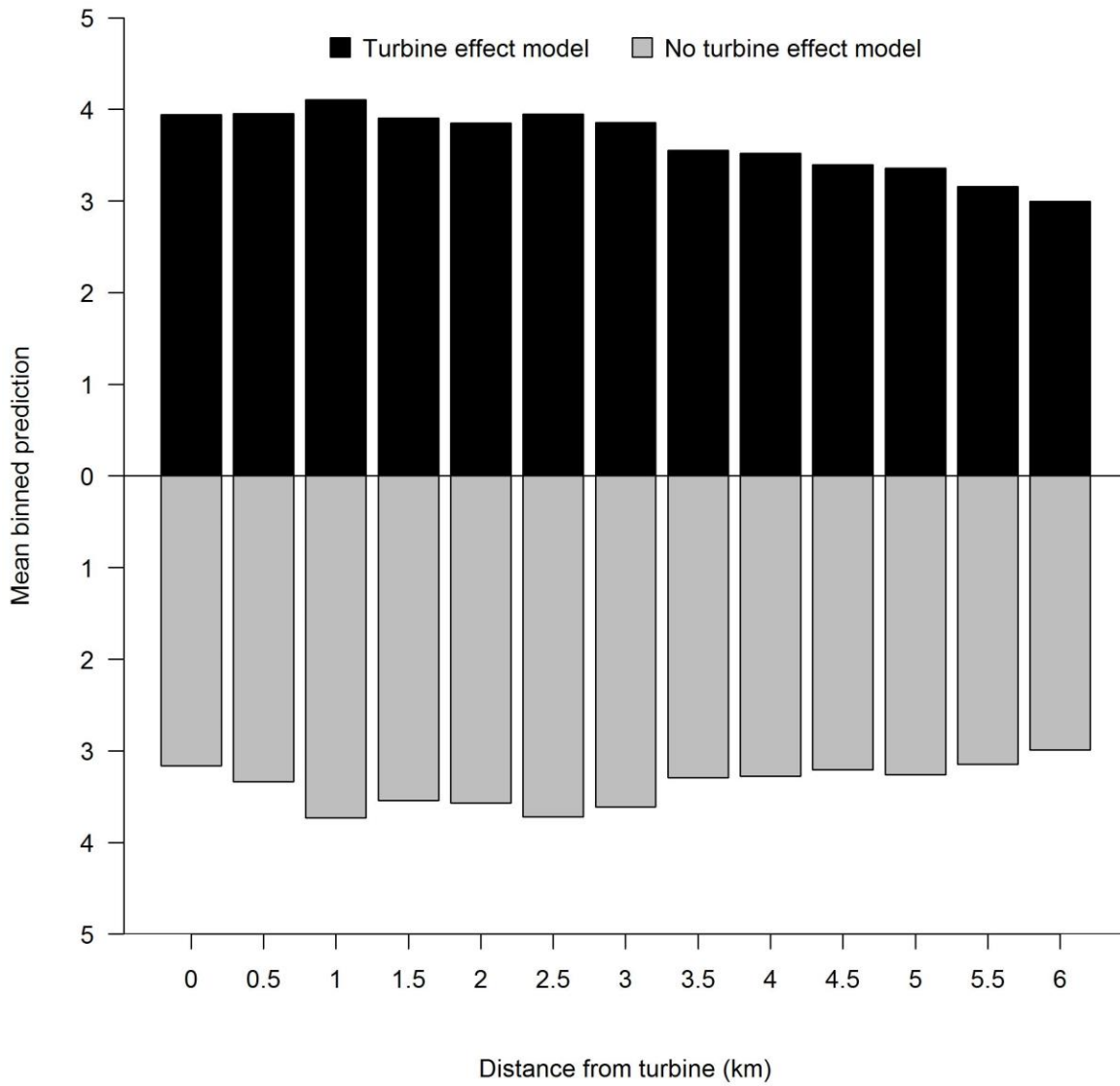
Similar to the home range scale model, LEPC selected areas that were relatively more rugged and areas with lower tree density at the local scale (Table 5, Figure 9). In addition, LEPC selected habitats with more shrub cover and closer to leks, and there was some evidence that they selected more heterogeneous areas (Table 5). No turbine metrics were included in the most parsimonious model. The percentage of wind facility disturbance ( $\beta = 1.81$ ; 90% CI: 1.25, 2.37) was included in a model that was 242.11  $AIC_c$  values from the most parsimonious model (Appendix A3).

**Table 5.** Coefficient estimates and 90% confidence intervals (CI) for covariates used in modeling lesser prairie-chicken non-breeding habitat selection. We obtained estimates by bootstrapping coefficients from models for each individual. An asterisk (\*) denotes covariates that were significant at the 90% confidence level.

Parameter	90 % CI		
	Estimate	Lower	Upper
<b>Home range scale</b>			
Ground_g15_460	0.16*	0.08	0.26
Patch_460	-0.02	-0.05	0.02
TPI_2200	0.09*	0.05	0.12
Tree_d_1045	-248.14*	-554.67	-53.95
Roadpad_dist	-0.96*	-1.33	-0.61
<b>Local scale</b>			
Patch_460	-0.01	-0.03	0.01
Shrub_g15_460	0.03*	0.02	0.04
TPI_1045	0.13*	0.10	0.16
Tree_d_460	-103.66*	-261.41	-11.91
Dist_leks_active	-0.68*	-1.20	-0.21



**Figure 9.** Lesser prairie-chicken relative probability of habitat selection at the home range and local scales during the non-breeding period at the Cimarron Bend Wind Energy Facility, Clark County, Kansas from 2017-2019.



**Figure 10.** The average distribution of binned predictions for lesser prairie-chicken non-breeding habitat selection at the home range scale with and without the effect of wind energy infrastructure within 0.5 km distance bands from wind turbines at the Cimarron Bend Wind Energy Facility, Clark County Kansas from 2017-2019.

## Survival

### Nest Survival

Seventeen assumed first nests were included in the nest survival analysis. Only one female had a nest in two consecutive years and no re-nests were observed. Average nest initiation date was May 12 for all assumed first nesting attempts. Two of the seventeen nests were successful, hatching May 27, 2017, and June 22, 2018. Only two nests were found in 2019 compared to eight and seven in 2017 and 2018, respectively. The nests used in the analysis were spatially distributed along the gradient of distance to wind turbines ranging from 0.54 to 7.26 km (median = 2.48 km). The two nests that were successful were 0.54 and 0.55 km from the nearest turbine.

Grass cover and distance to trees were included in the most parsimonious nest survival model (Table 6). The relative probability of a nest failing increased as grass cover increased and distance to trees increased (Table 6). Nine models were within two AIC<sub>c</sub> units of the most parsimonious model. The most competitive model that included a turbine effect included the percentage of wind facility disturbance along with grass cover and percentage of agriculture (Appendix A4). Similarly, in the competitive model that considered a WEI effect, the relative risk of a nest failing increased as grass cover increased. In addition, risk increased as the percentage of cropland increased and decreased as percentage of wind facility disturbance increased ( $\beta = -3.78$ ; 90% CI: -6.34, -1.21).

### Annual Survival

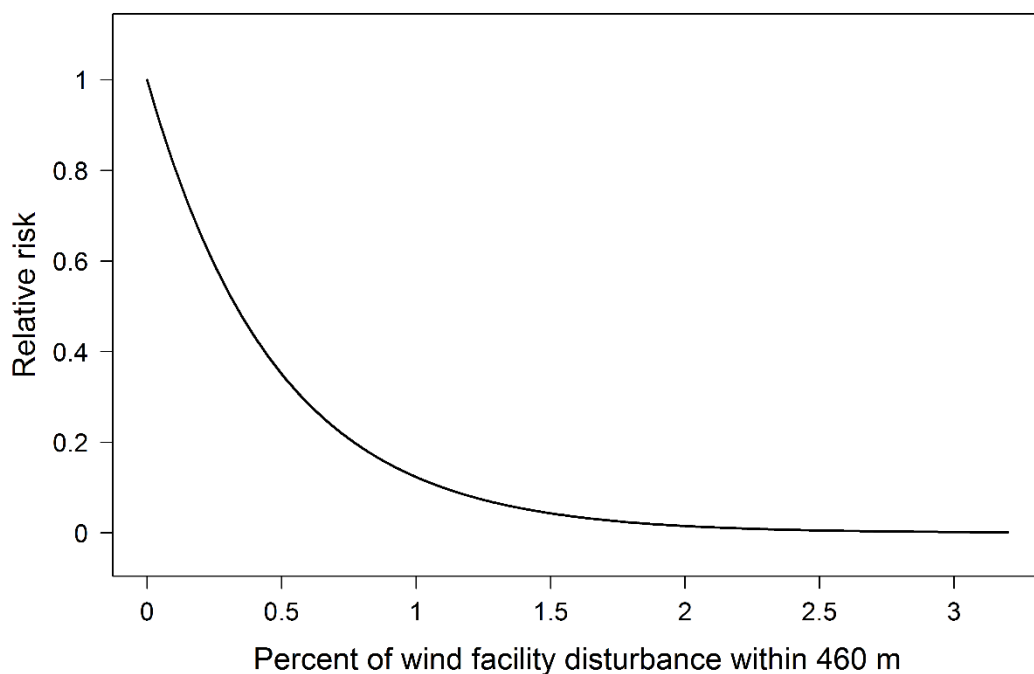
We evaluated the variability in LEPC survival on the landscape using location data from 23 females and 34 males. We observed 44 fatalities and attributed 26 fatalities to avian predators and 10 fatalities to mammalian predators based on the condition of the carcass upon telemetry visits. We included 31 fatalities that had sufficient data beyond two days of capture during the study period (12 females and 19 males) in our annual survival analysis. The remaining fatalities were excluded due to lack of consistent GPS data collection. The majority of the fatalities included in the analysis ( $n = 23$  [10 females and 13 males]) occurred in April and May. Similar to nest survival, fatalities were spatially distributed along a gradient from wind turbines ranging from 0.39 to 6.57 km (median = 2.51 km).

Similar to nest survival, we did not detect any negative effects of WEI on annual survival. Rather, we observed a decrease in risk of mortality for individuals that selected habitats with a higher percentage of wind facility disturbance. The most parsimonious model included shrub cover, tree density and percentage of wind facility disturbance. The relative probability of mortality increased with greater shrub cover, local (50 m) tree density, and less percentage wind facility disturbance (Table 6). We did consider differences in survival for males and females; however, inclusion of the main effect of sex and interactive covariates in the final model were not informative.

Twenty models were within two AIC<sub>c</sub> units of the most parsimonious model. All of the competitive models included a WEI covariate and the model that excluded a WEI covariate was more than four AIC<sub>c</sub> from the most parsimonious model (Appendix A4). More specifically, risk of mortality decreased by 88% for every 1% increase in wind facility disturbance suggesting higher survival in areas with higher density of turbines and access roads (Table 6; Figure 11). Risk also increased in areas of greater tree density at a relatively small scale (50 m; Table 6). The model with the lowest AIC<sub>c</sub> included the count of turbines along with other habitat features, but the effect was similar in that risk was lower in areas with a higher number of turbines (Appendix A4).

**Table 6.** Survival coefficient estimates and 90% confidence intervals (CI) for covariates used in nest and annual survival modeling. An asterisk (\*) denoted covariates that were significant at the 95% confidence level.

Parameter	Estimate	90 % CI	
		Lower	Upper
<b>Nest Survival</b>			
Grass_g5_1045	0.14*	0.06	0.21
Tree_dist	4.60*	1.70	7.60
<b>Annual survival</b>			
Shrub_g45_50	0.09*	0.05	0.13
Tree_d_50	52.32*	20.40	84.24
Durb_prop_460	-2.09*	-4.07	-0.11



**Figure 11.** The relative risk of mortality for lesser prairie-chicken relative to increasing levels of percentage of wind facility disturbance that included the area of access roads and turbine pads within 460 m of a location at the Cimarron Bend Wind Energy Facility, Clark County, Kansas from 2017-2019.

## Movements

### Females

Twenty females were included in the breeding movement analysis but only three were included in the non-breeding analysis. We did not find any evidence that the presence of the CBWEF negatively affected female movements at the site-specific scale during the breeding and non-breeding period as none of the most parsimonious models contained any WEI covariates (Appendix A5). The small sample of females observed during the non-breeding period limited our ability to interpret the site-specific movement patterns relative to turbines; however, we did find evidence that females moved to areas with less bare ground and greater ground cover and more rugged areas during this time period (Table 7). No females had steps that crossed between two turbines during the non-breeding period making the turbine intersection covariate uninformative and likely a result of small sample sizes during this time period.

Sample sizes were much higher during the breeding season ( $n = 22$ ) where we observed females move to areas with greater amounts of intermediate grass cover, areas that were relatively more rugged, and to areas with low tree density (Table 7). The next best model that included a WEI covariate was 3.58  $AIC_c$  values from the most parsimonious model and included the percentage of wind facility disturbance ( $\beta = -0.08$ ; 90% CI: -0.25, 0.10).

We observed 326 steps cross between two turbines out of 7,702 steps. The model that contained the turbine intersection covariate ( $\beta = 0.07$ ; 90% CI: -0.17, 0.47) was 3.69  $AIC_c$  values from the most parsimonious model, further suggesting that at site-specific scale, females were not avoiding areas with a higher percentage of surface disturbance nor, were the presence of turbines influencing female movement patterns given the number of crossings observed (Figure 12).

### Males

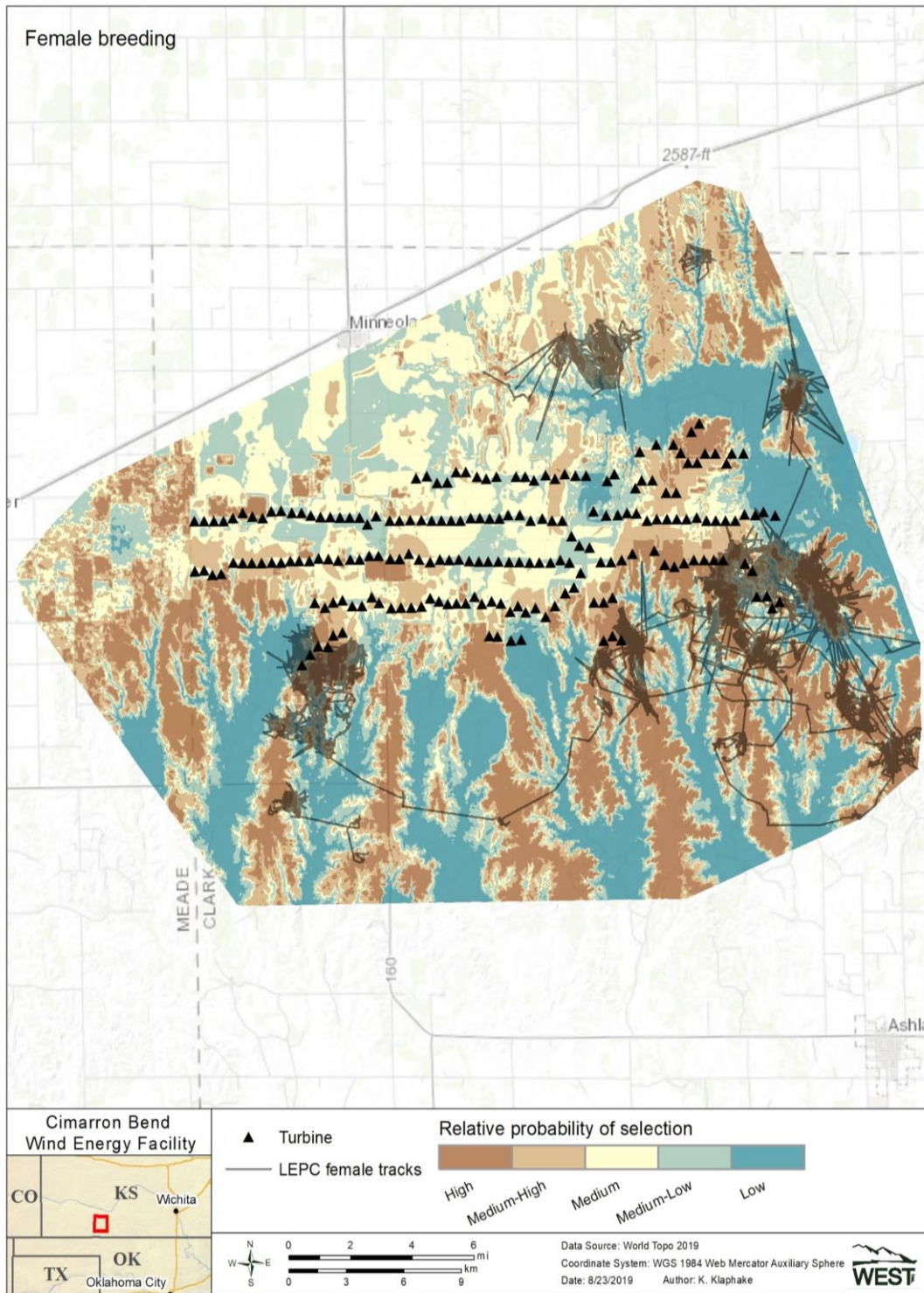
Thirty-three and 10 males were included in the site-specific movement analysis during the breeding and non-breeding periods, respectively. Similar to females, we did not find any evidence that the WEI negatively affected male movements during the breeding and non-breeding periods. We observed similar movement patterns at the site-specific scale during breeding and non-breeding seasons where males moved between two turbines more than available steps given the habitat was relatively closer to leks, rugged, and had greater grass cover (Table 7, Appendix A5).

Out of the 14,314 steps used to model male breeding and non-breeding site-specific movement patterns, 710 steps indicated movement between turbines suggesting these movements did not occur frequently. For movements that crossed between two turbines during the breeding season, the average distance to a wind turbine was 0.53 km (range 0.073 to 2.15 km). During the non-breeding season, the average distance to a wind turbine for steps crossing between two turbines was 0.66 km (range 0.02 to 2.38 km). Visual inspection of male movements between turbines during breeding and non-breeding seasons indicated that these movement primarily occurred on the periphery of the wind energy facility suggesting that large scale movements through the CBWEF were not observed during our study (Appendix C).



**Table 7.** Coefficient estimates and 90% confidence intervals (CI) for variables in the most parsimonious step models describing lesser prairie-chicken site-specific habitat selection and movements in Clark County, Kansas from 2017–2019. An asterisk (\*) denoted covariates that were significant at the 90% confidence level.

Parameter	Estimate	90 % CI	
		Lower	Upper
<b>Female–Breeding Season</b>			
Grass_g35_50	0.008*	0.006	0.010
Patch_50	-0.002	-0.004	0.0002
TPI_2200	0.064*	0.043	0.085
Tree_d_1045	-27.254*	-53.4963	-1.012
<b>Female–Non-Breeding Season</b>			
Bare_prop_1045	-5.988*	-8.036	-3.94
Ground_g5_1045	0.127*	0.120	0.135
TPI_1045	0.084*	0.045	0.122
<b>Male–Breeding Season</b>			
Dist_leks_active	-0.557*	-0.844	-0.270
Grass_g35_460	0.016*	0.011	0.021
TPI_2200	0.098*	0.072	0.123
Turb_intersect	0.419*	0.212	0.627
<b>Male–Non–Breeding Season</b>			
Dist_leks_active	-0.473*	-0.784	-0.162
Grass_g30_50	0.008*	0.006	0.011
TPI_1045	0.102*	0.089	0.115
Turbine_intersect	0.412*	0.210	0.613



**Figure 12.** Female lesser prairie-chicken (LEPC) movement patterns and relative probability of selection at the site-specific scale during the breeding period at the Cimarron Bend Wind Energy Facility, Clark County, Kansas from 2017-2019

## Discussion

Our prediction that LEPC would respond similarly to WEI as other grouse species was supported, and we did not find any evidence that the impacts observed were of greater intensity or occurred at a greater spatial extent than other studied grouse species. In fact, we found that the studied LEPC population was less affected by the presence WEI than has been reported in other studied grouse species. We support this conclusion with four main results:

- 1) We did not observe displacement during multiple seasons and at multiple scales of habitat selection. While this finding was similar during the nesting season in other grouse studies (McNew et al. 2014, Harrison et al. 2017, LeBeau et al. 2017a, Proett et al. 2019), it was contrary to findings during other seasons (see Winder et al. 2014b and LeBeau et al. 2017a).
- 2) We did not detect a negative effect of WEI on LEPC nest survival, which was similar to McNew et al. (2014), Harrison et al. (2017), LeBeau et al. (2017a), and Proett et al. (2019) but we had much smaller sample sizes.
- 3) LEPC survival was higher closer to WEI, which has been documented in two studies of other grouse species (Winder et al. 2014a, LeBeau et al. 2017a).
- 4) While not explicitly quantified in previous studies that evaluated the effects of WEI on grouse populations, we did not find evidence that wind turbines act as a barrier to local scale movements if suitable habitat is available. However, it is important to note that WEI could potentially act as a barrier to larger scale movements.

We hypothesize that the lack of negative LEPC responses to WEI at the CBWEF resulted from the CBWEF being located in previously disturbed habitat. Based on evidence that demonstrates the negative effect of anthropogenic disturbance on LEPC populations (Bartuszevige and Daniels 2016, Plumb et al. 2019), we conclude that LEPC at CBWEF have likely responded to previous habitat loss and fragmentation, and we were unable to detect any additional impacts from WEI at the CBWEF over the short term. This is consistent with our finding that LEPC continued to use suitable habitat near the WEI where suitable habitat exists, suggesting that availability of suitable habitat may have a greater influence on habitat use by this LEPC population than did the presence of WEI. However, this study lacks pre-construction data, which precluded us from quantifying changes in LEPC habitat use before and after construction. Thus, in the absence of pre-construction data, a longer-term dataset will be necessary to understand the effects of CBWEF on this LEPC population as the full extent of impacts may not be fully realized over the relative short duration of our study (i.e., lag effects). Further discussion on the results of the three metrics we evaluated are presented below.

Following breeding at a lek, female LEPC selected their nesting home range and habitat within their home range close to leks and in areas of relatively low shrub cover (at least shrub cover less than 35%), irrespective of WEI. Females then selected nest site locations in areas with greater grass and ground cover, in higher elevation, and farther from wind facility disturbance. While the nest site selection model indicated displacement relative to WEI, comparison of predictive surfaces indicates there is very little difference in habitat use on the landscape predicted by models with and without an effect of WEI covariates. This suggests that the habitat within the CBWEF does not provide a substantial amount of suitable nesting habitat regardless of the presence of WEI. A similar pattern is emerging in greater prairie-chicken and Columbian sharp-tailed grouse populations in that land management practices and site specific vegetation structures are influencing where a female selects a nest rather than presence of wind energy infrastructure (McNew et al. 2014, Harrison et al. 2017, Proett et al. 2019).

We did not observe displacement of males or females by WEI during the breeding or non-breeding seasons. We observed LEPC selecting habitats closer to wind facility disturbance during the non-breeding season at the home range scale. This analysis mostly comprised males and we attributed this selection

behavior to the larger scale of selection we evaluated and male fidelity to leks. The CBWEF was centered in our study area surrounded by lek locations and due to males' inherent site fidelity to leks (see Haukos and Zavaleta 2016), the extent of used and available habitat surrounded the CBWEF thus, selection for habitats closer to wind facility disturbance was likely due to the juxtaposition of the facility on the landscape relative to lek locations and not the actual WEI.

Although we did not detect any displacement effects, the habitats LEPC selected could potentially act as an ecological trap, appearing to be of high quality, while in reality posing fitness consequences such as reduced survival (Aldridge and Boyce 2007, Kirol et al. 2015). However, we did not find any evidence that the habitats LEPC selected resulted in reduced adult annual survival and nest survival. The variability in survival on the landscape was influenced more by habitat features (e.g. grass, shrub, and tree cover) than by the presence of WEI, which is similar to other studied grouse populations (McNew et al. 2014, Winder et al. 2014a, LeBeau et al. 2017a). While the sample size for our nest survival analysis was small, our models suggested that nest survival was higher in habitats having a greater percentage of wind facility disturbance, as the two successful nests were located less than 0.6 km from a wind turbine. A larger sample size of nests is necessary to completely assess the relationship of increased nest survival in habitats with a greater percentage of wind facility disturbance or the potential negative effects on nest survival associated with the facility.

Our results did not indicate that the presence of WEI reduced annual LEPC survival. Similar to other studies that have evaluated grouse survival relative to turbines, we observed a lower risk of mortality in habitats with a greater proportion of surface disturbance (Winder et al. 2014a, LeBeau et al. 2017a). Unlike our nest survival data, we had sufficient sample sizes and benefited from frequent, detailed location data to identify landscape characteristics that influenced the variability in survival on the landscape. In particular, risk of mortality was highest in areas of greater tree density at the local (50 m) scale, which may represent potential perch locations for avian predators. The reason for this increased survival in close proximity to WEI has been related to avoidance of WEI by predators, but evidence for this is weak (Smith et al. 2017), highlighting the need to better understand predator-prey dynamics that are influenced by WEI.

Another goal of the study was to determine if the presence of wind turbines acted as a barrier to LEPC movements between breeding and non-breeding habitats. Our results did not show that LEPC connectivity at the site-specific scale was negatively affected by the presence of WEI. We observed females and males crossing between wind turbines on the periphery of the WEI during the breeding season but only observed males crossing between wind turbines during the non-breeding season at the site-specific scale. While we did not observe females crossing between wind turbines during non-breeding, this could possibly be an artifact of sample size during that time period. On the other hand, we did not observe any large-scale (north and south) movements through the CBWEF but did observe maximum daily movements ranging from 2.3 to 3.1 km, which are movement distances that could connect habitats north and south of the CBWEF. The absence of large-scale movements through the facility could be related to lower quality habitat within the CBWEF as determined in our habitat selection analyses, or strong site fidelity by individuals to their respective leks (as summarized in Haukos and Zavaleta 2016) rather than the facility acting as a barrier to large scale movements.

Females moved to areas with relatively higher amounts of grass cover and with greater landscape heterogeneity, potentially providing concealment cover during the breeding period. Sample sizes for females during the non-breeding period were low, but in both seasons females centered their movement around large scale features such as areas with fewer trees and more rugged topography, which has been shown in other studies (Lautenbach et al. 2017). However, we caution the interpretation of female movements during the non-breeding season due to small sample sizes.

Males moved to habitats in relatively close proximity to leks during both the breeding and non-breeding seasons, providing further evidence that individual LEPC habitat selection and movements were tied to

lek locations (Hagen and Giesen 2005). As with females, males selected areas that provided generally more ridge-like topography compared to available areas, characteristic of the plateaus above the small drainages that may provide necessary foraging and concealment habitats. Movement models for males indicated that they were crossing between wind turbines more often than what was available to them, which suggests that wind turbines did not act as a barrier to site-specific movements ( $\beta = 0.412$ ; 90% CI: 0.210, 0.613). It appears that the habitat in areas where individuals were crossing had a greater influence on movements than the presence of WEI. This assumption aligns with our habitat selection findings at the larger scales, where LEPC selected previously undisturbed habitats regardless of the presence of WEI. This was most evident in the southeastern corner of the project where a series of five turbines intersected previously undisturbed habitats and movements between these habitats were observed frequently (Appendix C).

The interpretation of these results would have been strengthened if we had data collected over a longer period (i.e., >3 years) to capture multiple generations of LEPC and increase our sample sizes to account for potential lag effects of WEI on LEPC populations. LEPC, similar to other grouse species, exhibit high site fidelity to important habitats such as breeding and non-breeding (Hakous and Zavaleta 2016). It may take multiple generations to realize the impact of WEI as new individuals are recruited to the population. Pre-construction data would have been especially beneficial in the survival analyses due to the temporal variability in those fitness metrics (as summarized in Grisham et al. 2016). Overall, apparent nest success in our study was low (12%) compared to other rates observed elsewhere in the region during the study period (23% in 2019; personal communications Dan Sullins), which could reflect small sample sizes, the lack of quality nesting habitat throughout our study area, or the presences of WEI. Nonetheless, the three years of data collection directly following the development of the CBWEF provide insight into the short term effects of WEI on the LEPC monitored population. In support, results of this study suggest similar trends to those reported by other studies that evaluated grouse and wind energy development. However, many of these studies were also evaluated over a relatively short time period and the effects of WEI on grouse population metrics observed to date may be short term effects, with the long term effects remaining unknown (LeBeau et al. 2014, Smith et al. 2017, Harrison et al. 2017, Proett et al. 2019). In our study, the Starbuck fire introduced an unexpected variable to the study that likely changed the local area population dynamics, and should be further explored. Nonetheless, we were able to sample individual LEPC along a gradient from WEI over a 3-year period despite the residual effects of the Starbuck fire. Additional years of monitoring will increase our sample sizes, address temporal variability, and allow for assessment of potential time lags that may exist in this population relative to development of the WEI.

This study would have been strengthened by using a before-after study design to compare LEPC behaviors prior to the CBWEF with responses after the CBWEF was constructed and operational. For instance, female greater prairie-chicken space use was negatively affected by a wind energy facility in Kansas during the breeding season (Winder et al. 2014b); however, that study benefited from a before and after impact study design and the lack of pre-development data collected at CBWEF may have limited our ability to detect minor displacement behaviors or survival consequences. A before-after design would have also allowed us to evaluate if the facility acted as a barrier to large scale movements (e.g., connecting habitats to the south and north) or if habitat quality limitations precluded this type of movement prior to the facility's development because it is unknown if large scale LEPC movements occurred prior to the development of CBWEF.

The results reported here are similar to other studies that evaluated the effects of wind energy development on grouse species. For example, we did not detect any displacement effects during the nesting period (McNew et al. 2014, Harrison et al. 2017, LeBeau et al. 2017a, Proett et al. 2019) or negative effects on nest survival, although we had relatively low sample sizes compared to the other studies (McNew et al. 2014, Harrison et al. 2017, LeBeau et al. 2017a, Proett et al. 2019). Winder et al. (2014b) and LeBeau et al. (2017a) detected displacement effects during the breeding seasons, which may be related to the species studied (sage-grouse and greater prairie-chickens), study design (BACI), and/or study duration (greater than three years post-development). However, if displacement occurred at

our study site from pre- to post-development it would have been minor, as we observed LEPC using habitats relatively close to wind turbines during three years post development. Additional years of monitoring would better elucidate these results as spatial extent of displacement might not yet be fully realized (see LeBeau et al. 2014 and LeBeau et al. 2017a).

Reduced annual survival relative to WEI has not been detected in any of the studies that have evaluated the effects of wind turbines on grouse survival (Winder et al. 2014a, LeBeau et al. 2017a, Smith et al. 2017). In fact, an interesting trend is emerging from this study and others, in that survival is predicted to be higher for individuals that use habitats near turbines (e.g., Winder et al. 2014a, LeBeau et al. 2017a). We can only speculate as to why we are seeing higher survival near turbines, but one potential hypothesis is that avian predators, which are the main source of adult LEPC predation, avoid turbines. However, there is currently little evidence to suggest that LEPC predators are avoiding WEI (Behney et al. 2012, Bartuszevige and Daniels 2016, LeBeau et al. 2017a, Smith et al. 2017). A well-designed study to evaluate these potential mechanisms is necessary to thoroughly understand this relationship.

Lastly, our results provide important information for future studies to better characterize the impacts of wind energy development on LEPC movements and connectivity in disturbed landscapes. Despite some of the challenges presented with sample sizes (particularly during the nesting and non-breeding periods), results from this study provide the first quantitative evaluation of the effects of wind energy development on LEPC populations, which is necessary to begin understanding how future wind energy developments sited in LEPC range can affect LEPC populations.

## Conclusion

During our 3-year study, LEPC selected habitats regardless of the presence of WEI during time periods that are important for determining population viability. However, while our study results show that habitat selection did not result in nest and survival consequences, such impacts may not have been observed due to the relatively short study period and the influence of the Starbuck fire on the population. The WEI was placed in already altered habitats and the impacts of this alteration has likely already been realized on the parameters we analyzed. Thus, the current wind energy development practice of siting wind energy facilities in altered habitats and outside of intact habitats may be a useful impact minimization tool. It is clear that LEPC are susceptible to landscape change due to anthropogenic influences and their populations are at historic lows. As the demand for clean renewable energy increases, managers will need tools to avoid and minimize potential impacts to LEPC from future wind energy developments (Bartuszevige and Daniels et al. 2016, Garton et al. 2016). The purpose of this study was to create a body of evidence describing multiple population metrics that ultimately have the potential to influence population viability relative to WEI. Future analyses should consider multiple metrics when developing a single population viability metric that would provide an all-encompassing tool for managers. More robust studies in various habitat types, including intact grassland, are critical to understanding how LEPC respond to wind energy development and need to be a priority in the future, especially with the increase in demand for renewable energy. In the absence of these data, we can only make claims about correlation, but we need to understand causation to ensure LEPC populations can persist into the near future.

## Management Implications

We did not observe any disturbance thresholds in our study to support any siting measures, but as described, such thresholds may have not yet been fully realized. We can, however, draw correlations from LEPC behaviors we observed to the WEI, characteristics that can be used to inform future siting of wind projects in LEPC habitat, in particular within the mixed grass region of LEPC range. This facility was relatively large in the number of turbines (200) and area (216 km<sup>2</sup>) but was placed in previously altered habitat, which we hypothesize contributed to the lack of negative impacts observed during this study. We

also observed males and females successfully navigate through turbines at a site-specific scale and in particular, males on average were 0.6 km from the nearest turbine. The results suggest that impacts to local LEPC populations from WEI might be minimized by placing infrastructure in previously disturbed landscapes. In areas where LEPC habitat is present, our results suggested that turbine spacing of 1.2 km did not act as a barrier to movement between wind turbines.



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## Appendix A: Model Selection Tables

**Appendix A1.** Models explaining female lesser prairie-chickens pre-nesting and nest site habitat selection (resource selection functions) at the Cimarron Bend Wind Energy Facility, Clark County, Kansas from 2017–2019. The most parsimonious models and those including wind energy infrastructure covariates are listed and ranked by  $\Delta\text{AICc}$ . Model fit statistics include number of parameters (K), Akaike's Information Criterion (AICc), change in AICc ( $\Delta\text{AICc}$ ), and Akaike weights ( $w_i$ ).

Model	K	AICc	$\Delta\text{AICc}$	$w_i$
<b>Home range scale pre-nesting selection</b>				
Shrub_g35_460 + Dem + Dist_leks_active + Majroad_dist + Tline_dist	5	19917.42	0.00	1.00
Grass_g30_460 + Shrub_g35_460 + Dem + Dist_leks_active + Turb_dist	5	20045.30	127.88	0.00
Grass_g30_460 + Shrub_g35_460 + Dem + Dist_leks_active + Roadpad_dist	5	20049.35	131.94	0.00
Shrub_g35_460 + Dem + Dist_leks_active + Tline_dist + Turb_count_1045	5	20218.48	301.06	0.00
Shrub_g35_460 + Dem + Dist_leks_active + Tline_dist + Durb_prop_1045	5	20279.01	361.59	0.00
<b>Local scale pre-nesting selection</b>				
Grass_cont + Ground_g95_460 + TPI_1045 + Tree_d_2200 + Dist_leks_active	5	13407.84	0.00	1.00
Ground_g95_460 + Patch_460 + TPI_1045 + Tree_d_2200 + Roadpad_dist	5	13496.71	88.87	0.00
Ground_g95_460 + Patch_460 + TPI_1045 + Tree_d_2200 + Turb_dist	5	13500.7	92.86	0.00
Ag_prop_460 + Ground_g95_460 + TPI_1045 + Tline_dist + Durb_prop_1045	5	13509.07	101.23	0.00
Ag_prop_460 + Ground_g95_460 + TPI_1045 + Tree_d_2200 + Turb_count_2200	5	13560.36	152.52	0.00
<b>Site-Specific Scale Nest Site Selection</b>				
Grass_g30_50 + Ground_g10_50 + Dem + Roadpad_dist	4	105.96	0.00	0.10
Grass_g30_50 + Ground_g10_50 + Dem + Turb_dist	4	106.06	0.11	0.10
Grass_g30_50 + Ground_g10_50 + Patch_cell + Dem + Roadpad_dist	5	106.20	0.24	0.09
Grass_g30_50 + Ground_g10_50 + Patch_cell + Dem + Turb_dist	5	106.42	0.46	0.08
Ground_g10_50 + Patch_cell + Dem + Roadpad_dist	4	106.47	0.51	0.08
Ground_g10_50 + Patch_cell + Dem + Turb_dist	4	106.57	0.61	0.08
Bare_prop_1045 + Ground_g10_50 + Patch_cell + Dem + Roadpad_dist	5	107.19	1.24	0.06

Lesser Prairie-Chicken Response to Wind Energy

<b>Model</b>	<b>K</b>	<b>AICc</b>	<b>ΔAICc</b>	<b>Wi</b>
Bare_prop_1045 + Grass_g30_50 + Ground_g10_50 + Dem + Roadpad_dist	5	107.22	1.27	0.05
Grass_g30_50 + Ground_g10_50 + Dem + Majroad_dist + Roadpad_dist	5	107.31	1.35	0.05
Bare_prop_1045 + Ground_g10_50 + Patch_cell + Dem + Turb_dist	5	107.42	1.46	0.05
Bare_prop_1045 + Grass_g30_50 + Ground_g10_50 + Dem + Turb_dist	5	107.42	1.47	0.05
Grass_g30_50 + Ground_g10_50 + Dem + Majroad_dist + Turb_dist	5	107.70	1.75	0.04
Grass_g30_50 + Ground_g10_50 + Water_prop_2200 + Dem + Roadpad_dist	5	107.72	1.77	0.04
Grass_g30_50 + Ground_g10_50 + Tree_d_460 + Dem + Roadpad_dist	5	107.85	1.89	0.04
Grass_g30_50 + Ground_g10_50 + Water_prop_2200 + Dem + Turb_dist	5	107.92	1.96	0.04
Ground_g10_50 + Patch_cell + TPI_2200 + Water_prop_2200	4	108.81	2.85	0.02
Ground_g10_50 + Patch_cell + TPI_2200 + Water_prop_2200 + Turb_count_1045	5	109.87	3.92	0.01
Ground_g10_50 + Patch_cell + TPI_2200 + Water_prop_2200 + Durb_prop_2200	5	110.24	4.28	0.01

**Appendix A2.** Models explaining male and female lesser prairie-chicken breeding habitat selection (resource selection functions) at the Cimarron Bend Wind Energy Facility, Clark County, Kansas from 2017–2019. The most parsimonious models and those including wind energy infrastructure covariate are listed and ranked by  $\Delta AICc$ . Model fit statistics include number of parameters (K), Akaike’s Information Criterion (AICc), change in AICc ( $\Delta AICc$ ), and Akaike weights (wi).

Model	K	AICc	$\Delta AICc$	Wi
<b>Home range scale pre-nesting selection</b>				
Ground_g20_460 + Patch_460 + TPI_2200 + Dem+ Dist_leks_active	5	149570.9 4	0.00	1.00
Ground_g20_460 + Patch_460 + TPI_2200 + Dist_leks_active + Turb_dist	5	151578.6 3	2007.68	0.00
Ground_g20_460 + Patch_460 + TPI_2200 + Dist_leks_active + Roadpad_dist	5	151698.5 1	2127.56	0.00
Ground_g20_460 + Patch_460 + TPI_2200 + Dist_leks_active + Turb_count_1045	5	152516.9 7	2946.03	0.00
Ground_g20_460 + Patch_460 + TPI_2200 + Dist_leks_active + Durb_prop_2200	5	152615.6 6	3044.72	0.00
<b>Local scale pre-nesting selection</b>				
Grass_cont + Patch_460 + Shrub_g40_460 + TPI_1045 + Dist_leks_active	5	125385.2 5	0.00	0.70
Grass_cont + Patch_460 + Shrub_g40_460 + TPI_1045 + Tree_d_460	5	125386.9 3	1.68	0.30
Grass_cont + Patch_460 + Shrub_g40_460 + TPI_1045 + Durb_prop_2200	5	125726.2 0	340.95	0.00
Grass_cont + Patch_460 + Shrub_g40_460 + TPI_1045 + Turb_dist	5	125756.7 5	371.50	0.00
Grass_cont + Patch_460 + Shrub_g40_460 + TPI_1045 + Roadpad_dist	5	125758.6 6	373.41	0.00
Grass_cont_ssf + Patch_460 + Shrub_g40_460 + TPI_1045 + Turb_count_1045	5	125767.6 1	382.36	0.00

source: Akaike 1974

**Appendix A3.** Models explaining male and female lesser prairie-chicken non-breeding habitat selection (resource selection functions) at the Cimarron Bend Wind Energy Facility, Clark County, Kansas from 2017–2019. The most parsimonious models and those including wind energy infrastructure covariates are listed and ranked by  $\Delta AIC_c$ . Model fit statistics include number of parameters (K), Akaike's Information Criterion ( $AIC_c$ ), change in  $AIC_c$  ( $\Delta AIC_c$ ), and Akaike weights ( $w_i$ ).

Model	K	$AIC_c$	$\Delta AIC_c$	$w_i$
<b>Home range scale pre-nesting selection</b>				
Ground_g15_460 + Patch_460 + TPI_2200 + Tree_d_1045 + Roadpad_dist	5	110401.25	0.00	1.00
Ground_g15_460 + Patch_460 + TPI_2200 + Tree_d_1045 + Turb_dist	5	110573.78	172.53	0.00
Ground_g15_460 + Patch_460 + TPI_2200 + Tree_d_1045 + Tline_dist	5	112478.03	2076.79	0.00
Grass_g30_460 + TPI_2200 + Tree_d_1045 + Tline_dist + Turb_count_2200	5	115800.20	5398.96	0.00
Grass_g30_460 + TPI_2200 + Tree_d_1045 + Dist_leks_active + Durb_prop_2200	5	115825.30	5424.05	0.00
<b>Local scale pre-nesting selection</b>				
Patch_460 + Shrub_g15_460 + TPI_1045 + Tree_d_460 + Dist_leks_active	5	133611.97	0.00	0.00
Patch_460 + Shrub_g15_460 + TPI_1045 + Dist_leks_active + Durb_prop_1045	5	133854.09	242.11	0.00
Patch_460 + Shrub_g15_460 + TPI_1045 + Dist_leks_active + Turb_count_1045	5	134038.06	426.09	0.00
Patch_460 + Shrub_g15_460 + TPI_1045 + Dist_leks_active + Roadpad_dist	5	134227.63	615.66	0.00
Patch_460 + Shrub_g15_460 + TPI_1045 + Dist_leks_active + Turb_dist	5	134234.44	622.47	0.00

source: Akaike 1974

**Appendix A4.** Models explaining nest and lesser prairie-chicken annual survival at the Cimarron Bend Wind Energy Facility, Clark County, Kansas from 2017–2019. The most parsimonious models and those including wind energy infrastructure covariates are listed and ranked by  $\Delta\text{AICc}$ . Model fit statistics include number of parameters (K), Akaike's Information Criterion (AICc), change in AICc ( $\Delta\text{AICc}$ ), and Akaike weights ( $w_i$ ).

Model	K	AICc	$\Delta\text{AICc}$	$W_i$
<b>Nest Survival</b>				
Grass_g5_1045 + Tree_dist	2	48.76	0.07	0.18
Ground_g5_1045 + Tree_dist	2	49.52	0.84	0.12
Ground_g5_1045 + Tree_dist + Water_prop_2200	3	49.83	1.15	0.10
Ag_prop_1045 + Grass_g5_1045 + Tree_dist	3	50.15	1.46	0.09
Ag_prop_1045 + Grass_g5_1045 + Durb_prop_1045	3	50.26	1.58	0.08
Ground_g5_1045 + Tree_dist + Dist_leks_active	3	50.29	1.61	0.08
Grass_g5_1045 + Tree_dist + Water_prop_2200	3	50.30	1.62	0.08
Grass_g5_1045 + Tree_dist + Dist_leks_active	3	50.31	1.63	0.08
Grass_g5_1045 + Tree_dist + Urban_dist	3	50.57	1.89	0.07
Grass_g5_1045 + Tree_dist + Turb_count_1045	3	51.05	2.37	0.06
Grass_g5_1045 + Tree_dist + Roadpad_dist	3	51.56	2.87	0.04
<b>Annual Survival</b>				
Bare_prop_2200 + Shrub_g45_50 + TPI_460 + Tree_d_50 + Turb_count_1045	5	150.75	0.00	0.08
Bare_prop_2200 + Dem + Shrub_g45_50 + Tree_d_50 + Durb_prop_460	5	151.03	0.29	0.07
Shrub_g45_50 + TPI_460 + Tree_d_50 + Durb_prop_460	4	151.06	0.32	0.07
Bare_prop_2200 + Patch_cell + Shrub_g45_50 + Tree_d_50 + Durb_prop_460	5	151.10	0.35	0.07
Dem + Shrub_g45_50 + Tree_d_50 + Durb_prop_460	4	151.30	0.56	0.06
Bare_prop_2200 + Majroad_dist + Shrub_g45_50 + Tree_d_50 + Durb_prop_460	5	151.31	0.57	0.06
Shrub_g45_50 + Tree_d_50 + Durb_prop_460	3	151.40	0.66	0.06
Dem + Shrub_g45_50 + TPI_460 + Tree_d_50 + Turb_count_1045	5	151.63	0.89	0.05
Bare_prop_2200 + Shrub_g45_50 + Tline_dist + Tree_d_50 + Durb_prop_460	5	151.64	0.89	0.05
Bare_prop_2200 + Patch_cell + Shrub_g45_50 + Tree_d_50 + Turb_count_1045	5	152.18	1.43	0.04
Grass_g5_cell + Shrub_g45_50 + TPI_460 + Tree_d_50 + Durb_prop_460	5	152.22	1.48	0.04
Ground_g25_cell + Shrub_g45_50 + TPI_460 + Tree_d_50 + Turb_count_1045	5	152.25	1.50	0.04



Lesser Prairie-Chicken Response to Wind Energy

<b>Model</b>	<b>K</b>	<b>AICc</b>	<b>ΔAICc</b>	<b>Wi</b>
Ground_g25_cell + Patch_cell + Shrub_g45_50 + Tree_d_50 + Durb_prop_460	5	152.27	1.52	0.04
Shrub_g45_50 + TPI_460 + Tree_d_50 + Turb_count_1045	4	152.36	1.61	0.04
Ground_g25_cell + Shrub_g45_50 + Tree_d_50 + Turb_count_1045	4	152.45	1.70	0.04
Shrub_g45_50 + TPI_460 + Tree_d_50 + Urban_dist + Durb_prop_460	5	152.60	1.85	0.03
Grass_g5_cell + Shrub_g45_50 + Tree_d_50 + Durb_prop_460	4	152.63	1.89	0.03
Bare_prop_2200 + Grass_g5_cell + Shrub_g45_50 + Tree_d_50 + Turb_count_1045	5	152.69	1.94	0.03
Shrub_g45_50 + Tree_d_50 + Urban_dist + Durb_prop_460	4	152.70	1.95	0.03
Dist_leks_active + Shrub_g45_50 + TPI_460 + Tree_d_50 + Durb_prop_460	5	152.73	1.98	0.03
Ag_dist + Dem + Shrub_g45_50 + TPI_460 + Tree_d_50	5	154.86	4.11	0.01
Bare_prop_2200 + Shrub_g45_50 + TPI_460 + Tree_d_50 + Roadpad_dist	5	156.45	5.70	0.00

**Appendix A5.** Models explaining lesser prairie-chicken site-specific habitat selection (step-selection functions) at the Cimarron Bend Wind Energy Facility, Clark County, Kansas from 2017–2019. The most parsimonious models and those including wind energy infrastructure covariates are listed and ranked by  $\Delta AICc$ . Model fit statistics include number of parameters (K), Akaike's Information Criterion (AICc), change in AICc ( $\Delta AICc$ ), and Akaike weights ( $w_i$ ).

Model	K	AICc	$\Delta AICc$	$W_i$
<b>Female breeding</b>				
Grass_g_35_50 + Patch_50 + TPI_2200 + Tree_d_1045	4	20087.48	0.00	0.69
Grass_g35_50 + TPI_2200 + Tree_d_1045 + Turb_count_1045	4	20091.06	3.58	0.11
Grass_g35_50 + TPI_2200 + Tree_d_1045 + Turb_intersect	4	20091.17	3.69	0.11
Grass_g35_50 + TPI_2200 + Tree_d_1045 + Turb_dist	4	20093.65	6.17	0.03
Grass_g35_50 + TPI_2200 + Tree_d_1045 + Roadpad_dist	4	20094.26	6.78	0.02
Grass_g35_50 + TPI_2200 + Tree_d_1045 + Durb_prop_1045	4	20094.60	7.12	0.02
Grass_g35_50 + TPI_2200 + Tree_d_1045 + Tline_dist	4	20095.15	7.67	0.01
<b>Female non-breeding</b>				
Bare_prop_1045 + Ground_g5_1045 + TPI_1045 + Water_prop_50	4	8068.07	0.00	0.32
Bare_prop_1045 + Ground_g5_1045 + TPI_1045	3	8069.59	1.52	0.15
Bare_prop_1045 + Ground_g5_1045 + TPI_1045 + Durb_prop_2200	4	8070.02	1.95	0.12
Bare_prop_1045 + Shrub_g5_1045 + TPI_1045 + Water_prop_50	4	8070.05	1.98	0.11
Bare_prop_1045 + Ground_g5_1045 + TPI_1045 + Tline_dist	4	8071.26	3.19	0.06
Bare_prop_1045 + Ground_g5_1045 + TPI_1045 + Roadpad_dist	4	8071.48	3.41	0.06
Bare_prop_1045 + Ground_g5_1045 + TPI_1045 + Turb_dist	4	8071.50	3.43	0.06
Bare_prop_1045 + Ground_g5_1045 + TPI_1045 + Turb_intersect	4	8071.55	3.48	0.06
Bare_prop_1045 + Ground_g5_1045 + TPI_1045 + Turb_count_1045	4	8071.56	3.49	0.06
<b>Male breeding</b>				
Dist_leks_active + Grass_g35_460 + TPI_2200 + Turb_intersect	4	31530.96	0.00	1.00
Dist_leks_active + Grass_g35_460 + TPI_2200 + Turb_count_2200	4	31560.38	29.42	0.00
Dist_leks_active + Grass_g35_460 + TPI_2200 + Turb_dist	4	31560.87	29.91	0.00

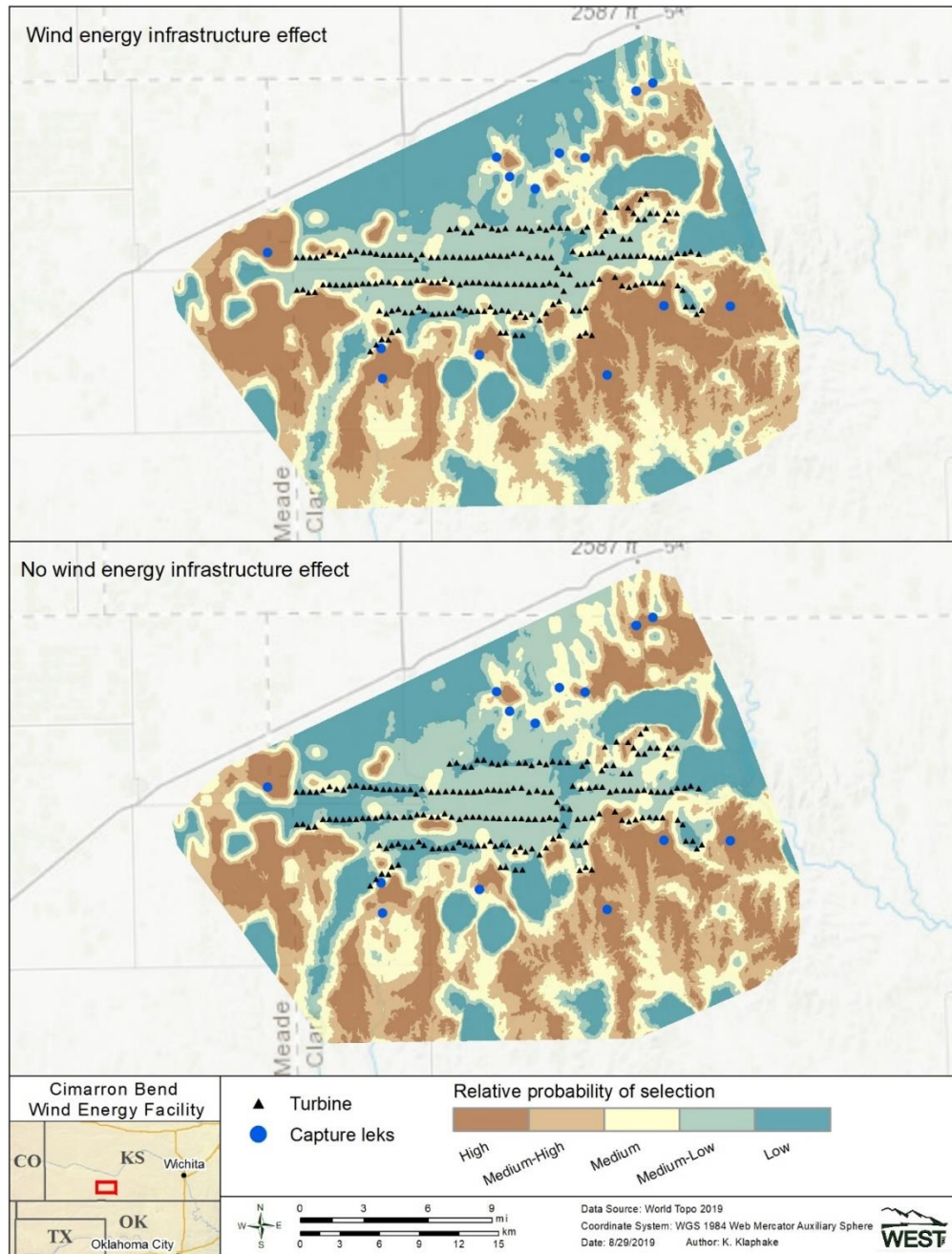
Lesser Prairie-Chicken Response to Wind Energy

<b>Model</b>	<b>K</b>	<b>AICc</b>	<b>ΔAICc</b>	<b>Wi</b>
Dist_leks_active + Grass_g35_460 + TPI_2200 + Durb_prop_1045	4	31560.94	29.98	0.00
Dist_leks_active + Grass_g35_460 + TPI_2200 + Roadpad_dist	4	31560.99	30.03	0.00
Grass_g35_460 + TPI_2200 + Tline_dist + Turb_intersect	4	31579.74	48.78	0.00
<b>Male non-breeding</b>				
Dist_leks_active + Grass_g30_50 + TPI_1045 + Turb_intersect	4	21265.94	0.00	0.52
Grass_g30_50 + TPI_1045 + Water_dist + Turb_intersect	4	21266.10	0.16	0.48
Grass_g30_50 + TPI_1045 + Water_dist + Turb_dist	4	21275.84	9.90	0.00
Grass_g30_50 + TPI_1045 + Water_dist + Roadpad_dist	4	21277.55	11.61	0.00
Grass_g30_50 + TPI_1045 + Tline_dist + Turb_intersect	4	21289.75	23.81	0.00
Grass_g30_50 + TPI_1045 + Turb_count_1045 + Turb_intersect	4	21290.26	24.32	0.00
Grass_g30_50 + TPI_1045 + Durb_prop_1045 + Turb_intersect	4	21290.72	24.78	0.00

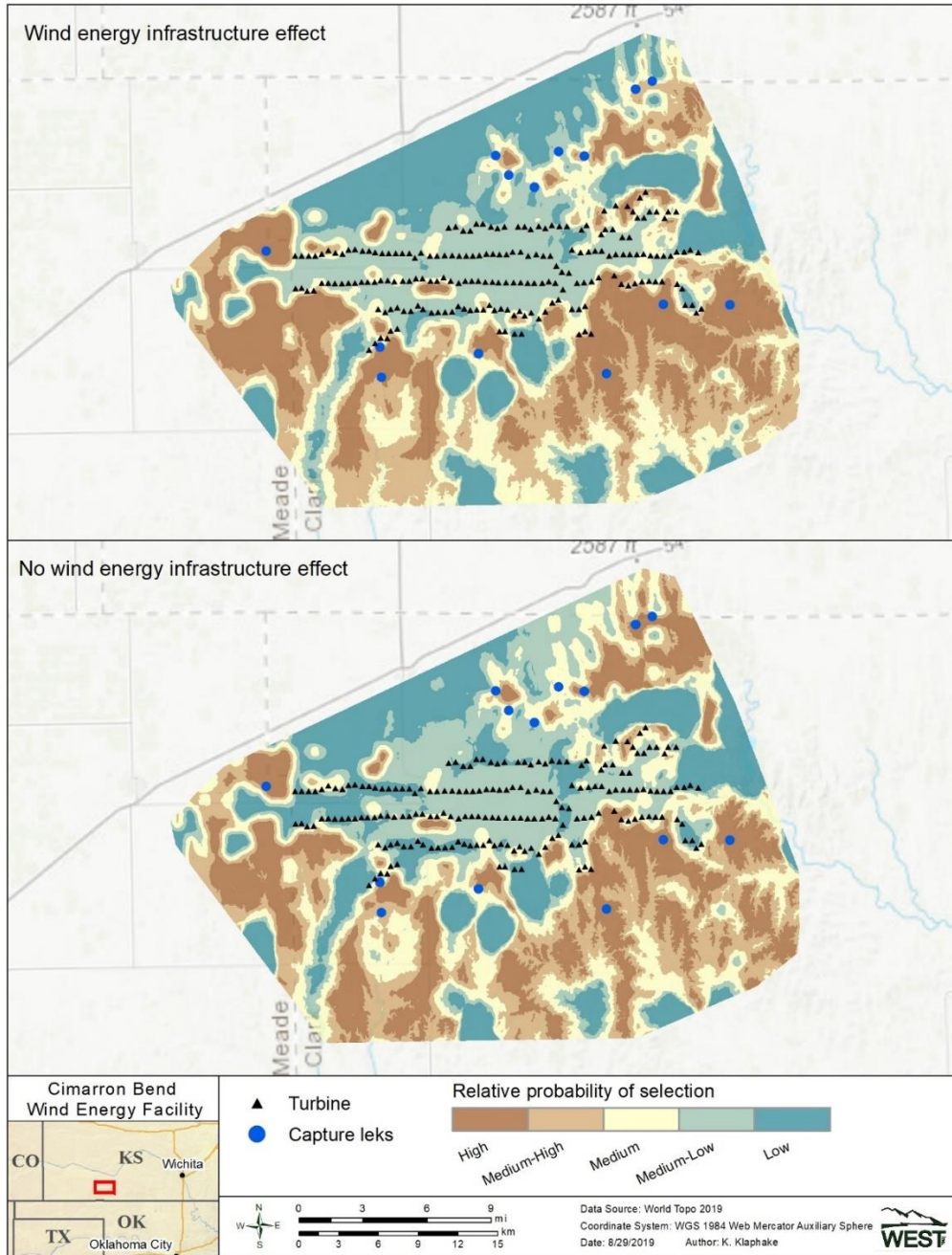
Source: Akaike 1974

## Appendix B: Relative Probability of Habitat Selection

**Appendix B1.** Female lesser prairie-chicken relative probability of nest site habitat selection with and without the effect of wind energy infrastructure covariates at the Cimarron Bend Wind Energy Facility, Clark County Kansas from 2017-2019.



**Appendix B2.** Lesser prairie-chicken relative probability of non-breeding habitat selection with and without the effect of wind energy infrastructure covariates at the Cimarron Bend Wind Energy Facility, Clark County, Kansas from 2017-2019.





## Appendix C: Male Lesser Prairie-Chicken Movements

**Appendix C1.** Male lesser prairie-chicken (LEPC) movement patterns and relative probability of selection at the site-specific scale during the breeding and non-breeding period at the Cimarron Bend Wind Energy Facility, Clark County, Kansas from 2017-2019.

