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Effects of Wind Energy Development on Nesting Ecology of Greater Prairie-Chickens in Fragmented Grasslands

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Abstract: *Wind energy is targeted to meet 20% of U.S. energy needs by 2030, but new sites for development of renewable energy may overlap with important habitats of declining populations of grassland birds. Greater Prairie-Chickens (*Tympanuchus cupido*) are an obligate grassland bird species predicted to respond negatively to energy development. We used a modified before–after control–impact design to test for impacts of a wind energy development on the reproductive ecology of prairie-chickens in a 5-year study. We located 59 and 185 nests before and after development, respectively, of a 201 MW wind energy facility in Greater Prairie-Chicken nesting habitat and assessed nest site selection and nest survival relative to proximity to wind energy infrastructure and habitat conditions. Proximity to turbines did not negatively affect nest site selection ($\beta = 0.03$, 95% CI = −1.2–1.3) or nest survival ($\beta = -0.3$, 95% CI = −0.6–0.1). Instead, nest site selection and survival were strongly related to vegetative cover and other local conditions determined by management for cattle production. Integration of our project results with previous reports of behavioral avoidance of oil and gas facilities by other species of prairie grouse suggests new avenues for research to mitigate impacts of energy development.*

Keywords: before–after control–impact, grassland bird, habitat use, nest placement, nest survival, *Tympanuchus*, wind power

Efectos del Desarrollo de la Energía Eólica sobre la Ecología de Anidación de Gallinas de la Gran Pradera en Pastizales Fragmentados

Resumen: *Se calcula que la energía eólica aportará el 20% de las necesidades energéticas de los Estados Unidos para el 2030, pero nuevos sitios para el desarrollo de energía renovable pueden traslaparse con hábitats importantes de poblaciones declinantes de aves de pastizal. La gallina de la Gran Pradera (*Tympanuchus cupido*) es una especie de ave obligada de pastizal que se pronostica responderá negativamente al desarrollo energético. Usamos un diseño ADCI modificado para probar los impactos del desarrollo de la energía eólica sobre la ecología reproductiva de las gallinas en un estudio de 5 años. Ubicamos 59 y 185 nidos antes y después del desarrollo, respectivamente, de una instalación de energía eólica de 201 MW en el hábitat de anidación de las gallinas y estudiamos la selección de sitio de anidación y la supervivencia de nidos en relación con la proximidad a la infraestructura y las condiciones de hábitat. La proximidad con las turbinas no afectó negativamente a la selección de sitios de anidación (β = -0.3, 95% CI = -0.6–0.1). En su lugar, la selección de sitios de anidación y la supervivencia estuvieron fuertemente relacionadas con la cobertura vegetal y otras condiciones locales determinadas por el manejo de la producción de ganado. La integración de*

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los resultados de nuestro proyecto con reportes previos de la evitación conductual de instalaciones de petróleo y gas por otras especies de pastizales sugiere nuevas vías para que la investigación mitigue los impactos del desarrollo energético.

Palabras Clave: Ave de pastizal, control-impacto-antes-después, energía eólica, supervivencia de nido, *Tympanuchus*, ubicación de nido, uso de hábitat

Introduction

Interest in wind power as an alternative source of renewable energy has increased in recent years. In the United States, wind energy facilities have been constructed in at least 38 states, most in the past 5 years. The best sites for wind energy development are likely in the Great Plains (Erickson et al. 2001; Obermeyer et al. 2011). Within this region, large and unfragmented prairies are often targeted for wind energy development because winds can be high and land ownership parcels are relatively large, which reduces contract costs and minimizes logistical constraints of contract development.

Grassland birds are declining faster than any other avian guild in North America due to habitat loss, fragmentation of native prairies, and intensification of land use for agricultural production (Igl & Johnson 1997; Peterjohn & Sauer 1999; Coppedge et al. 2001). Wind energy development may impact grassland birds directly through collision mortality or indirectly through behavioral avoidance, habitat loss, or changing trophic interactions. Previous research on wind-wildlife impacts focused on risk of collision mortality from turbines and transmission lines (Kuvlesky et al. 2007; Johnson & Stephens 2011). Studies evaluating the indirect impacts of wind energy development on populations of grassland birds have been limited, and potential impacts are often extrapolated or inferred from studies of other types of energy development or tall structures not associated with wind energy development (Pruett et al. 2009*a*; Holloran et al. 2010). In the United States, federal or state-mandated environmental assessments are not required for development of wind energy projects because data on negative impacts are lacking. Field studies evaluating impacts of wind energy development are needed to inform management actions and policy related to renewable energy development and grassland bird conservation.

The Greater Prairie-Chicken (*Tympanuchus cupido*, hereafter prairie-chicken) is an obligate grassland bird, an indicator species for tallgrass prairie ecosystems, and is among species that have been the most affected by habitat loss and degradation. Extant populations are estimated to inhabit only 10–25% of their former range (Svedarsky et al. 2000; Johnson et al. 2011). Prairie-chickens are a good study species for investigations of potential impacts of wind energy development because their breeding arenas or leks are often on hilltops and other sites with good potential for wind power (Gregory et al. 2011); rangeland management and habitat quality affects their movements, space use, and population dynamics (McNew et al. 2012*a*, 2012*b*); their reproductive potential is high but most losses are due to predators associated with fragmented habitats (McNew et al. 2012*a*); and most lek-mating grouse are sensitive to other types of energy development (Pitman et al. 2005; Walker et al. 2007).

We tested for impacts of construction of a commercial wind energy facility on the nesting ecology of prairie-chickens in the center of their extant range. We examined the following hypotheses. First, female prairie-chickens avoid wind energy features when selecting nest sites, and there are lag effects of this avoidance due to learning or lack of recruitment to developed areas. Second, nest survival is reduced in areas close to wind energy facilities if habitat fragmentation or presence of carrion due to collisions with turbines attracts predators. Third, proximity to wind energy development may have minimal effects on prairie-chickens if nest site selection and nest survival are primarily determined by effects of rangeland management on habitat conditions.

Methods

Study Area

The Meridian Way Wind Energy Facility is located in Smoky Hills Ecoregion in northcentral Kansas (Fig. 1). The facility has 67 3-MW turbines (model V90, Vestas, Aarhus, Denmark), 2 substations, 33 km of access roads, 25 km of high-capacity energy transmission lines, and a total installed capacity of 201 MW. Horizon Wind Energy began site preparation in April 2008, erected turbines in 2 phases of construction in August, and began commercial operation in December 2008. Our study area of approximately 1300 km^2 included leks and nests <0.5 to 30 km from wind turbines. The area was fragmented by state highways and county roads (1.4 km of roads/km^2). The landscape was mainly native grasslands managed for cattle production (58%) and cultivated crops (35%). Grasslands were burned infrequently, grazing was of low to moderate intensity (1 head/> 2 ha for 180 d), and stocking occurred 1 May to mid-September. Pastures were dominated by native warm season grasses with a diverse mix of forbs and a low density of woody plants.

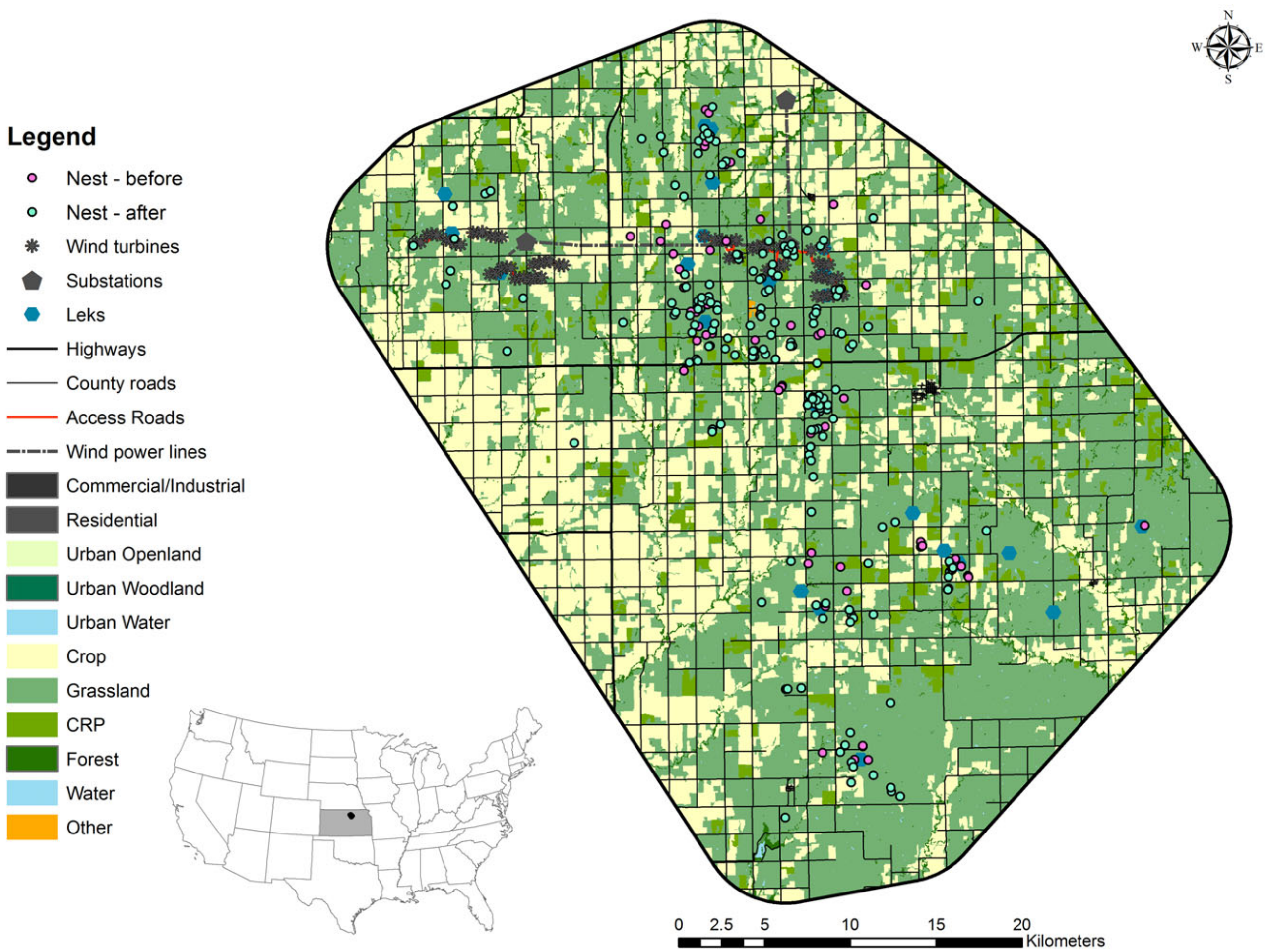

Figure 1. Location of leks and nests of Greater Prairie-Chickens before and after construction of the Meridian Way Wind Power Facility in north central Kansas, 2007–2011.

Study Design

We conducted field work over 5 years (2007–2011) and used a modified before–after control–impact (BACI) design to test for impacts of wind energy development on nest site selection and daily nest survival (Anderson et al. 1999). We collected field data for 2 years before construction (2007–2008) and 3 years after construction (2009–2011). Data collected in 2008 were included in the preconstruction period because construction started after the nesting season. One challenge for BACI designs is to determine a threshold distance where exposure has negative impacts. We did not use an arbitrary distance to separate control and impact areas. Instead, we evaluated potential thresholds in avoidance and demographic responses with a modified BACI design similar to analysis of covariance. We tested for effects of distance to wind energy features as a continuous variable, treatment period as a categorical variable (preconstruction, postconstruction), and the interaction between the 2 factors. Demographic performance should be unaffected by distance to eventual sites of wind energy features during the preconstruction period. The expected slope for the relationship between response and distance should be zero or negative if construction occurs in habitat. If wind energy development has negative impacts, we predicted a positive slope coefficient for a linear (or curvilinear) relationship between demographic performance and distance to wind energy infrastructure (Fig. 2).

Sampling

We captured prairie-chickens during March–May at 23 leks with box traps or drop-nets. Distances from leks to wind turbine sites ranged from 0.5 to 27 km. We sexed birds by plumage, and each female received an 11-g VHF radio transmitter attached with a necklace collar (model RI-2B, Holohil Systems, Ontario, Canada, or Model A3950, Advanced Telemetry Systems, Minnesota, U.S.A.). We monitored radio-marked females by triangulation ≥3 times/week during the nesting period (April—August). We used portable radio receivers and handheld Yagi antennas to locate nests of incubating females once daily

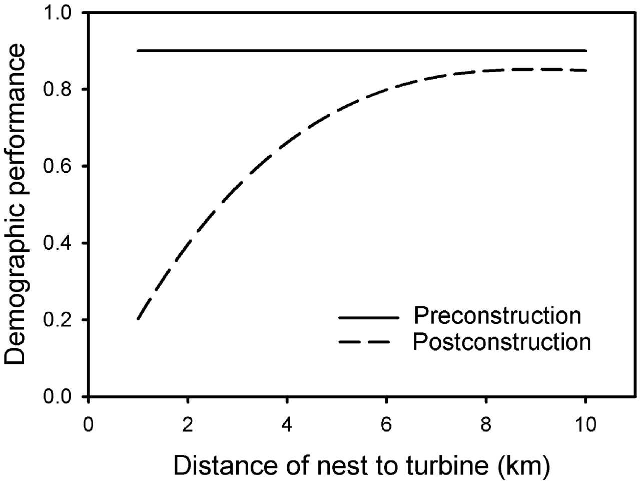

Figure 2. Hypothetical changes in nest site selection or daily nest survival (demographic performance) of Greater Prairie-Chickens predicted under negative impacts of wind power development. Baseline slope coefficients during the preconstruction period should be zero or negative, and response slope coefficients during the postconstruction period should be positive.

fixes indicated female movements were localized. We marked nest locations with inconspicuous rock cairns ≥25 m from the nest and recorded coordinates with a GPS unit. We flushed females once only in early incubation to determine clutch size and stage of incubation. We minimized disturbance of nests by checking females daily from >30 m via radio telemetry. If telemetry indicated a female had departed a completed nesting attempt, we visited the nest site to determine nest fate. We classified nest fate as failed or successful (produced ≥1 one chick) based on eggshells and other evidence at the nest site and female behavior.

We sampled habitat conditions within 3 d of hatching or failure at nests and random points within a study area delineated by a minimum convex hull placed 5 km outside all nest locations (McNew et al. 2013; Supporting Information). We determined the average of 4 visual obstruction readings (VORs) at a distance of 2 m and a height of 0.5 m. Vegetative cover was estimated as the proportion of grass, forb, shrub, or bare ground in a 20 × 50 cm Daubenmire quadrat frame at 12 subsampling locations within 6 m of each nest or random point. We measured the heights of the tallest grass and forb within 5 cm of the sampling point, recorded distance to nearest shrub, and classified shrubs as short (<1 m) or tall (≥1 m). We calculated Euclidean distance from each point to the nearest wind turbine, substation, or transmission line; nearest state highway, county road, or wind turbine access road; nearest telecommunication tower, cultivated agriculture field, and forest patch (≥0.9 ha) with ArcMap 10 (Environmental Systems Research Institute, Redlands, CA, U.S.A.).

We evaluated habitat conditions at the nest site (≤0.01 ha), a core use area (13-ha circle, radius 200 m), and average home range (310 ha, radius 1 km). Core use areas contained habitat associated with nest sites within a female's home range. Locations of females were usually restricted to 10−15 ha during nesting (L.B.M., unpublished data). Home range was based on space use of female prairie-chickens during the breeding season (Robel et al. 1970; Augustine & Sandercock 2011). We assessed habitat conditions at core use and home range scales with remote-sensing data and ArcMap 10. For land-cover analyses, we used the 30-m resolution land-cover map depicting 11 biologically relevant land-cover classes in Kansas in 2005 (Whistler et al. 2006). We included road system data sets for Kansas in 2006 (Kansas Department of Transportation, Topeka). Land use in northcentral Kansas changed little from 2005 to 2011; thus, we used remote imagery from 2005 to 2006 to determine landscape conditions during our field study. We used ArcMap and the Geospatial Modeling Environment (Ver. 0.7.1.0; Beyer 2012) to measure the proportion of the landscape in grassland, cultivated agriculture, and forest. Edges and roads may influence nest site selection and daily nest survival through increased predation risk (Winter et al. 2000; Bollinger & Gavin 2004). We measured total edge length for all land-cover types and total length of state highways and unimproved county roads at core use and home range scales.

Statistical Analyses

We conducted a series of multivariate correlation analyses and univariate comparisons of habitat variables between nest sites and random points to assess within-scale correlations of our explanatory variables (Supporting Information). If habitat metrics within a spatial scale were correlated ($r \geq 0.5$, $p < 0.05$), we used single-factor logistic regression to determine which variable accounted for more variation. We considered variables with a lower residual model deviance the primary habitat variable and correlated variables of secondary importance. Distance to nearest wind turbine was strongly correlated with distances to all other wind energy features ($r \geq 0.8$, $p < 0.001$). Therefore, we retained distance to nearest wind turbine as the single explanatory variable related to wind energy development.

We randomly selected 80% of nests and random points for inclusion in model development and withheld 20% of our sample for model validation. Selection of random points was stratified; numbers of nests and random points were equal each year and model intercepts were directly comparable. To evaluate whether wind turbines were constructed in habitats preferred by nesting prairie-chickens, we used generalized additive models (GAMs) to model the distance of random points to the nearest turbine as a function of habitat variables that affect nest site selection at 3 spatial scales (Supporting Information).

To examine nonlinear relationships between nest site selection versus wind energy development and habitat conditions, we explored different shapes for responses to each covariate before fitting models with resource selection functions (RSFs) (Supporting Information). We built univariate GAMs with nests and random points as binary responses and fitted smoothing splines to model nonlinear relationships with wind turbines and habitat variables (Wood 2006). We inspected plots of predicted relationships and partial residuals to transform smoothed variables into polynomials that approximated nonlinear relationships (Crawley 2005). We tested pseudothreshold models with natural log of the explanatory variable (i.e., $\ln[x + 0.001]$) (Franklin et al. 2000; Dugger et al. 2005).

Fine-scale spatial variability in nest site selection by prairie-chickens can be aggregated at scales comparable to the size of our study area (McNew et al. 2013). Thus, we evaluated nest placement with spatially stationary RSFs where nest sites (use) and random points (available) were independent samples (Manly et al. 2001). We used generalized linear mixed models (GLMMs) with the logistic link function, a binomial error structure, and linear or nonlinear responses to fixed effects following patterns from our GAM analyses to evaluate RSFs. Female identity was a random term in all models because a few females laid more than one clutch per season or were monitored for multiple years.

We used a hierarchical approach based on forward stepwise variable selection and adjusted Akaike's Information Criterion for model selection (AIC_c; Burnham & Anderson 2002). We selected the most parsimonious models at each of 3 spatial scales and then combined key variables to build a full model of nest site selection at multiple scales (Supporting Information). In the multiscale analysis, we excluded models with $\Delta AIC_c \leq 2$ that differed from the top model by a single parameter if confidence intervals indicated the parameter was noninformative (or $\Delta AIC_c \leq 4$ if $\Delta K = 2$, Burnham & Anderson 2002; Arnold 2010). Habitat conditions could mitigate impacts of wind energy if development occurs in the highest quality habitat. Thus, we evaluated models with 3-way interactions between habitat variables, treatment period, and proximity of wind turbines. All statistical analyses were performed in R statistical software (ver. 2.4; R Development Core Team 2011, Vienna, Austria), where GAM and GLMM models were fit with the mgcv and lme4 packages (Wood 2006; Bates et al. 2012).

We validated our top RSF with a holdout data set of 48 nest sites and 48 random points (20% of data) (Boyce et al. 2002). The top model was used to calculate RSF values for each nest in the training and holdout data sets. We placed raw RSF values into quantile bins representing increasing likelihood of points being classified as a nest site. Bins 1 and 5 contained the lowest 20% and highest 20% of the raw RSF values. We regressed the observed proportion of holdout nest locations in each RSF bin against the proportion of nests in each bin from the training data set. We based good model fit on Johnson et al. (2006).

We used the nest survival procedure of Program Mark (ver. 6.0) to test competing models and estimate daily survival rates (DSRs) of nests during an 86-d nesting period between 18 April and 12 July (White & Burnham 1999; Dinsmore et al. 2002). We developed 5 sets of candidate models to evaluate temporal covariates, habitat covariates at 3 spatial scales, and the effects of wind energy disturbance. Temporal covariates included year of study, day of nesting season, and daily weather variables (temperature and precipitation). Model selection started with an intercept-only model, and variables were retained if they led to a reduction in AIC_c. We modeled nest survival as a function of habitat covariates measured at the nest site or habitat conditions at the core use (13 ha) or home range scales (310 ha, Supporting Information). Environmental covariates included the proportion of different land-cover types (grassland, cultivated agriculture, and forest) and edge lengths of different land-cover types within the core area and home range extents. We evaluated covariates associated with proximity to anthropogenic structures, including distances to nearest wind turbine, transmission line, telecommunication tower, county road, or state highway. All models for wind energy development included an interaction term between treatment period (pre vs. post) and distance to the nearest turbine. To test for possible lag effects, we included a fixed effect model with a group effect for each year of the postconstruction period (i.e., 2009–2011).

We took parsimonious models from each of the 5 candidate sets and combined variables to evaluate models for temporal conditions, habitat at 3 spatial scales, and impacts of disturbance. We used a backward selection technique to drop covariates and evaluated candidate models with AIC_c. All models were constructed using design matrices and the logit link function, and model selection was based on differences in AIC_c and evidence ratios from Akaike weights (Burnham & Anderson 2002). We calculated expected nest survival for a 35-d exposure period based on an average clutch size of 12 eggs and a 23-d incubation period (McNew et al. 2011) and used the delta method to calculate the standard error for the extrapolated estimate (Dinsmore et al. 2002).

Results

We located 264 prairie-chicken nests (207 first nests and 57 renests). Twenty (8%) nests failed due to abandonment, trampling or hay cutting, or had incomplete data. We analyzed 59 nests from the 2-year preconstruction

Table 1. Model selection for multiscale models of nest site selection and nest survival of female Greater Prairie-Chickens, 2007–2011.[a]

Model factors[b]	*K*	*Dev*	*AIC*$_c$	Δ*AIC*$_c$	w_i	*Cum* w_i
Nest site selection						
VOR + VOR^2 + %forb + Shrub ht. + ln(Distance to forest) + %grassland CA + %forest CA + Road length CA + %agriculture HR + Forest edge HR	12	279.4	304.3	0.0	0.7	0.7
VOR + VOR^2 + Shrub ht. + ln(Distance to forest) + %grassland CA + %forest CA + Road length CA + %agriculture HR + Forest edge HR	11	285.1	307.7	3.4	0.1	0.8
VOR + VOR^2 + %forb + Shrub ht. + ln(Distance to forest) + %grassland CA + Road length CA + %agriculture HR + Forest edge HR	11	285.4	308.1	3.8	0.1	0.9
Null model	2	421.4	425.4	121.1	0.0	1.0
Period × ln(Distance to turbine)	6	421.2	433.4	129.1	0.0	1.0
Nest survival						
VOR + VOR^2 + %Grass + %Forb + Distance to forest	6	1091.3	1103.4	0.0	0.1	0.1
VOR + VOR^2 + %Grass + %Forb + Distance to forest + Precipitation	7	1089.4	1103.4	0.0	0.1	0.3
VOR + VOR^2 + %Grass + %Forb	5	1093.6	1103.7	0.3	0.1	0.4
VOR + VOR^2 + %Grass + %Forb + Precipitation	6	1091.7	1103.7	0.3	0.1	0.5
VOR + VOR^2 +%Grass + Distance to forest	5	1094.3	1104.3	0.9	0.1	0.6
VOR + VOR^2 + %Grass + %Forb + Distance to forest + %Agriculture HR	7	1090.5	1104.5	1.1	0.1	0.7
VOR + VOR^2 + %Grass + %Forb + Distance to forest + Period × Distance to turbine	9	1091.0	1105.0	1.6	0.1	0.8
VOR + VOR^2 + %Grass + %Forb + Distance to forest + Distance to water + Precipitation	8	1089.1	1105.2	1.8	0.1	0.8
VOR + VOR^2	3	1099.4	1105.4	2.0	0.1	0.9
VOR + VOR^2 + %Grass + %Forb + Distance to forest + Distance to water + %Agriculture HR + Precipitation	9	1088.0	1106.1	2.7	0.0	0.9
VOR + VOR^2 + %Grass + %Forb + Distance to forest + Year	7	1086.3	1106.4	3.0	0.0	1.0
VOR + VOR^2 + %Forb + Distance to forest	5	1097.1	1107.1	3.7	0.0	1.0
Null model	1	1139.2	1141.2	37.8	0.0	1.0
Period × Distance to turbine	4	1136.6	1144.6	41.2	0.0	1.0

[a]*Only models with Akaike weights* (w_i) $\geq$ *0.01 are presented except for the null model and models testing effects of wind power development with an interactive term for treatment period and distance to turbine.*
[b]*Variables at the core area scale are denoted by CA, variables at the home range scale are denoted by HR, all others are at the nest site scale. Abbreviation: VOR, visual obstruction reading.*

period (48 first nests, 11 renests) and 185 nests from the 3-year postconstruction period (142 first nests, 43 renests).

Compared with random points, nest sites had greater visual obstruction and vegetative canopy, were farther from roads and habitat edges, and occurred in areas with a greater proportion of grassland and lower proportions of other types of land cover (Supporting Information). Wind turbines were constructed in an area with a relatively high proportion of grassland and with lower edge densities (Fig. 1). Distance to turbine was not related to VORs, an index of vegetation structure (Supporting Information).

Nest Site Selection

Multiscale models received a majority of statistical support among models of nest site selection ($w_i > 0.99$, Table 1). The model that received the most support ($w_i =$ 0.71) included a quadratic function for visual obstruction, forb cover, shrub height, and distance to forest at the nest site; core area grassland and forest cover and road density; and home range proportion of agriculture and forest edge. Models with an interaction between treatment period × distance to turbine received almost no support ($w_i < 0.01$).

Relative probability of use for nest site selection did not vary with distance to turbine during either the pre- or postconstruction periods (Fig. 3). The main factor driving nest site selection was the VOR, which was maximized at 3–6 dm in a quadratic function (Table 2, Fig. 4). Probability of use increased with grassland cover in the core use area and above a threshold distance of 300 m from forest patches. Conversely, probability of use was negatively affected in core use areas by forb cover at the nest, forest cover, and road density and in home range by proportion of agriculture and forest edge (Supporting Information).

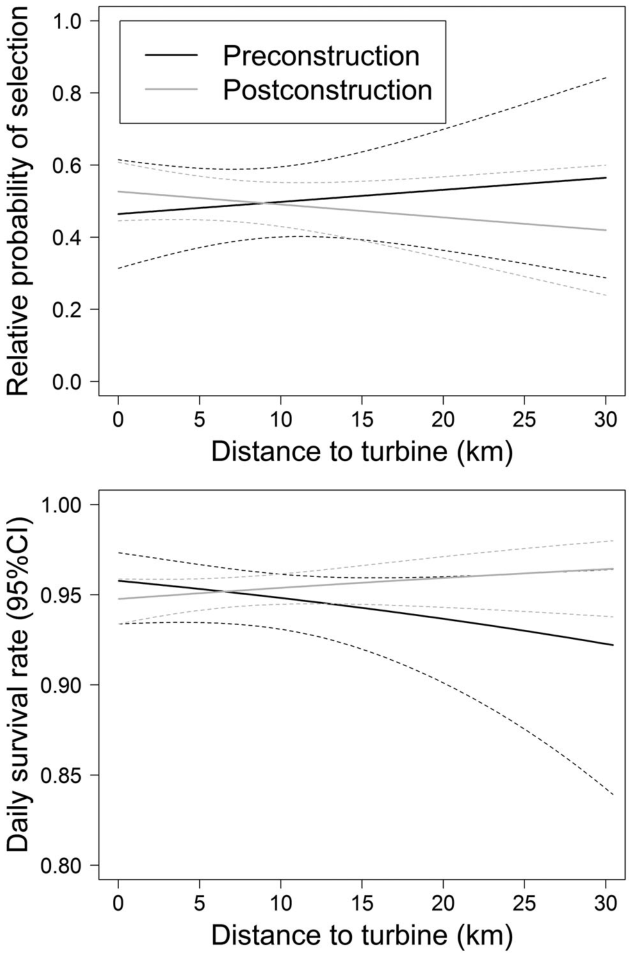

Figure 3. Relative probability (95% CI) of nest site selection (top) and daily survival rate of Greater Prairie-Chicken nests (bottom) versus distance of the nest to the nearest wind turbine during the preconstruction (2007–2008) and postconstruction periods (2009–2011) at the Meridian Way Wind Power Facility in northcentral Kansas. Parameter estimates were taken from factorial models with the effects of treatment period and distance to turbine.

The top model correctly classified 47 of 48 (98%) hold-out nest observations as nest sites. Validation based on linear regression indicated a high predictive accuracy with an intercept of 0 (95% CI: −0.02–0.04), slope of 0.94 (95% CI: 0.88–1.0), and high coefficient of determination ($r^2 = 0.99$).

Nest Survival

Nest survival analyses included 244 nests. Predators destroyed 170 nests (70%) and 74 nests (30%) were successful. Models with habitat variables assessed at the nest site scale received a majority of support among the candidate models ($w_i > 0.90$), and top models included a quadratic

Table 2. Estimated coefficients for the effects of standardized covariates from the most parsimonious models of nest site selection and daily nest survival in northcentral Kansas, 2007–2011.

Variable[a]	*Nest site selection (SE)*	*Daily nest survival (SE)*
VOR	19.6 (5.5)	0.60 (0.12)
VOR^2	−6.0 (2.0)	−0.10 (0.13)
%grass	–	0.22 (0.09)
%forb	−2.4 (3.2)	0.17 (0.10)
Shrub height	−4.8 (5.1)	-
Distance to forest	–	0.13 (0.09)
Ln(Distance to forest)	3.7 (3.2)	–
%grassland CA	2.2 (3.4)	–
%forest CA	−4.3 (10.4)	–
Road length CA	−4.9 (2.6)	–
%agriculture HR	−4.7 (3.4)	–
Forest edge HR	−2.1 (3.1)	–

[a]*Abbreviations: VOR, visual obstruction reading; CA, core area; HR, home range.*

effect of VOR, proportion of grass or forb cover at the nest, distance of nest to forest, and daily precipitation (Table 1). Models with habitat variables at the core use or home range scales explained little of the variation in nest survival ($w_i < 0.05$; Supporting Information). Models with a period × distance to turbine interaction received essentially no support ($w_i < 0.001$).

DSRs of nests were not affected by distance to turbine during pre- or postconstruction (Fig. 3). Daily nest survival was higher during postconstruction, especially at distances >5 km. The ecological factor with the greatest effect on the daily nest survival was VOR at the nest (Tables 1 & 2). Models that treated daily nest survival as a quadratic function of VOR accounted for essentially all the support among candidate models ($\Sigma w_i > 0.99$). Daily nest survival increased from a low of 0.85 for nests with little vegetative cover (dm < 2) to 0.97 when nesting cover exceeded 5 dm (Fig. 4). Other factors that had a positive effect on daily nest survival included the proportion of cover in grass or forbs at the nest site and distance of the nest from forest patches (Supporting Information).

Discussion

Wind energy development in the Great Plains has increased dramatically during the past decade, raising concerns about its potential impacts on grassland wildlife (Pruett et al. 2009*b*; Johnson & Stephens 2011). The potential for conflict was high in our study area because the wind energy facility was constructed in tallgrass prairie habitats occupied by Greater Prairie-Chickens. Our ability to assess demographic impacts was good because demographic rates were estimated from a large sample of radio-marked birds that were monitored for multiple years before and after construction. We found no evidence

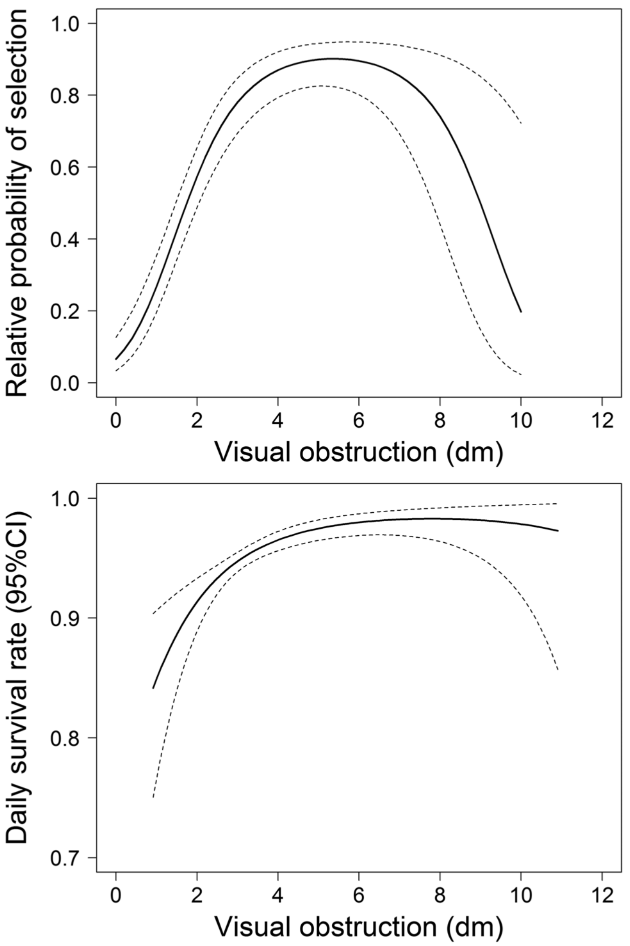

Figure 4. Relative probability (95% CI) of nest site selection (top) and daily nest survival (bottom) versus visual obstruction reading (VOR) as an index of vegetative structure and nest concealment at the Meridian Way Wind Power Facility in northcentral Kansas, 2007–2011. Parameter estimates were taken from models with a quadratic effect of VOR.

that development of the 201 MW wind energy facility affected either nest site selection or nest survival of prairie-chickens. Instead, the strongest ecological correlates of reproductive performance were local conditions of native grasslands associated with rangeland management for cattle production.

Nest Site Selection

Nest site selection by prairie-chickens was related to habitat conditions at multiple spatial scales, similar to other prairie and forest grouse (Doherty et al. 2008; Zimmerman et al. 2009; McNew et al. 2013). At a local scale, nest site selection exhibited a quadratic relationship with vertical nesting cover, suggesting an optimal range of 3–6 dm for nesting prairie-chickens in northcentral Kansas. Quality of nest sites is determined by prescribed burning and grazing practices that directly influence vertical nesting cover in tallgrass prairie ecosystems (Robbins et al. 2002; McNew et al. 2013). Nesting females avoided woody cover, forest patches, and edges. The structural form of the relationship between nest site selection and distance to forest suggested a negative edge effect within 300 m of a forest edge. Avoidance of nongrassland areas by nesting prairie-chickens was also supported at the core area and home range scales. Site use was greatest for core areas lacking forest and home ranges lacking crop fields and forest edges. Prairie-chickens may have selected areas dominated by grassland cover without forested edges to minimize demographic impacts of nest predators associated with forest and agricultural edges (Kuehl & Clark 2002; McNew et al. 2012*a*).

Wind energy development did not affect nest placement by female prairie-chickens. Models with postdevelopment year as a fixed effect performed poorly and provided no evidence for possible lag effects. Similarly, 3-way interactions among habitat variables, treatment period, and proximity to wind energy were not supported, suggesting that local conditions did not affect how females assessed wind energy infrastructure during nest site selection. Overall, our research results do not support impacts of wind energy development predicted for prairie-chickens (Pruett et al. 2009*b*; Johnson & Stephens 2011; Obermeyer et al. 2011). A lack of effect of wind energy on nest placement is in contrast with previous reports of negative impacts of oil and gas infrastructure and transmission lines on movements, lek attendance, and nest site selection in other prairie grouse (Pitman et al. 2005; Walker et al. 2007; Holloran et al. 2010).

Variation in avian responses may be related to the types of disturbance associated with different types of energy development. The proximate cues for avoidance are poorly understood, but might include changes in predator or human activity or visual or auditory disturbance from wind turbines, wellheads, compressor stations, or other structures (e.g., Pitman et al. 2005; Walker et al. 2007; Blickley et al. 2012). Oil and gas development provides vertical structures that are suitable nest platforms for corvids or hunting perches for raptors. Benefits to corvids and raptors were unlikely in our study because the wind turbines were of a tubular design and most transmission lines were buried under access roads. Vehicle traffic may be an avoidance cue; female prairie-chickens avoid state highways but not local county roads when initiating nests (McNew et al. 2013). Similarly, road noise has a greater impact on lek attendance of Sage-Grouse (*Centrocercus urophasianus*) than sounds of drilling (Blickley et al. 2012). Wind turbines require relatively little maintenance once operational, and vehicle traffic within the wind power facility was limited to private landowners and our research team. We found that nest site selection was affected more by rangeland management than by wind energy infrastructure and sites with poor cover were avoided.

Nest Survival

Nest survival is a limiting factor for prairie-chicken populations, and most nest failures are due to predation (Wisdom & Mills 1997; McNew et al. 2012*a*). We predicted that wind energy development would negatively affect nest survival if collision mortalities were a food resource for nest predators or if grassland fragmentation improved predator access (Tigas et al. 2002). However, nest survival was not affected by proximity to wind energy development after construction; nest survival was strongly related to local habitat conditions at the nest site. At the nest, VOR was the most important variable associated with nest survival. The probabilities of nest site selection and nest survival were maximized for VORs between 3 and 7 dm. Thus, females preferred nest sites with greater vertical cover, and nesting cover had positive benefits for nest survival.

The relationship between nest survival and habitat condition is critical information for conservation of prairie-chickens. Cattle production has intensified in eastern Kansas, and increasing use of prescribed fire and grazing pressure have negatively affected habitat conditions for prairie chickens and other grassland birds (With et al. 2008; McNew et al. 2013). The average VOR measurement was 25 cm for nests in our study, which yielded an expected probability of nest survival of 0.17. Changes to rangeland management that improve habitat by doubling vertical nesting cover to 50 cm could triple the probability of nest survival from 0.17 to 0.52. Our demographic models predict that higher productivity could stabilize declining populations of prairie-chickens in Kansas (McNew et al. 2012*a*).

We may have failed to detect an effect of development if our sample was a biased subset of the population. We reject this possibility because we standardized field protocols among years and maintained consistent sampling effort at all distances from the wind energy facility. Nests were found by radio-tracking highly mobile birds, and this method should provide an unbiased sample for nest placement and nesting success (Powell et al. 2005). The potential effects of wind energy development could have been offset by improvements in environmental conditions during the postconstruction period. No mitigation plans for rangeland management were implemented and habitat conditions were unaffected by wind power development. Seasonal patterns of temperature and precipitation showed some annual variation, but the pre- and postconstruction period did not differ (B.K.S., unpublished data). Finally, 3 years of postconstruction monitoring may be short compared with demographic responses of grassland birds or their predators. Prairie-chickens are short-lived, and 3 years postconstruction should have been sufficient time to detect potential changes in nest survival. Responses of nest predators to fragmentation may be complex and depend on the species or spatial scale of fragmentation (Chalfoun et al. 2002). In a separate study, we found evidence for avoidance of wind turbines but no negative impacts on female survival (V. L. Winder et al., unpublished data). Thus, wind energy development appears to have little impact on the population dynamics of a sensitive species of grassland bird in a fragmented landscape. Caution should be applied when extrapolating our study results to other sites or ecosystems. We started our project with 3 replicate study areas that differed in fragmentation and rangeland management, but energy development occurred at only one site (McNew et al. 2012*a*). Our study site was fragmented and the wind turbines were constructed in large tracts of prairie surrounded by a matrix of unsuitable agricultural fields and roads. If prairie-chickens perceive wind power infrastructure as more desirable than agricultural fields, a study in a continuous landscape may be more likely to detect avoidance or demographic impacts. We could not examine lag effects of longer than 3 years. Future studies will advance understanding if similar BACI designs can be replicated with other species and landscapes to assess impacts of wind energy development on space use and demography under different ecological conditions and longer postconstruction periods.

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Supporting Information

Multicollinearity analyses of predictor variables (Appendix S1), methods for the selection of starting models at each spatial scale for nest site selection (Appendix S2) and nest survival (Appendix S4), and assessment of nonlinearity in ecological responses (Appendix S3) are available on-line. The authors are solely responsible for the content and functionality of these materials. Queries (other than the absence of the material) should be directed to the corresponding author.

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