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RESEARCH ARTICLE

Trends in greater sage-grouse lek counts relative to existing wind energy development in Wyoming

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Abstract

Rapid increases in wind energy development globally highlight the need to evaluate how electricity generation may impact wildlife. The greater sage-grouse (*Centrocercus urophasianus*; hereafter, sage-grouse) has experienced range-wide population declines, primarily due to habitat loss and degradation. Studies have documented a negative association between oil and gas development and sage-grouse populations. However, potential sage-grouse population declines associated with wind energy development have not been adequately addressed. We investigated the relationship between wind energy infrastructure and changes in male sage-grouse counted on leks from 2000–2020 in Wyoming, USA, using Bayesian state-space models. Our study was conducted in central and southwest Wyoming in the vicinity of 10 wind energy facilities that were in proximity to sage-grouse leks occurring outside of Wyoming's Core Areas (i.e., areas of high breeding densities of sage-grouse designated for restricted development by the State of Wyoming) and dominated by big sagebrush (*Artemisia* spp.) communities. Facilities became operational between 1998 and 2010 and had an average of 67 turbines. Covariates describing wind energy infrastructure included distance to the nearest wind

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turbine, and the number and distribution (clustering) of turbines within 1.0, 2.0, 4.0, 6.0, 8.0, and 10.0 km. We also explored whether males attending leks exhibited lagged responses of 1–7 years following development. We used counts from 78 leks located within 15 km of the 10 wind energy facilities, consisting of 288 counts before and 845 counts after development. We expected that trends in male lek attendance would experience a delayed negative response following wind energy development like other forms of anthropogenic features. However, we failed to detect a relationship between male sage-grouse lek attendance and proximity to, density of, or distribution of wind turbines following development in all models. Our findings were based on the average lek in our analysis being 6.5 km from a wind turbine and most turbines were clustered such that undisturbed habitat surrounding leks remained. Therefore, interpretation of our results should be restricted to siting practices of the facilities that we evaluated because direct habitat removal and fragmentation resulting from any form of energy development is unlikely to benefit sage-grouse populations. Our study evaluated the response of low-density, peripheral populations of sage-grouse to wind energy development outside or near the edge of Core Areas. As such, our results should not be extrapolated to higher density sage-grouse populations occurring in Core Areas.

KEYWORDS

Centrocercus urophasianus, energy development, lek trends, population response, renewable energy

Identifying potential impacts associated with energy development is often necessary for agencies tasked with managing wildlife populations. It is well documented that activities associated with extractive energy development can directly remove or fragment habitat, which adversely impact wildlife (Northrup and Wittemyer 2013, Hovick et al. 2014). Renewable energy development can cause direct collision mortality (Allison et al. 2019, Kosciuch et al. 2020) and habitat loss (Sawyer et al. 2022), but there is little information currently available to assess how these effects manifest at a population level (Northrup and Wittemyer 2013). Between 2000 and 2020, an average of 2,885 wind turbines were built per year in the conterminous United States (an increase of approximately 15% per year; Hoen et al. 2018), highlighting a need to evaluate how this rapidly growing industry may impact wildlife.

Greater sage-grouse (*Centrocercus urophasianus*, hereafter sage-grouse) occupy sagebrush steppe across the western Great Plains and Intermountain West (Schroeder et al. 2004), a region with high potential for renewable energy development (Agha et al. 2020, Ott et al. 2021). Sage-grouse have experienced range-wide declines over the last half century (Coates et al. 2021), primarily due to habitat loss and degradation (Connelly et al. 2004). One threat to sage-grouse populations is direct and indirect loss of habitat resulting from both extractive and renewable energy development (Naugle et al. 2011, Agha et al. 2020). Sage-grouse population trends are consistently negatively associated with energy development, such as oil and coal bed natural gas (Walker et al. 2007, Harju et al. 2010, Green et al. 2017), where year-round avoidance behaviors (Aldridge and Boyce 2007, Doherty et al. 2008, Smith et al. 2014, Kirol et al. 2015) and reduced fitness (Aldridge and Boyce 2007, Kirol et al. 2015) have ultimately led to sage-grouse population declines (Gregory and Beck 2014, Green et al. 2017).

Currently, the effects of wind energy development on sage-grouse have been evaluated at one wind energy facility in Wyoming, USA (LeBeau et al. 2014; LeBeau et al. 2017*a*, *b*). There is evidence that wind energy development is avoided by females during brood-rearing and summer periods (LeBeau et al. 2017*a*) and is associated with lower nest and brood survival up to 2 years following development (LeBeau et al. 2014). However, reduced nest and brood survival relative to wind energy infrastructure was not detected over a longer, 6-year period following development at the same study site (LeBeau et al. 2017*a*). In addition, there is currently no evidence that trends in male sage-grouse lek counts are negatively associated with wind energy infrastructure (LeBeau et al. 2017*b*). While these studies found that wind energy development may not adversely affect sage-grouse demography (LeBeau et al. 2017*a*, *b*), long-term and replicated studies will be necessary to adequately address any impacts to sage-grouse associated with wind energy development (Coppes et al. 2020, Lloyd et al. 2022, LeBeau et al. 2023).

Implementing long-term studies over the near term may be unrealistic, but utilizing existing sage-grouse lek count data will help address the knowledge gap in our understanding of wind energy impacts to sage-grouse populations. Sage-grouse lek counts are the primary data used to monitor trends in populations across their range and are relevant for assessing landscape-scale relationships between habitat attributes and population trends (Dahlgren et al. 2016, Edmunds et al. 2018). In addition, trends in sage-grouse lek counts have been used to evaluate population level responses of sage-grouse to oil and gas development (Harju et al. 2010, Gregory and Beck 2014, Green et al. 2017) and wind energy development (LeBeau et al. 2017*b*). The purpose of our study was to evaluate sage-grouse responses to existing wind energy facilities using male lek count data over a 21-year period. Using Bayesian state-space models, we investigated the relationships between distance to wind turbines, wind turbine density, and wind turbine distribution and changes in male sage-grouse counted on leks in Wyoming, USA from 2000–2020 (Kèry et al. 2009, Kèry and Schaub 2012).

STUDY AREA

Our study was conducted in central and southwest Wyoming in the vicinity of 10 wind energy facilities that were in proximity to sage-grouse leks and dominated by big sagebrush (*A. tridentata*) communities. These 10 wind energy facilities became operational between 1998 and 2010 and had an average of 67 turbines (min–max = 9–110). There were 4 facilities in Carbon County Wyoming. The Dunlap Ranch wind energy facility consisted of 74, 1.5-MW turbines that became operational in 2010. The Seven Mile Hill wind energy facility consisted of 79, 1.5-MW turbines that became operational in 2008. The Medicine Bow (9, 0.6–0.66-MW turbines) and Rock River 1 (50, 1.0-MW turbines) facilities became operational in 1998 and 2001, respectively. The Campbell Hill (66, 1.5-MW turbines), Glenrock (66, 1.5-MW), Rolling Hills (66, 1.5-MW), and Top of the World Windpower (110, 1.5–2.3-MW) facilities in Converse County became operational between 2008 and 2010. In Uinta County, the Evanston facility (80, 1.8-MW turbines) became operational in 2003 and the Mountain Wind I and II facilities (67, 2.1-MW turbines) became operational in 2008. Except for the Medicine Bow wind energy facility which occurred in the Hanna Core Area, wind facilities were outside of Wyoming's Sage-Grouse Core Areas (State of Wyoming 2019).

METHODS

Sage-grouse lek-count data

Sage-grouse lek locations and count data were obtained from the Wyoming Game and Fish Department sage-grouse lek database (Christiansen 2012). Annual counts are performed range-wide by state and federal agencies and provide estimates of relative population abundance (Fedy and Aldridge 2011, Green et al. 2017). We used the maximum male count in each year for each lek as the measure of interest. We used information from all leks that were located within 15 km of a wind turbine. We chose 15 km as a cutoff distance because it represented approximately 1.5 times the distance where sage-grouse are expected to be impacted by anthropogenic activities based on a literature review (Manier et al. 2014) and allowed for a range in distance and number of turbines that each lek was exposed to. Our dataset consisted of maximum male lek counts for 78 leks from 1980 to 2020. Between 1980 and 1999, only 62 of 78 total leks were surveyed, and the average number of years each lek was surveyed was 4.5 (min–max = 0–18 years). Between 2000 and 2020, all 78 leks were surveyed and the average number of years each lek was surveyed was 14.5 (min–max = 8–21 years). Hence, we limited our analysis to maximum male lek counts from 2000 to 2020, when survey effort increased and became more consistent over time and across leks. Our study period coincided with the timing of initial wind turbine construction within Wyoming. Additional wind energy facilities have been constructed since 2020, but we did not include these facilities due to insufficient lek-count data post-construction. We also restricted data to leks with at least 2 non-zero counts within the survey period.

Covariates

We estimated percent sagebrush cover within 6.4 km of each lek using U.S. Geological Survey (USGS) sagebrush products (Rigge et al. 2019, USGS 2021). Sagebrush layers estimated cover each year from 1985 to 2021 and we therefore time stamped layers to reflect conditions during the year when each lek count was performed. We used 6.4 km based on the spatial relationship of sage-grouse use in proximity to leks and its adoption in federal and state sage-grouse policy guidelines (Doherty et al. 2011, BLM 2015, State of Wyoming 2019). We assessed percent sagebrush cover within 6.4 km as a potential mediator variable to describe lek trends in relation to wind turbines. Locations and year when turbines became operational were obtained from the USGS Wind Turbine database (Hoen et al. 2018). We considered several covariates describing wind energy infrastructure including distance to nearest wind turbine, and the number of turbines within 1.0, 2.0, 4.0, 6.0, 8.0, and 10.0 km.

In addition, we calculated Euclidean distance to wind turbines present in each year across the study area and then calculated the average Euclidean distance to a turbine within buffers of each lek. This metric (hereafter turbine distribution) was used to assess the distribution of turbines without consideration of turbine density. There is evidence that the distribution of infrastructure may better predict male sage-grouse lek counts compared to density alone (Doherty et al. 2010), and methods have been employed to address an area of impact in addition to infrastructure density (Walker et al. 2007). For example, Walker et al. (2007) buffered infrastructure by 350 m and estimated the proportion of area covered by dissolved infrastructure buffers surrounding leks. In contrast, the turbine distribution metric makes no assumption of the amount of area affected by an individual turbine. Low mean Euclidean distance values indicated that the average location within each buffer surrounding a lek was relatively close to turbines (uniform distribution of turbines surrounding a lek); intermediate values indicated that turbines were relatively clumped within buffers surrounding a lek; large values indicated that turbines were largely absent from buffers surrounding a lek (Appendix A, Figures A1, A2). All measures of wind energy infrastructure were standardized to have a mean of zero and a variance of 1 across all leks.

Analytical approach

We evaluated the effects of wind energy development on trends in male sage-grouse attending leks using a before-after-gradient design (Ellis and Schneider 1997). We first considered the percent sagebrush within 6.4 km and included it in subsequent models if it was predictive of lek attendance. All models contained a single wind energy covariate (detailed above), a period term (before or after development), and a wind energy covariate and period term interaction. Wind energy covariates were fixed for each lek and were set to reflect conditions at the conclusion of our study period. Because the Glenrock (operational in 2008), Campbell Hill (operational in 2009), Rolling Hills (operational in 2009), and Top of the World Windpower (operational in 2010) facilities were in close proximity, we set the period term for leks in that region to reflect the time when the nearest facility became operational.

Not all leks were surveyed in all years between 2000 and 2020. Therefore, we considered 3 subsets of the data. The first dataset included data from all 78 leks (i.e., full data). The second data subset only included leks in which the proportion of missed years between the first and last years the lek was surveyed did not exceed 0.2 (i.e., at most 20% missing data). The third data subset only included leks with observed data for each consecutive year between the first and last year the lek was surveyed (i.e., complete data). We also explored whether males attending leks exhibited lagged responses to wind energy development. There is evidence that measurable effects of oil and gas development on sage-grouse lek counts may take 2–10 years to manifest (Harju et al. 2010). Therefore, we hypothesized that sage-grouse would also exhibit delayed responses to wind energy development. We conducted additional analyses using the full dataset to evaluate potential lags in the effect of wind energy development on lek trends. We considered lags, by shifting the period term to adjust when facilities were considered operational by 1, 3, 5, and 7 years.

We implemented a Bayesian hierarchical state-space model to investigate changes in male sage-grouse lek attendance relative to wind energy development. A state-space model is a dynamic time series model that estimates dependence between a latent state and observed data. We constructed state-space models similar to that described by Green et al. (2017), who used a state-space model to estimate changes in male sage-grouse lek attendance in response to oil and gas development:

Let $y_{i,t}$ be the observed maximum male lek-count data for lek $i = 1, \ldots n$ and year $t = 1, \ldots, T_i$, where n is the total number of leks and T_i is the number of years between the last measured year and the first measured year for lek i. Let $N_{i,t}$ denote the unobserved true number of males for lek i and year t. We assume the observed maximum male lek-counts follows a Poisson distribution conditional on the true male count, that is,

$$y_{i,t}|N_{i,t} \sim Pois(N_{i,t}).$$

We model the unobserved true male counts in year 1, $N_{i,1}$, as

$$\log(N_{i,1}) \sim Normal\left(\mu_1, \sigma_1^2\right),$$

where $\mu_1$and σ_1^2 are fixed parameters set to the mean and variance of the log of maximum male counts in year 1 across all leks. We modeled $N_{i,t}$ for $t > 1$ as

$$\log(N_{i,t})|N_{i,t-1}, x_{it}, \beta_{0i}, \ \beta, \ \sigma_r^2 \sim Normal\left(\log(N_{i,t-1}) + \beta_{0i} + x'_{i,t}\beta, \ \sigma_r^2\right),$$

where β_{0i} is the random intercept for the wind facility nearest to lek i, $x'_{i,t}$ is the row vector of covariates for lek i at year t, β is the column vector of regression coefficients, and σ_r^2 is the variance on the intrinsic growth rate. With this formulation, the mean intrinsic rate of growth is $\beta_{0i} + x'_{i,t}\beta$ for lek i and year t. We modeled the random intercept as

$$\beta_{0i}|\mu_\beta, \ \sigma_\beta^2 \sim Normal\left(\mu_\beta, \ \sigma_\beta^2\right)$$

$$\mu_\beta \sim Normal(0,\ 1)$$

$$\sigma_\beta^2 \sim Inverse\ Gamma(1,\ 1).$$

We modeled the regression coefficients as $\beta \sim MVN(0,\ I)$, where MVN stands for the multivariate normal distribution, and I is the identity matrix. We modeled the intrinsic growth rate variance as

$$\sigma_r^2 \sim Inverse\ Gamma(1, 1).$$

We implemented a Metropolis-within-Gibbs Markov chain Monte Carlo (MCMC) sampling algorithm to sample from the posterior distribution. Evidence of convergence appeared within 5,000 iterations; hence, we ran the MCMC chain for 10,000 iterations and discarded the first 5,000 as burn-in. We assessed model fit through posterior predictive checks (Gelman et al. 2014, Conn et al. 2018). Specifically, we visualized the observed maximum male count versus the predicted male count, where predictions were simulated from the posterior distribution of the model. All analysis code was written in R version 4.1.3 (R Core Team 2022).

Because the state-space model is dependent on data from the previous time step, it requires observations for each consecutive time step. Often, leks are not surveyed each consecutive year due to resource or access constraints. Due to the Bayesian nature of the state-space model, missing data are treated as additional parameters to be estimated by the model. With our MCMC sampling approach, we handled missing lek count data by sampling from the posterior predictive distribution of the missing data given the observed data (Reich and Gosh 2019). We assumed that missing lek count data in the full data and the at most 20% missing data subset were missing at random (Little and Rubin 2019). For each lek, we imputed lek count data for missed survey years between the first surveyed year and the last surveyed year (i.e., we did not extrapolate beyond the first and last surveyed years in our imputation approach). For t^* where y_{it^*} is missing, the posterior predictive distribution is

$$y_{it^*}|N_{it^*} \sim Pois(N_{it^*}),$$

which is conditional on the current sampled value for N_{it^*}. Since missing data are treated as additional parameters, we imputed 5,000 values for each missing data point. The advantage of incorporating a multiple imputation approach for missing lek count data is that it allows for an increased sample size for analysis. If restricted to complete data only, we would greatly reduce the number of leks included. Furthermore, due to the Bayesian nature of the algorithm, our posterior estimates for the regression coefficients incorporated the uncertainty associated with the missing data multiple imputation approach. Hence, we appropriately represent the uncertainty in our analysis that arose from leks not being surveyed each year. The uncertainty associated with the regression coefficients in the presence of missing data will be larger than with complete data, though some of the uncertainty may be offset through the increased sample size attained when including leks with some missing data.

RESULTS

The average percent missing data per lek in the full dataset was 16.6% (min–max = 0– 50%) and in the at most 20% missing data subset was 8.4% (min–max = 0–20%; Figures A3–A5). The full lek dataset consisted of 78 leks located within 15 km of the 10 wind energy facilities and included 288 counts before and 845 counts after development (Table 1; Figures 1 and 2). The average distance of a lek to the nearest turbine was 6.54 km (min–max = 0.23–14.96 km) and the number of turbines within buffers that we assessed averaged 0.35 within 1.0 km (min–max = 0–8), and up to 48 within 10.0 km (min–max = 0–202) across all wind energy facilities (Table 2; Figure 3).

In the full lek data analysis (78 total leks), the percent of sagebrush within 6.4 km was not a meaningful predictor of male sage-grouse lek counts (β = 0.17, 95% credible interval = −0.26 to 0.57). Therefore, we excluded the percent of sagebrush covariate from additional models. Posterior estimates (mean and 95% credible interval) of

TABLE 1 Number of greater sage-grouse leks within 15 km of a wind turbine and number of yearly counts before and after development of wind energy facilities in southwest and south-central Wyoming, USA from 2000 to 2020.

Wind energy facility	Number of leks	Counts before development	Counts after development
Dunlap Ranch	6	48	38
Evanston	12	20	177
Campbell Hill, Glenrock, Rolling Hills, Top of the Worldpower[a]	29	99	272
Medicine Bow	6	0	98
Mountain Wind I and II	11	51	108
Rock River 1	3	6	44
Seven Mill Hill	11	64	108
All facilities	78	288	845

[a]Campbell Hill (operational in 2009), Glenrock (operational in 2008), Rolling Hills (operational in 2009), and Top of the World Windpower (operational in 2010) facilities were in close proximity, so sage-grouse lek counts were assigned to periods of before or after development based on the nearest facility to each lek.

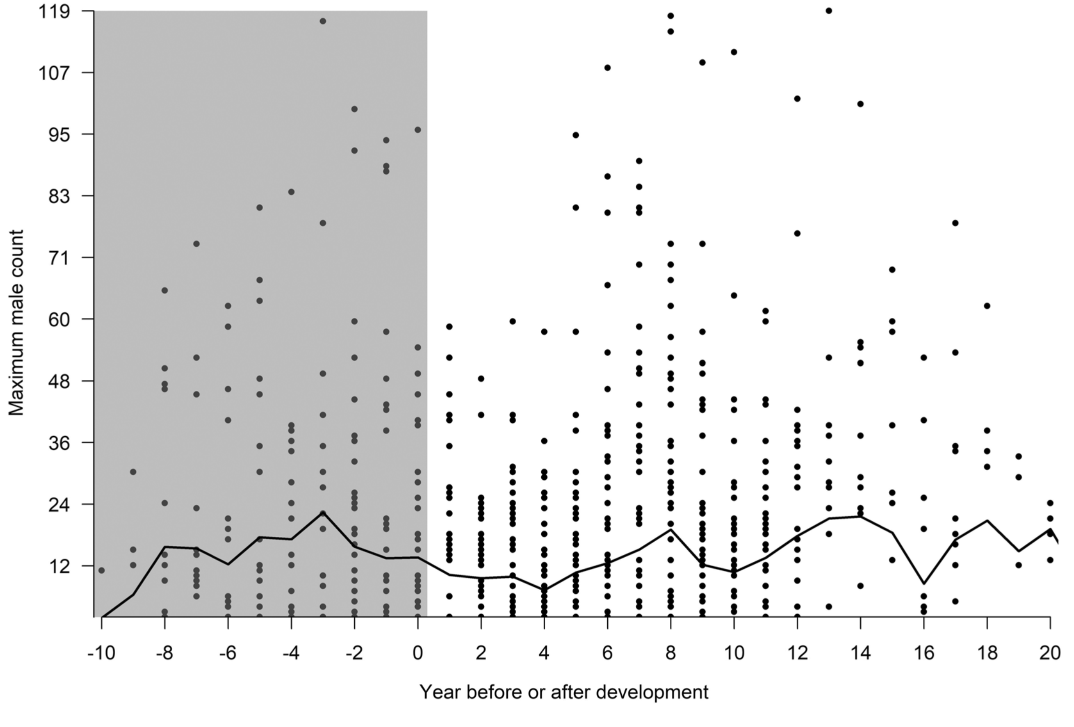

FIGURE 1 Lek counts of male greater sage-grouse within 15 km of wind energy facilities up to 10 years before (gray) and up to 20 years after (white) development in southwest and south-central Wyoming, USA, from 2000 to 2020. The solid line depicts the trend in average male sage-grouse maximum lek counts (n = 78 leks) over the study period.

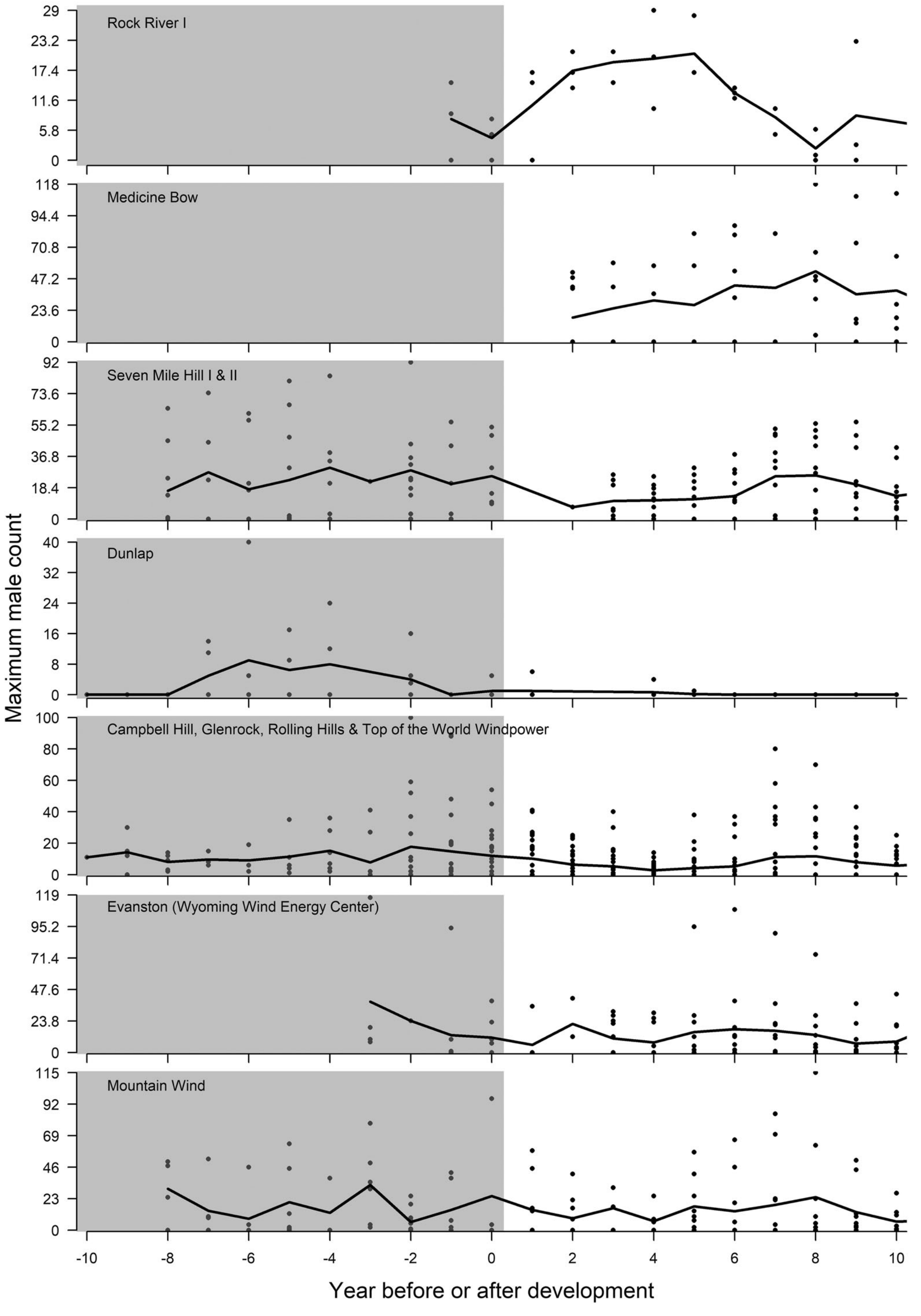

FIGURE 2 Lek counts of male greater sage-grouse within 15 km of each wind energy facility up to 10 years before (gray) and up to 20 years after (white) development used to assess responses in lek counts from 2000 to 2020 in southwest and south-central Wyoming, USA. Solid lines depict the trends in average male sage-grouse maximum lek counts ($n = 78$ total leks) over the study period.

TABLE 2 Average percent sagebrush within 6.4 km, average distance to nearest turbine (km; min-max in parentheses), and average number of turbines within 1.0, 2.0, 4.0, 6.0, 8.0, and 10.0 km of leks (range in parentheses) at wind energy facilities in southwest and south-central Wyoming, USA from 2000 to 2020.

Wind energy facility	Percent sagebrush (6.4 km)	Nearest turbine (km)	Count of Turbines (1.0 km)	Count of Turbines (2.0 km)	Count of Turbines (4.0 km)	Count of Turbines (6.0 km)	Count of Turbines (8.0 km)	Count of Turbines (10.0 km)
Dunlap Ranch	7.07 (5.03–9.82)	6.34 (0.79–10.38)	1 (0–5)	5 (0–19)	14 (0–54)	21 (0–74)	24 (0–74)	30 (0–74)
Evanston	13.59 (9.32–20.37)	7.79 (1.06–14.96)	0 (0–0)	1 (0–6)	1 (0–15)	5 (0–37)	11 (0–37)	21 (0–63)
Campbell Hill, et al.[a]	6.22 (4.34–9.54)	5.18 (0.45–14.17)	0 (0–3)	2 (0–15)	15 (0–62)	34 (0–103)	58 (0–150)	83 (0–202)
Medicine Bow	11.91 (9.45–14.79)	8.48 (4.51–11.10)	0 (0–0)	0 (0–0)	0 (0–0)	3 (0–9)	3 (0–9)	7 (0–22)
Mountain Wind I and II	12.49 (5.27–17.69)	8.61 (0.23–14.71)	1 (0–8)	2 (0–21)	7 (0–61)	11 (0–67)	16 (0–67)	23 (0–67)
Rock River 1	11.03 (9.27–12.37)	4.55 (2.30–9.03)	0 (0–0)	0 (0–0)	20 (0–44)	39 (0–68)	54 (0–113)	69 (17–113)
Seven Mill Hill	14.24 (9.03–20.29)	6.25 (0.53–13.92)	1 (0–6)	3 (0–17)	11 (0–47)	18 (0–70)	30 (0–79)	40 (0–79)
All facilities	10.40 (3.09–20.37)	6.54 (0.23–14.96)	0.35 (0–8)	1.86 (0–21)	10.20 (0–62)	33.73 (0–150)	33.70 (0–150)	48.67 (0–202)

[a]Campbell Hill (operational in 2009), Glenrock (operational in 2008), Rolling Hills (operational in 2009), and Top of the World Windpower (operational in 2010) facilities were in close proximity, so sage-grouse lek counts were assigned to periods of before or after development based on the nearest facility to each lek.

the main effects and interaction regression coefficients in each of the wind energy covariate models were not predictive of sage-grouse lek trends in any of the models (i.e., all 95% credible intervals contained 0; Table 3, Figure 4). Posterior predictive checks for a sample of 4 leks from the model with turbine distance as the wind covariate demonstrated the high level of uncertainty associated with predicting lek counts in the presence of missing data (Figure A6).

Using the dataset that contained no more than 20% missing lek data (47 total leks), the percent of sagebrush within 6.4 km was not a meaningful predictor (β = 0.16, 95% credible interval = −0.27 to 0.59) and was therefore excluded from additional models. In addition, no models contained regression coefficients where 95% credible intervals did not overlap zero (Appendix A, Table A1). Posterior predictive checks for a sample of 4 leks from the model with turbine distance as the wind covariate demonstrated uncertainty in predicted lek counts reflected by the level of missing data (Figure A7).

We found a similar relationship with the complete case lek data analysis (16 total leks), where the percent of sagebrush was not a meaningful predictor (β = 0.07, 95% credible interval = −0.48 to 0.67) and no turbine models had meaningful regression coefficients based on 95% credible intervals (Appendix A, Table A2). The posterior predictive checks for a sample of 4 leks with turbine distance as the covariate demonstrated uncertainty in the predicted lek counts was small compared to that associated with leks with missing data (Figure A8). No turbine covariate, period, or interactions terms were predictive of sage-grouse lek trends in 1-, 3-, 5-, or 7-year lag models (Appendix A, Tables A3–A6).

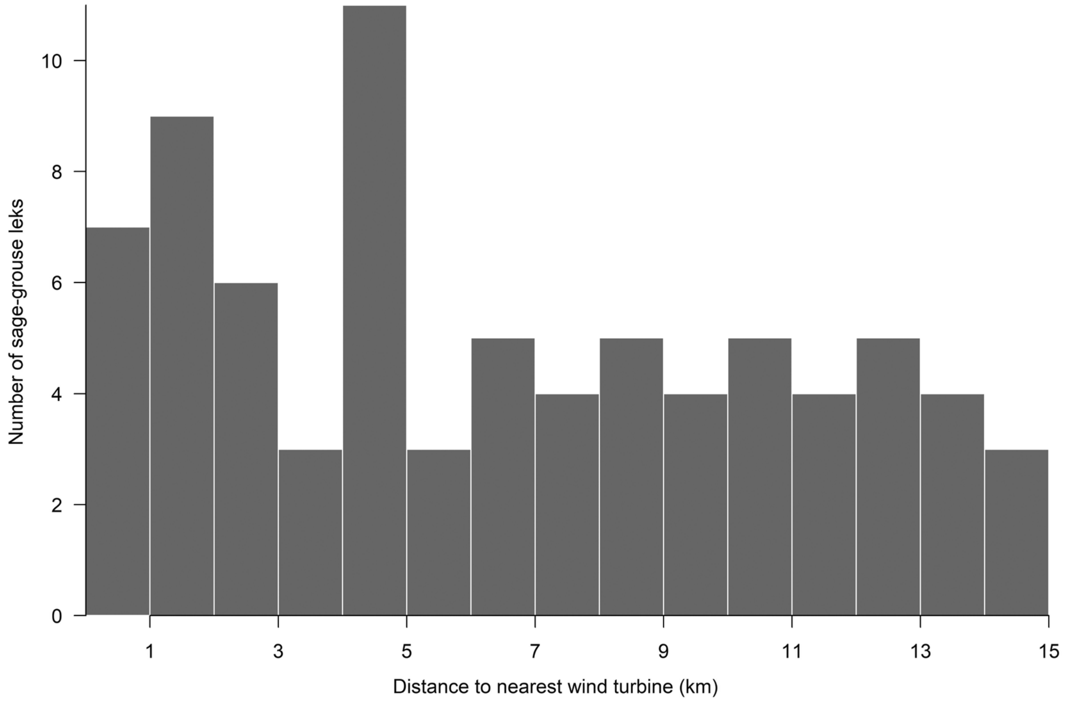

FIGURE 3 Number of greater sage-grouse leks (*n* = 78) in relation to distance to wind turbines, Wyoming, USA, 2000–2020.

We found no evidence of lack of model fit based on posterior predictive checks. We supplied a sample of trace plots demonstrating convergence by 5,000 iterations for the regression coefficients and random wind facility effect terms for each of the 3 datasets (Appendix A, Figures A9–A14).

DISCUSSION

Based on findings from other studies evaluating sage-grouse population responses to oil and gas development (Walker et al. 2007, Harju et al. 2010, Gregory and Beck 2014), we expected that trends in male lek attendance would experience a delayed negative response following development of wind energy facilities. However, we failed to detect a relationship between male sage-grouse lek attendance and proximity to or density of wind turbines up to 10 years following development, and these results were consistent across the 3 related datasets that we evaluated, which were intended to address potential uncertainty with inconsistent lek counts. Our results suggested that sage-grouse may respond differently to wind energy compared to other types of energy development, in particular oil and natural gas development, where near ubiquitous support for negative responses to sage-grouse populations have been identified (e.g., Naugle et al. 2011).

Negative trends in sage-grouse populations indexed by lek counts have been associated with oil and natural gas well pad densities across a range of scales. For instance, lek counts or lek persistence was negatively associated with greater than 1, 3, 12, and 6 well pads within 0.4, 1.0, 3.2, and 10.0 km of a lek, respectively (Doherty et al. 2010, Harju et al. 2010, Hess and Beck 2012, Gregory and Beck 2014). Other studies have found similar relationships with lek attendance and well pad density within 0.8 km–3.2 km from leks (Walker et al. 2007, Harju et al. 2010, Dinkins et al. 2021). In contrast, we failed to detect a trend in male lek counts when the number of

TABLE 3 Posterior estimates and 95% credible intervals (CI; in parentheses) of regression coefficients in full data models evaluating the effect of wind energy on male sage-grouse lek counts in southwest and south-central Wyoming, USA, from 2000 to 2020. Each model included a covariate describing wind energy development, period (before or after development), and an interaction term.

Model and covariate	Mean (95% CI)	Mean (95% CI)
Distance to turbine		
Distance to turbine	−0.08 (−0.58, 0.42)	--
Period	−0.21 (−0.63, 0.18)	--
Interaction	0.21 (−0.30, 0.73)	--
	Count of turbines	Turbine distribution
Turbines within 1.0 km		
$\text{Turbines}_{1.0\text{km}}$	0.05 (−0.41, 0.49)	−0.09 (−0.53, 0.33)
Period	−0.18 (−0.64, 0.30)	−0.21 (−0.62, 0.21)
Interaction	−0.10 (−0.65, 0.42)	0.20 (−0.26, 0.65)
Turbines within 2.0 km		
$\text{Turbines}_{2.0\text{km}}$	0.12 (−0.27, 0.52)	−0.07 (−0.55, 0.47)
Period	−0.20 (−0.60, 0.22)	−0.18 (−0.59, 0.28)
Interaction	−0.22 (−0.64, 0.22)	0.20 (−0.37, 0.71)
Turbines within 4.0 km		
$\text{Turbines}_{4.0\text{km}}$	0.13 (−0.32, 0.53)	−0.07 (−0.55, 0.44)
Period	−0.23 (−0.63, 0.15)	−0.23 (−0.68, 0.22)
Interaction	−0.27 (−0.71, 0.17)	0.19 (−0.29, 0.69)
Turbines within 6.0 km		
$\text{Turbines}_{6.0\text{km}}$	0.10 (−0.35, 0.54)	−0.04 (−0.53, 0.43)
Period	−0.21 (−0.60, 0.20)	−0.23 (−0.63, 0.19)
Interaction	−0.25 (−0.71, 0.19)	0.13 (−0.35, 0.64)
Turbines within 8.0 km		
$\text{Turbines}_{8.0\text{km}}$	0.08 (−0.47, 0.58)	−0.08 (−0.61, 0.43)
Period	−0.20 (−0.59, 0.18)	−0.20 (−0.60, 0.26)
Interaction	−0.21 (−0.70, 0.28)	0.20 (−0.31, 0.75)
Turbines within 10.0 km		
$\text{Turbines}_{10.0\text{km}}$	−0.01 (−0.65, 0.65)	−0.07 (−0.63, 0.48)
Period	−0.28 (−0.79, 0.29)	−0.21 (−0.66, 0.26)
Interaction	−0.14 (−0.84, 0.48)	0.18 (−0.41, 0.76)

turbines across scales that we assessed averaged 0.35 within 1.0 km (min–max = 0–8) and up to 48 within 10.0 km (min–max = 0–202).

Our ability to detect slight changes in trends was potentially limited by relatively small sample sizes and the presence of missing data. LeBeau et al. (2017*b*) determined that the number of leks included in their longitudinal

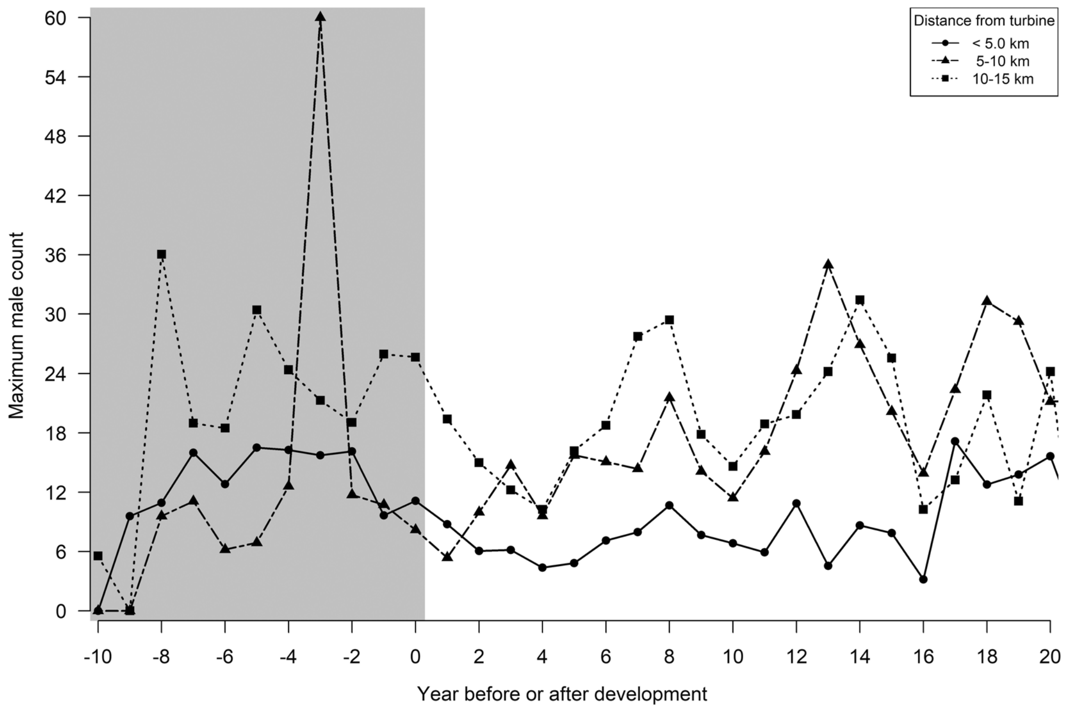

FIGURE 4 Average male greater sage-grouse lek counts before (up to 10 years before development, gray) and after development (up to 20 years after development, white) of wind energy facilities for leks located less than 5 km, 5–10 km, and 10–15 km from a wind turbine, respectively, southwest and south-central Wyoming, USA, 2000–2020.

dataset was the main factor influencing statistical power to detect changes. For example, an 11-year dataset including 14 leks with missing data (9%) and time lag effects (2 years post-development) had an 80% power to detect a 20% change in trends (LeBeau et al. 2017*b*). A similar pattern was observed in our dataset where we did not find statistically significant effects from wind energy development. This is likely a result of small changes in male lek count data over our study period and our ability to detect those changes. Our analysis did contain more missing data but by analyzing 3 different datasets and incorporating a Bayesian multiple imputation approach to estimate missing lek data, we were able to reduce the uncertainty associated with imputing the missing lek count data. The multiple imputation approach estimates the missing data along with regression coefficients and other model parameters, creating a posterior distribution for the missing maximum male lek counts. Hence, our model captures the uncertainty associated with imputing the missing lek count data, and this uncertainty is incorporated when estimating the regression coefficients. The imputation of missing data, sample size, and longitudinal nature of this dataset allowed us to statistically evaluate changes in trends of male lek counts. The main results from our evaluation of turbine distance, density, or distribution on male sage-grouse lek counts did not differ, regardless of whether we considered 78, 47, or 16 leks. This point supports our findings, which were similar regardless of the sample size of leks available for analysis.

Differences in the physical footprint and amount of human activity between oil and gas and wind energy development may partially explain the lack of population level responses that have been observed by sage-grouse relative to wind energy development. Direct habitat loss and density of infrastructure per unit area is similar between oil and gas and wind energy development (Jones and Pejchar 2013), but there are more oil and gas fields than wind energy facilities. For example, there were 61,082 well pads across Wyoming as of 2014 (Gamo and

Beck 2017) and 1,456 wind turbines in Wyoming as of 2022 (Hoen et al. 2018). Furthermore, the average wind energy facility in this study contained 67 turbines, whereas the number of oil and gas wells or well pads at facilities can be much greater. For example, there were approximately 600 wells at one field where the effects of development on sage-grouse was evaluated (Kirol et al. 2015). Human activity is often greater near oil and gas development compared to wind energy facilities. During the production phases of natural gas development, vehicular traffic may reach up to 75 vehicles per hour (Ingelfinger and Anderson 2004), whereas traffic levels at one wind energy facility was an order of magnitude less (Smith et al. 2020). The amount of industrial activity associated with oil and gas development has been negatively related to sage-grouse space use during winter (Holloran et al. 2015) and during the breeding season (Walker 2022). Therefore, it is plausible that levels of human activity could provide a partial explanation for our findings. Future research will be necessary to better isolate the effects of infrastructure and levels of industrial activity on wildlife responses.

Although our study lacked data to evaluate resource selection and demography in response to wind energy infrastructure, studies evaluating these effects in association with energy development provide further support for our findings. Negative responses by sage-grouse have been consistently associated with direct loss of habitat and increased human activity resulting from oil and natural gas development. Impacts included displacement and increased stress on males attending leks (Blickley et al. 2012*a*, *b*), lower nest initiation rates (Lyon and Anderson 2003), reduced nest and brood survival (Kirol et al. 2020), and lower survival and recruitment of yearling grouse (Holloran et al. 2010). Avoidance of wind energy infrastructure during the breeding season may result in indirect habitat loss (LeBeau et al. 2017*a*), nonetheless avoidance may not translate to detectable population level impacts (LeBeau et al. 2017*b*, current study). Other studies evaluating the effects of wind energy development on prairie grouse support these conclusions (Lloyd et al. 2022, LeBeau et al. 2023).

That we failed to detect a relationship between male sage-grouse lek attendance and wind energy infrastructure does not indicate that sage-grouse are compatible with this form of energy development. Although we do not know if siting decisions were intentional, the 10 wind facilities that we evaluated could have minimized impacts to sage-grouse by building turbines away from known leks in relatively clustered distributions. There is evidence that leks may remain active in oil and gas fields when infrastructure is clustered to maintain undeveloped areas surrounding a lek (Doherty et al. 2010). In our study, most wind turbines were clustered in this way and only approximately 20% of the leks used in our analyses were within 2.0 km of a turbine. Of the 3 leks with a low turbine distribution value, signifying a relatively uniform distribution of turbines surrounding the lek, 2 had male lek counts of zero beginning 4 to 10 years after development and one had persistent counts of zero beginning one year before development. Additional research is needed to evaluate whether infrastructure siting can minimize impacts to sage-grouse.

The current approach to managing sage-grouse with respect to wind energy development in Wyoming is to restrict development in Core Areas (State of Wyoming 2019), and all but one of the wind energy facilities we evaluated (Medicine Bow) was located outside of Core Areas. In contrast, oil and natural gas development is allowed in Core Areas if restrictions intended to limit habitat disturbance are met. An important note is that some wind energy facilities that we evaluated were developed prior to the implementation of Core Areas and in some cases Core Area boundaries were modified to exclude previous development (Gamo and Beck 2017). Nonetheless, Wyoming's Core Areas contain the highest breeding population densities of sage-grouse in the state (Doherty et al. 2011) and contain large areas of connected sagebrush habitats necessary to support sage-grouse populations (Burkhalter et al. 2018). Our study evaluated the response of low-density, peripheral populations of sage-grouse (the average maximum male count at all leks in 2020 was approximately 10) to wind energy development outside or near the edge of Core Areas. As such, our results cannot be extended to Core Areas where sage-grouse population densities are typically higher. To effectively manage wind energy development in sagebrush habitats in a manner that is sustainable for sage-grouse, research that builds upon current knowledge will be necessary to understand responses in areas with higher breeding densities of sage-grouse.

MANAGEMENT IMPLICATIONS

We did not detect negative effects of wind turbines within 15 km on counts of male sage-grouse at leks outside Core Areas for up to 10 years following development. Our findings were based on the average lek in our analysis being 6.5 km from a wind turbine (approximately 80% of leks were greater than 2.0 km from a turbine) and most turbines were clustered such that undisturbed habitat surrounding leks remained. Nonetheless, direct habitat removal and fragmentation resulting from any form of energy development is unlikely to benefit sage-grouse populations. Therefore, managers should use caution if applying our findings to placement of future wind energy facilities, especially in areas with higher densities of breeding sage-grouse and when considering potential impacts to other species of conservation importance. Given the importance of understanding sage-grouse responses to anthropogenic activities, we recommend that managers count leks annually to limit the need for data imputation in future studies.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

ETHICS STATEMENT

Our research used observational sage-grouse lek count data from the Wyoming Game and Fish Department.

DATA AVAILABILITY STATEMENT

Data available on request from the authors.

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APPENDIX A: MODEL RESULTS FROM DATA SUBSETS (AT MOST 20% MISSING LEK COUNT DATA AND NO MISSING DATA) AND 1, 3, 5, AND 7-YEAR TIME LAGS IN SAGE-GROUSE RESPONSES TO WIND ENERGY DEVELOPMENT

TABLE A1 Posterior estimates and 95% credible intervals (CI; in parenthesis) of regression coefficients in data subset (at most 20% missing lek count data) models evaluating the effect of wind energy on male sage-grouse lek counts in southwest and south-central Wyoming, USA, from 2000 to 2020. Each model included a covariate describing wind energy development, period (before or after development), and an interaction term.

Model and covariate	Mean (95% CI)	Mean (95% CI)
Distance to turbine		
Distance to turbine	0.09 (−0.45, 0.65)	--
Period	−0.27 (−0.70, 0.20)	--
Interaction	0.07 (−0.45, 0.64)	--
	Count of turbines	Turbine distribution
Turbines within 1.0 km		
$\text{Turbines}_{1.0\text{km}}$	0.11 (−0.25, 0.49)	0.02 (−0.67, 0.83)
Period	−0.24 (−0.72, 0.22)	−0.24 (−0.75, 0.28)
Interaction	−0.21 (−0.64, 0.22)	0.07 (−0.64, 0.74)
Turbines within 2.0 km		
$\text{Turbines}_{2.0\text{km}}$	0.01 (−0.39, 0.40)	0.09 (−0.50, 0.67)
Period	−0.23 (−0.63, 0.20)	−0.27 (−0.72, 0.20)
Interaction	−0.18 (−0.59, 0.23)	0.06 (−0.52, 0.63)
Turbines within 4.0 km		
$\text{Turbines}_{4.0\text{km}}$	−0.06 (−0.68, 0.50)	0.10 (−0.66, 0.89)
Period	−0.26 (−0.72, 0.23)	−0.31 (−0.84, 0.21)
Interaction	−0.13 (−0.70, 0.45)	0.11 (−0.63, 0.87)
Turbines within 6.0 km		
$\text{Turbines}_{6.0\text{km}}$	−0.17 (−0.89, 0.52)	0.03 (−0.53, 0.60)
Period	−0.26 (−0.73, 0.21)	−0.25 (−0.70, 0.19)
Interaction	−0.08 (−0.74, 0.51)	0.12 (−0.42, 0.65)
Turbines within 8.0 km		
$\text{Turbines}_{8.0\text{km}}$	−0.13 (−0.76, 0.45)	0.12 (−0.53, 0.78)
Period	−0.24 (−0.70, 0.23)	−0.31 (−0.82, 0.20)
Interaction	−0.09 (−0.63, 0.44)	0.06 (−0.57, 0.71)
Turbines within 10.0 km		
$\text{Turbines}_{10.0\text{km}}$	−0.15 (−0.76, 0.48)	0.10 (−0.52, 0.69)
Period	−0.31 (−0.75, 0.17)	−0.26 (−0.74, 0.18)
Interaction	0.02 (−0.59, 0.56)	0.06 (−0.50, 0.66)

TABLE A2 Posterior estimates and 95% credible intervals (CI; in parenthesis) of regression coefficients in complete data subset (no missing lek count data) models evaluating the effect of wind energy on male sage-grouse lek counts in southwest and south-central Wyoming, USA, from 2000 to 2020. Each model included a covariate describing wind energy development, period (before or after development), and an interaction term.

Model and covariate	Mean (95% CI)	Mean (95% CI)
Distance to turbine		
Distance to turbine	−0.29 (−1.05, 0.45)	--
Period	−0.43 (−1.02, 0.23)	--
Interaction	0.26 (−0.37, 0.97)	--
	Count of turbines	Turbine distribution
Turbines within 1.0 km		
$Turbines_{1.0km}$	0.00 (−0.77, 0.81)	−0.26 (−1.15, 0.54)
Period	−0.49 (−1.05, 0.10)	−0.51 (−1.09, 0.06)
Interaction	−0.16 (−0.82, 0.40)	0.39 (−0.34, 1.16)
Turbines within 2.0 km		
$Turbines_{2.0km}$	−0.09 (−1.00, 0.68)	−0.19 (−1.22, 0.84)
Period	−0.57 (−1.23, 0.01)	−0.41 (−1.07, 0.22)
Interaction	−0.08 (−0.70, 0.57)	0.19 (−0.65, 1.08)
Turbines within 4.0 km		
$Turbines_{4.0km}$	−0.23 (−1.15, 0.53)	−0.23 (−1.02, 0.54)
Period	−0.58 (−1.30, 0.03)	−0.46 (−1.06, 0.19)
Interaction	0.06 (−0.64, 0.73)	0.22 (−0.45, 0.95)
Turbines within 6.0 km		
$Turbines_{6.0km}$	−0.23 (−1.11, 0.77)	−0.18 (−1.07, 0.69)
Period	−0.54 (−1.15, 0.03)	−0.46 (−1.11, 0.23)
Interaction	0.08 (−0.74, 0.76)	0.18 (−0.54, 0.97)
Turbines within 8.0 km		
$Turbines_{8.0km}$	−0.10 (−0.97, 0.73)	−0.29 (−1.17, 0.65)
Period	−0.54 (−1.19, 0.08)	−0.47 (−1.09, 0.19)
Interaction	−0.02 (−0.71, 0.70)	0.26 (−0.55, 1.05)
Turbines within 10.0 km		
$Turbines_{10.0km}$	0.02 (−0.93, 0.98)	−0.36 (−1.29, 0.48)
Period	−0.46 (−1.02, 0.08)	−0.46 (−1.23, 0.25)
Interaction	0.00 (−0.76, 0.78)	0.32 (−0.42, 1.16)

TABLE A3 Posterior estimates and 95% credible intervals (CI; in parenthesis) of regression coefficients in full data models evaluating the effect of wind energy on male sage-grouse lek counts with a 1-year lag in southwest and south-central Wyoming, USA, from 2000 to 2020. Each model included a covariate describing wind energy development, period (before or after development), and an interaction term.

Model and covariate	Mean (95% CI)	Mean (95% CI)
Distance to turbine		
Distance to turbine	−0.06 (−0.51, 0.42)	--
Period	−0.11 (−0.55, 0.33)	--
Interaction	0.21 (−0.31, 0.72)	--
	Count of turbines	Turbine distribution
Turbines within 1.0 km		
$\text{Turbines}_{1.0\text{km}}$	0.11 (−0.34, 0.49)	−0.06 (−0.66, 0.57)
Period	−0.09 (−0.55, 0.43)	−0.23 (−0.69, 0.22)
Interaction	−0.20 (−0.66, 0.32)	0.20 (−0.37, 0.77)
Turbines within 2.0 km		
$\text{Turbines}_{2.0\text{km}}$	0.09 (−0.29, 0.48)	−0.02 (−0.69, 0.61)
Period	−0.11 (−0.55, 0.32)	−0.26 (−0.81, 0.30)
Interaction	−0.22 (−0.69, 0.21)	0.18 (−0.48, 0.89)
Turbines within 4.0 km		
$\text{Turbines}_{4.0\text{km}}$	0.10 (−0.35, 0.59)	−0.07 (−0.56, 0.37)
Period	−0.10 (−0.54, 0.37)	−0.13 (−0.53, 0.26)
Interaction	−0.31 (−0.81, 0.20)	0.16 (−0.33, 0.63)
Turbines within 6.0 km		
$\text{Turbines}_{6.0\text{km}}$	0.06 (−0.52, 0.65)	−0.03 (−0.56, 0.50)
Period	−0.08 (−0.63, 0.45)	−0.23 (−0.65, 0.22)
Interaction	−0.29 (−0.89, 0.28)	0.17 (−0.37, 0.73)
Turbines within 8.0 km		
$\text{Turbines}_{8.0\text{km}}$	0.12 (−0.37, 0.61)	−0.08 (−0.63, 0.45)
Period	−0.05 (−0.50, 0.44)	−0.23 (−0.68, 0.22)
Interaction	−0.30 (−0.78, 0.22)	0.17 (−0.41, 0.74)
Turbines within 10.0 km		
$\text{Turbines}_{10.0\text{km}}$	0.03 (−0.38, 0.46)	−0.03 (−0.65, 0.57)
Period	−0.12 (−0.57, 0.30)	−0.22 (−0.68, 0.28)
Interaction	−0.16 (−0.62, 0.26)	0.13 (−0.50, 0.71)

TABLE A4 Posterior estimates and 95% credible intervals (CI; in parenthesis) of regression coefficients in full data models evaluating the effect of wind energy on male sage-grouse lek counts with a 3-year lag in southwest and south-central Wyoming, USA, from 2000 to 2020. Each model included a covariate describing wind energy development, period (before or after development), and an interaction term.

Model and covariate	Mean (95% CI)	Mean (95% CI)
Distance to turbine		
Distance to turbine	−0.10 (−0.60, 0.41)	--
Period	−0.01 (−0.51, 0.53)	--
Interaction	0.35 (−0.23, 0.95)	--
	Count of turbines	Turbine distribution
Turbines within 1.0 km		
$\text{Turbines}_{1.0\text{km}}$	0.08 (−0.30, 0.46)	0.00 (−0.64, 0.65)
Period	−0.07 (−0.53, 0.40)	−0.22 (−0.67, 0.26)
Interaction	−0.19 (−0.70, 0.31)	0.15 (−0.40, 0.73)
Turbines within 2.0 km		
$\text{Turbines}_{2.0\text{km}}$	0.12 (−0.23, 0.44)	−0.08 (−0.63, 0.49)
Period	0.01 (−0.41, 0.46)	−0.25 (−0.69, 0.21)
Interaction	−0.31 (−0.77, 0.12)	0.19 (−0.38, 0.75)
Turbines within 4.0 km		
$\text{Turbines}_{4.0\text{km}}$	0.14 (−0.28, 0.55)	−0.05 (−0.61, 0.50)
Period	−0.04 (−0.53, 0.45)	−0.26 (−0.71, 0.26)
Interaction	−0.40 (−0.94, 0.16)	0.19 (−0.37, 0.77)
Turbines within 6.0 km		
$\text{Turbines}_{6.0\text{km}}$	0.11 (−0.30, 0.58)	−0.10 (−0.74, 0.45)
Period	−0.01 (−0.49, 0.49)	−0.20 (−0.71, 0.30)
Interaction	−0.40 (−0.93, 0.16)	0.26 (−0.32, 0.90)
Turbines within 8.0 km		
$\text{Turbines}_{8.0\text{km}}$	0.07 (−0.42, 0.59)	−0.07 (−0.51, 0.36)
Period	−0.07 (−0.61, 0.47)	−0.21 (−0.62, 0.22)
Interaction	−0.32 (−0.87, 0.26)	0.18 (−0.30, 0.66)
Turbines within 10.0 km		
$\text{Turbines}_{10.0\text{km}}$	0.06 (−0.39, 0.57)	−0.07 (−0.60, 0.44)
Period	−0.01 (−0.51, 0.46)	−0.21 (−0.62, 0.24)
Interaction	−0.25 (−0.82, 0.28)	0.17 (−0.39, 0.74)

TABLE A5 Posterior estimates and 95% credible intervals (CI; in parenthesis) of regression coefficients in full data models evaluating the effect of wind energy on male sage-grouse lek counts with a 5-year lag in southwest and south-central Wyoming, USA, from 2000 to 2020. Each model included a covariate describing wind energy development, period (before or after development), and an interaction term.

Model and covariate	Mean (95% CI)	Mean (95% CI)
Distance to turbine		
Distance to turbine	0.03 (−0.31, 0.41)	--
Period	−0.04 (−0.48, 0.43)	--
Interaction	0.13 (−0.37, 0.62)	--
	Count of turbines	Turbine distribution
Turbines within 1.0 km		
$\text{Turbines}_{1.0\text{km}}$	0.00 (−0.31, 0.32)	−0.04 (−0.83, 0.74)
Period	−0.02 (−0.55, 0.52)	−0.19 (−0.68, 0.35)
Interaction	−0.05 (−0.58, 0.47)	0.17 (−0.45, 0.85)
Turbines within 2.0 km		
$\text{Turbines}_{2.0\text{km}}$	−0.02 (−0.40, 0.37)	−0.11 (−0.68, 0.44)
Period	−0.05 (−0.62, 0.57)	−0.20 (−0.64, 0.22)
Interaction	−0.13 (−0.76, 0.49)	0.23 (−0.29, 0.78)
Turbines within 4.0 km		
$\text{Turbines}_{4.0\text{km}}$	−0.04 (−0.40, 0.31)	−0.10 (−0.59, 0.40)
Period	−0.06 (−0.54, 0.41)	−0.21 (−0.68, 0.24)
Interaction	−0.18 (−0.70, 0.33)	0.25 (−0.25, 0.71)
Turbines within 6.0 km		
$\text{Turbines}_{6.0\text{km}}$	−0.05 (−0.47, 0.34)	−0.03 (−0.59, 0.46)
Period	−0.07 (−0.58, 0.44)	−0.23 (−0.65, 0.21)
Interaction	−0.16 (−0.71, 0.42)	0.14 (−0.38, 0.71)
Turbines within 8.0 km		
$\text{Turbines}_{8.0\text{km}}$	−0.03 (−0.43, 0.42)	−0.05 (−0.52, 0.44)
Period	−0.10 (−0.60, 0.41)	−0.19 (−0.61, 0.28)
Interaction	−0.18 (−0.74, 0.36)	0.17 (−0.37, 0.68)
Turbines within 10.0 km		
$\text{Turbines}_{10.0\text{km}}$	−0.01 (−0.42, 0.38)	−0.07 (−0.59, 0.47)
Period	−0.05 (−0.56, 0.47)	−0.24 (−0.73, 0.22)
Interaction	−0.16 (−0.66, 0.35)	0.18 (−0.34, 0.73)

TABLE A6 Posterior estimates and 95% credible intervals (CI; in parenthesis) of regression coefficients in full data models evaluating the effect of wind energy on male sage-grouse lek counts with a 7-year lag in southwest and south-central Wyoming, USA, from 2000 to 2020. Each model included a covariate describing wind energy development, period (before or after development), and an interaction term.

Model and covariate	Mean (95% CI)	Mean (95% CI)
Distance to turbine		
Distance to turbine	0.09 (−0.34, 0.52)	--
Period	−0.14 (−0.80, 0.49)	--
Interaction	0.13 (−0.55, 0.77)	--
	Count of turbines	Turbine density
Turbines within 1.0 km		
$Turbines_{1.0km}$	−0.01 (−0.30, 0.28)	−0.07 (−0.72, 0.54)
Period	−0.05 (−0.62, 0.50)	−0.19 (−0.64, 0.25)
Interaction	−0.02 (−0.63, 0.56)	0.22 (−0.38, 0.80)
Turbines within 2.0 km		
$Turbines_{2.0km}$	−0.03 (−0.37, 0.28)	−0.06 (−0.59, 0.45)
Period	−0.10 (−0.69, 0.46)	−0.17 (−0.60, 0.30)
Interaction	−0.09 (−0.74, 0.54)	0.16 (−0.38, 0.71)
Turbines within 4.0 km		
$Turbines_{4.0km}$	−0.09 (−0.38, 0.23)	−0.05 (−0.61, 0.52)
Period	−0.11 (−0.63, 0.41)	−0.24 (−0.71, 0.24)
Interaction	−0.09 (−0.69, 0.47)	0.20 (−0.37, 0.77)
Turbines within 6.0 km		
$Turbines_{6.0km}$	−0.09 (−0.42, 0.28)	−0.11 (−0.65, 0.41)
Period	−0.09 (−0.61, 0.45)	−0.21 (−0.66, 0.30)
Interaction	−0.10 (−0.70, 0.49)	0.27 (−0.29, 0.84)
Turbines within 8.0 km		
$Turbines_{8.0km}$	−0.09 (−0.55, 0.32)	−0.03 (−0.54, 0.48)
Period	−0.14 (−0.75, 0.47)	−0.25 (−0.66, 0.18)
Interaction	−0.14 (−0.81, 0.54)	0.14 (−0.38, 0.64)
Turbines within 10.0 km		
$Turbines_{10.0km}$	−0.03 (−0.46, 0.36)	−0.09 (−0.60, 0.44)
Period	−0.15 (−0.77, 0.43)	−0.20 (−0.63, 0.27)
Interaction	−0.15 (−0.79, 0.44)	0.21 (−0.33, 0.78)

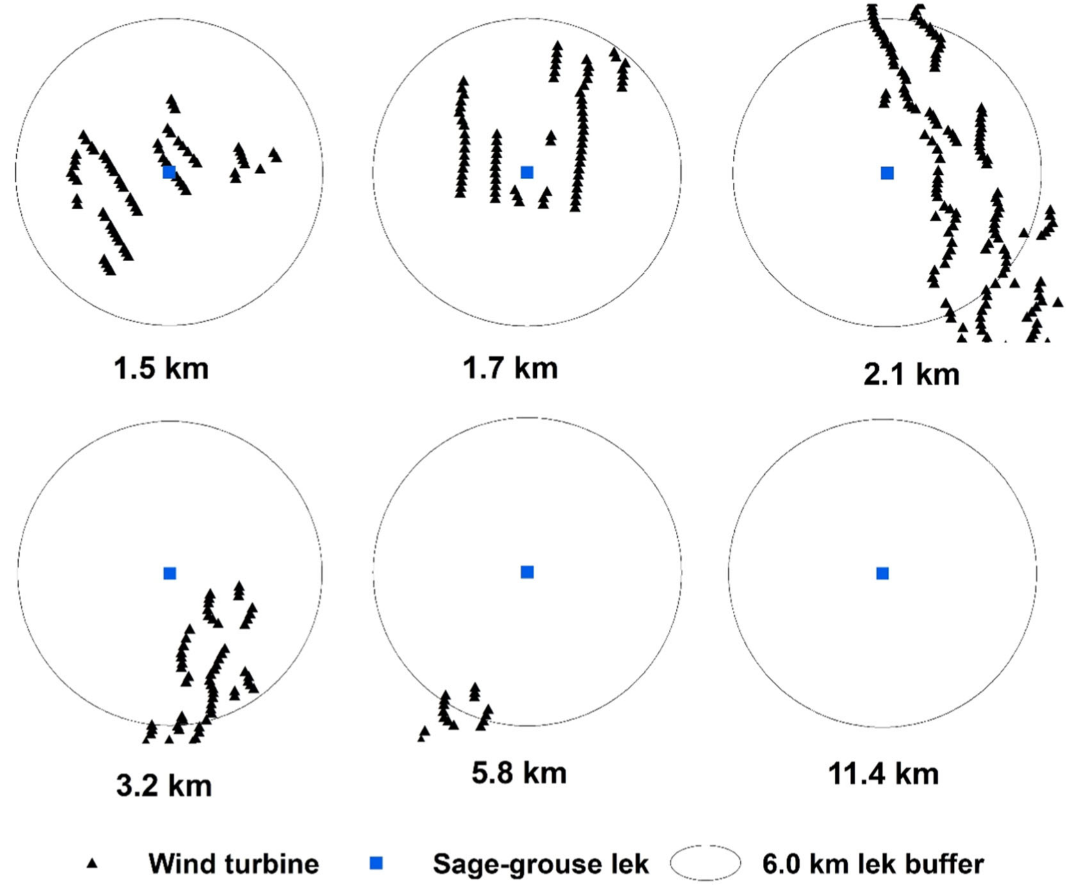

FIGURE A1 Examples of the spatial configuration of wind turbines within 6.0 km of a sage-grouse lek in southwest and south-central Wyoming, USA, from 2000 to 2020. Numbers below each lek correspond to the turbine distribution metric which was equal to the average Euclidean distance to a wind turbine within each buffer of a lek used to evaluate the response of sage-grouse to wind energy facilities. Low mean Euclidean distance values indicated that the average location within each buffer surrounding a lek were relatively close to turbines (uniform distribution of turbines surrounding a lek); intermediate values indicated that turbines were relatively clumped within buffers surrounding a lek; large values indicated that turbines were largely absent from buffers surrounding a lek.

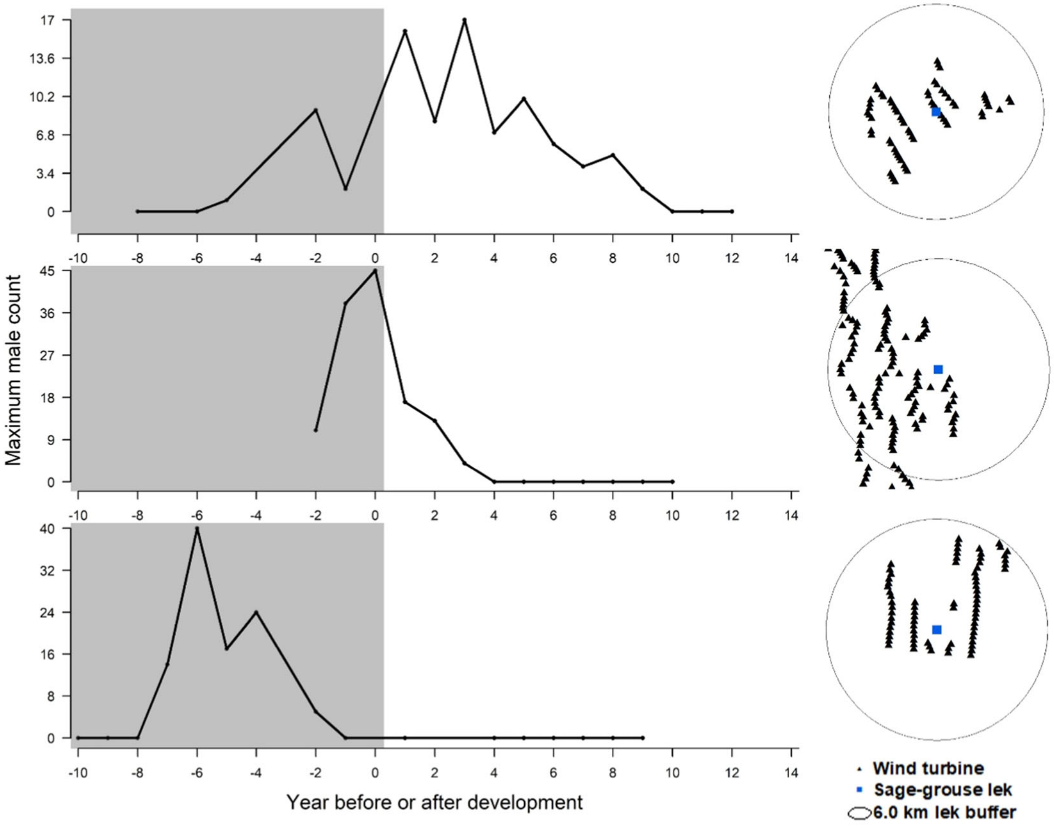

FIGURE A2 Greater sage-grouse leks in southwest and south-central Wyoming, USA, during 2000 to 2020, that had turbine distribution within 6.0-km values less than 1.7. This value indicates that the average location within the 6.0-km lek buffer was within 1.7 km of a turbine and represents the only 3 leks in our study that were surrounded by turbines.

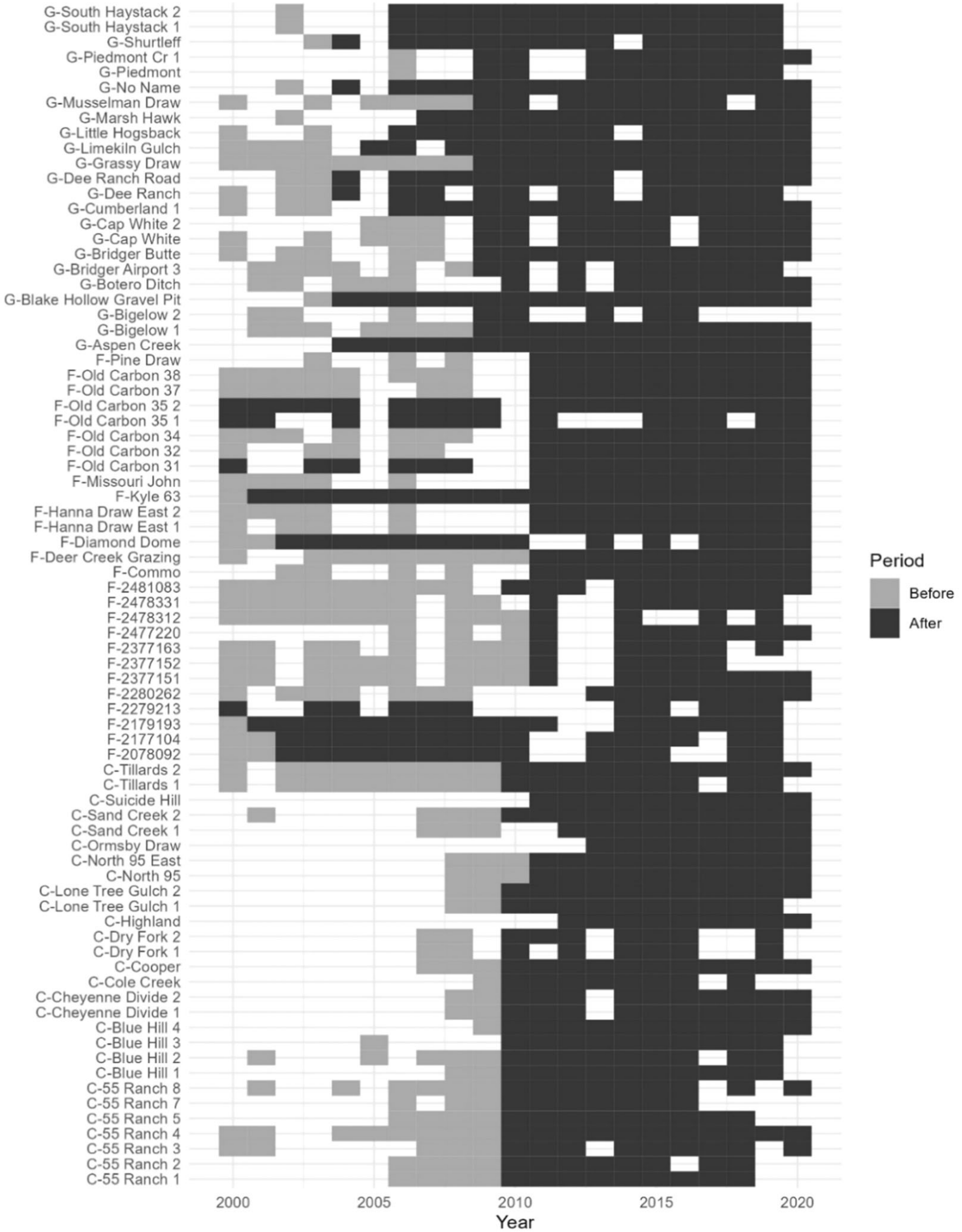

FIGURE A3 Observed data pattern for the full data subset of greater sage-grouse leks in southwest and south-central Wyoming, USA, during 2000–2020. Blank tiles represent missing data years. Grey tiles represent surveyed years before wind development and black tiles represent surveyed years after wind development. Missing data in between the first and last surveyed year were imputed for each lek.

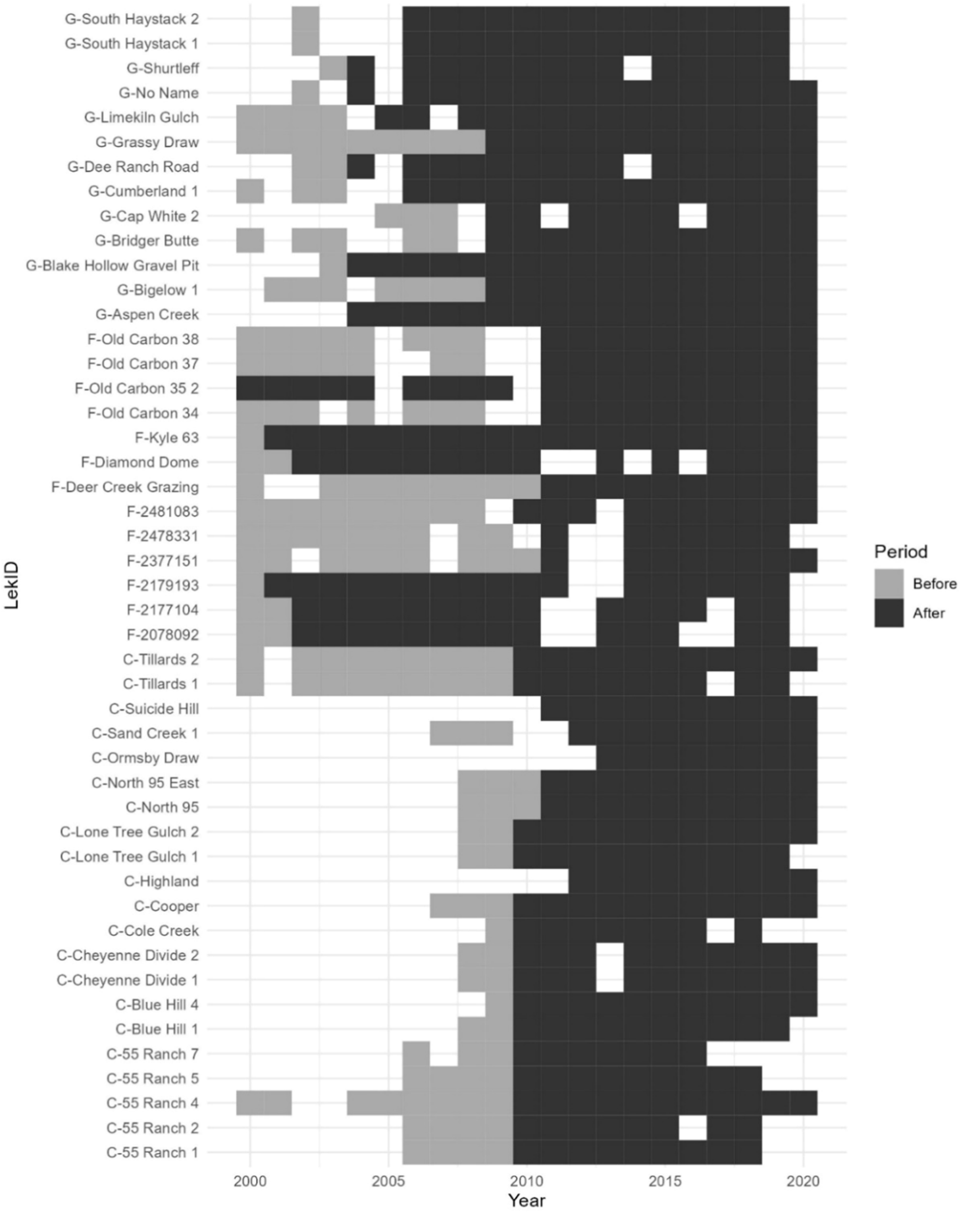

FIGURE A4 Observed data pattern for the at most 20% missing data subset of greater sage-grouse leks in southwest and south-central Wyoming, USA, during 2000–2020. Blank tiles represent missing data years. Grey tiles represent surveyed years before wind development and black tiles represent surveyed years after wind development. Missing data in between the first and last surveyed year were imputed for each lek.

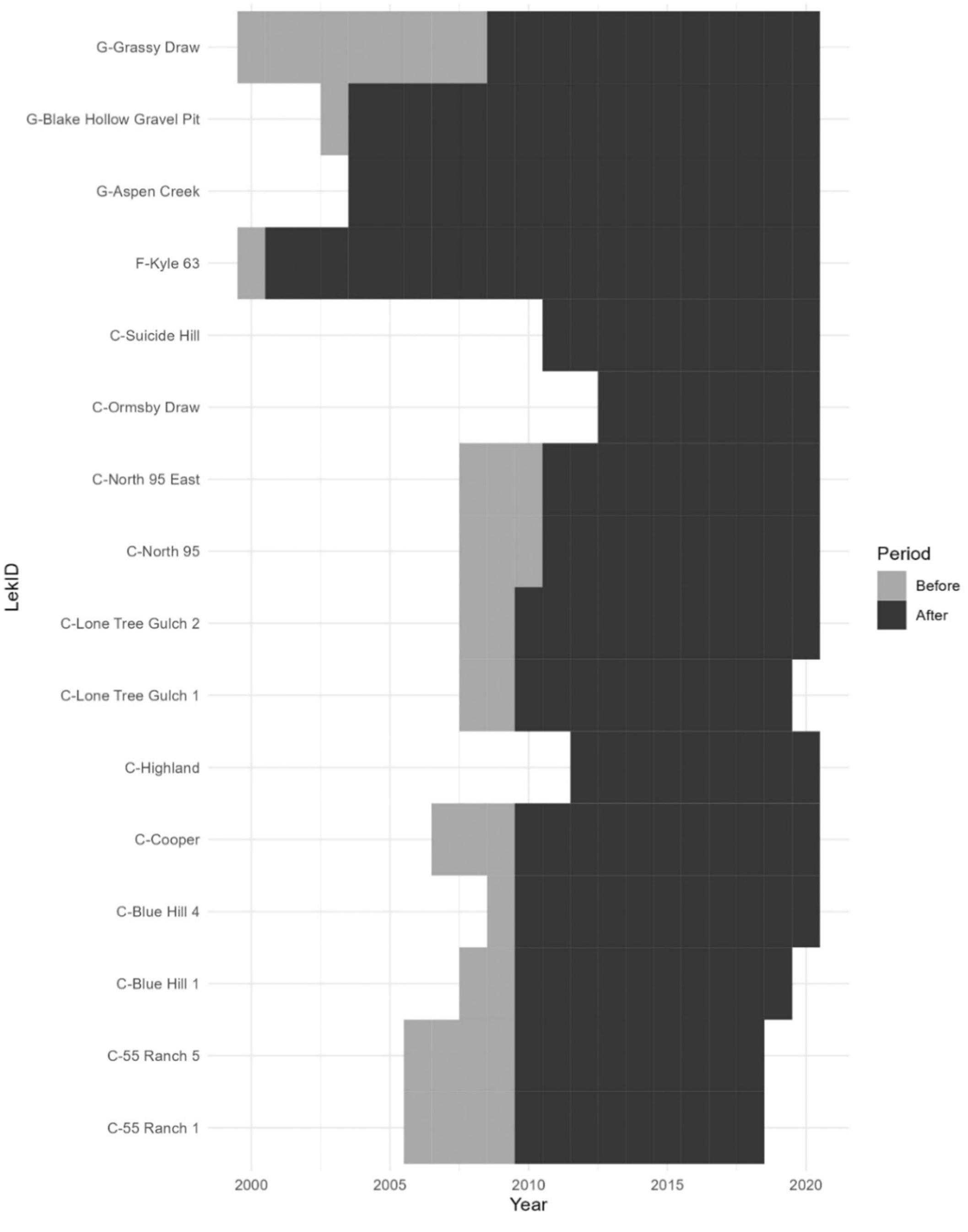

FIGURE A5 Observed data pattern for the complete data subset of greater sage-grouse leks in southwest and south-central Wyoming, USA, during 2000–2020. Blank tiles represent missing data years. Grey tiles represent surveyed years before wind development and black tiles represent surveyed years after wind development. Data included in the analysis only consisted of the consecutively observed years between the first surveyed year and the last surveyed year.

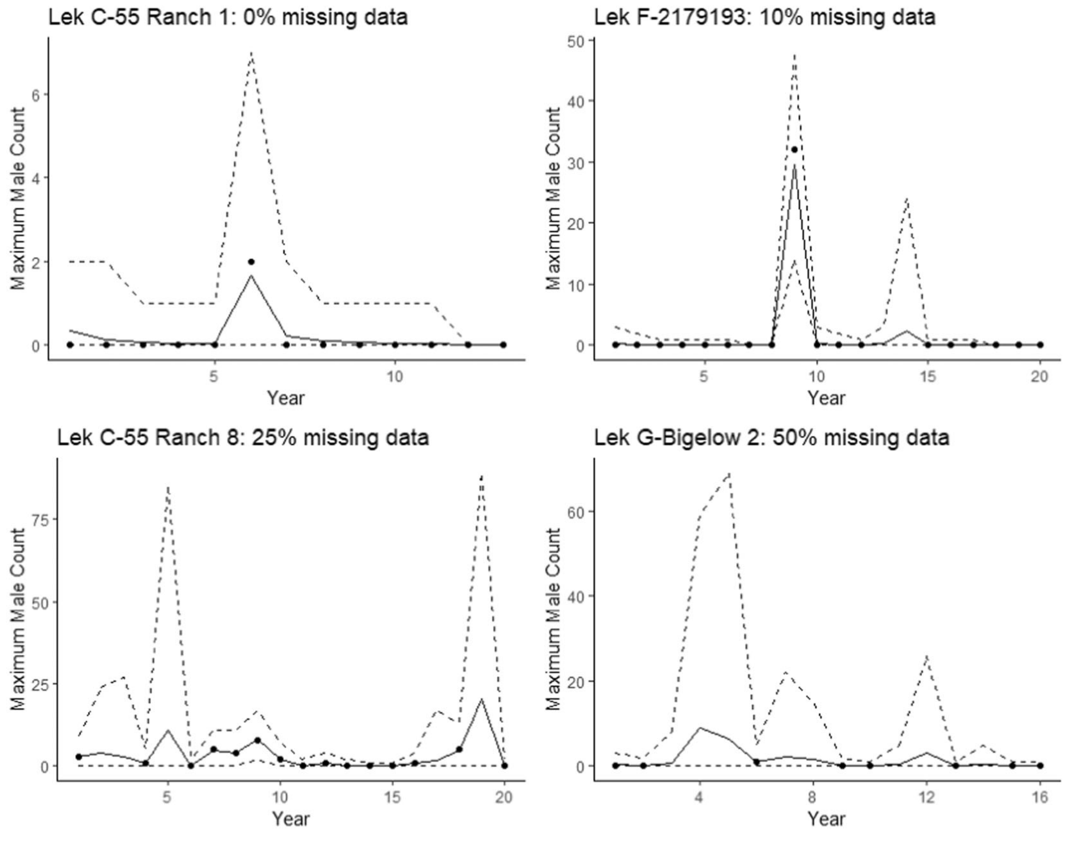

FIGURE A6 Posterior predictive checks for a subset of 4 leks from the full data analysis (turbine distance as the wind covariate) using greater sage-grouse male lek counts from southwest and south-central Wyoming, USA, during 2000–2020. Points represent the observed maximum male lek counts, solid lines represent the posterior mean prediction for the true male lek counts, and dotted lines represent the 95% credible intervals for the predicted male lek counts.

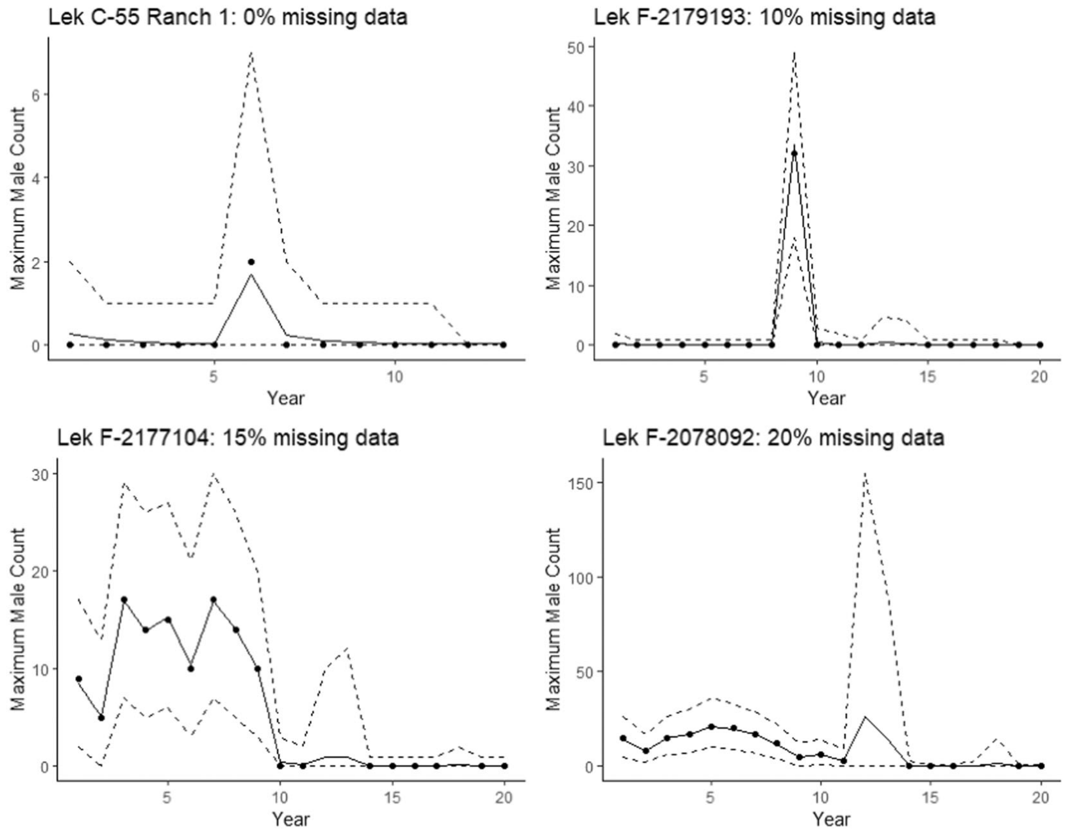

FIGURE A7 Posterior predictive checks for a subset of 4 leks from the subset data analysis with at most 20% missing data (turbine distance as the wind covariate) using greater sage-grouse male lek counts from southwest and south-central Wyoming, USA, during 2000–2020. Points represent the observed maximum male lek counts, solid lines represent the posterior mean prediction for the true male lek counts, and dotted lines represent the 95% credible intervals for the predicted male lek counts.

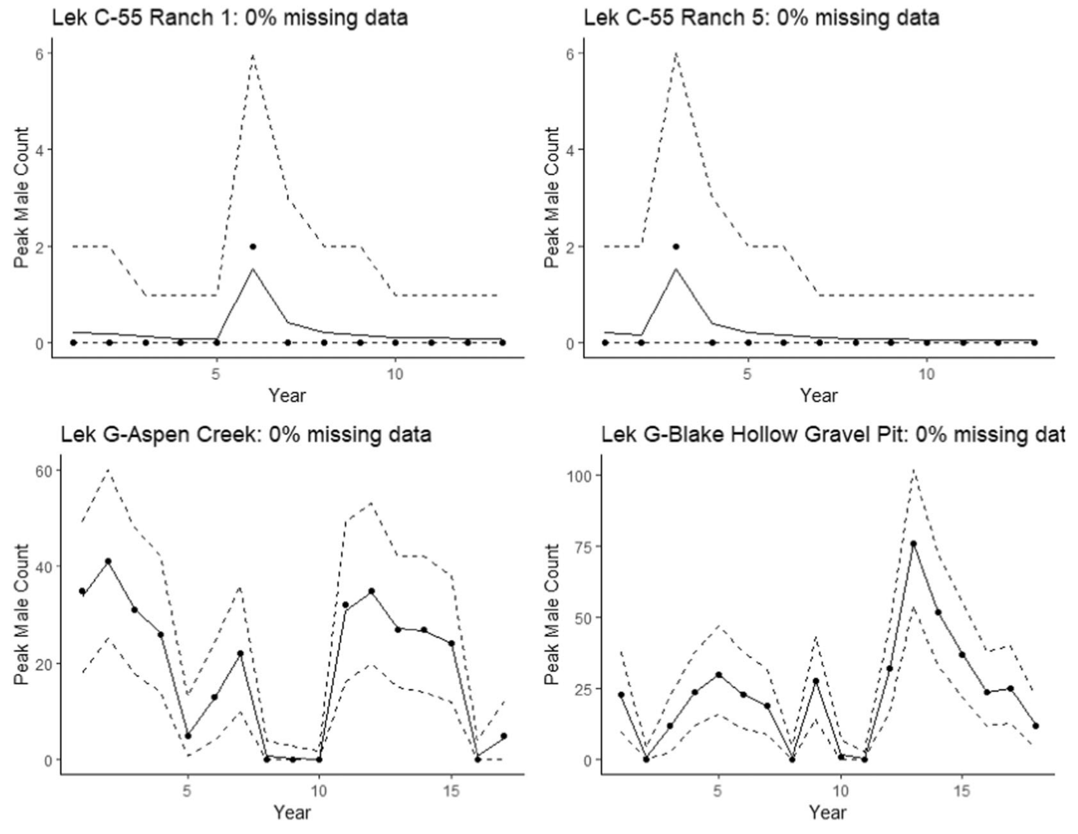

FIGURE A8 Posterior predictive checks for a subset of 4 leks from the complete data analysis (turbine distance as the wind covariate) using greater sage-grouse male lek counts from southwest and south-central Wyoming, USA, during 2000–2020. Points represent the observed maximum male lek counts, solid lines represent the posterior mean prediction for the true male lek counts, and dotted lines represent the 95% credible intervals for the predicted male lek counts.

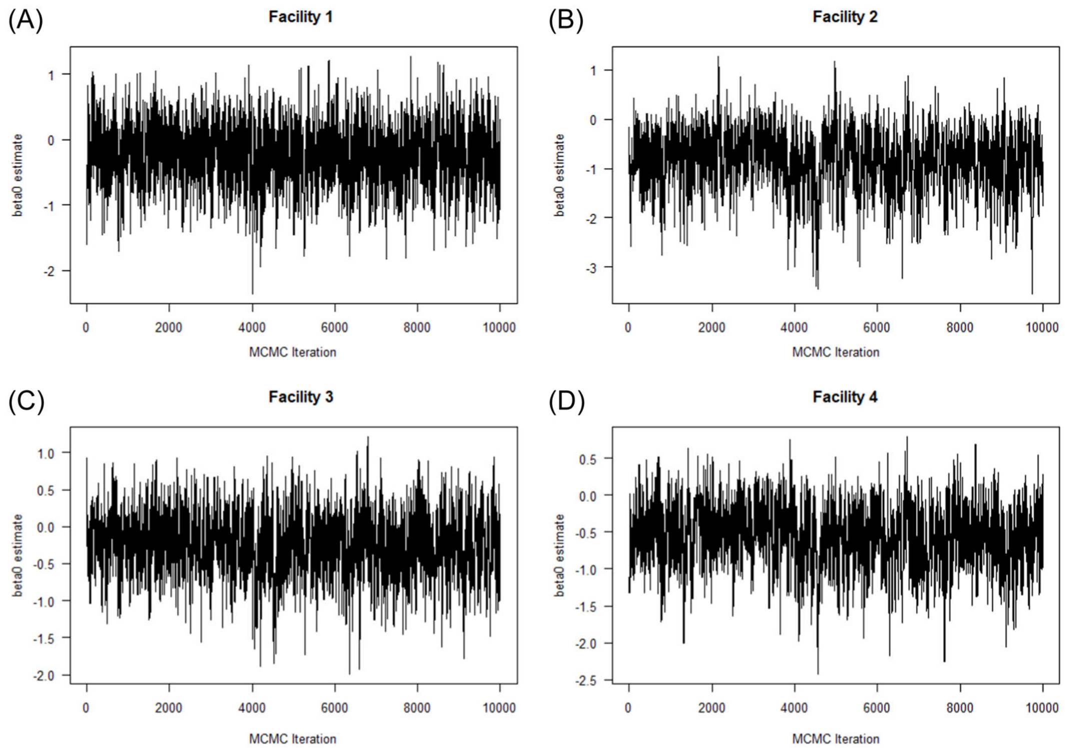

FIGURE A9 Trace plots for a subset of 4 random intercept terms in the full data analysis (turbine distance as the covariate) using greater sage-grouse male lek counts from southwest and south-central Wyoming, USA, during 2000–2020. Trace plots show that the parameters converge by 5,000 iterations of the MCMC sampler.

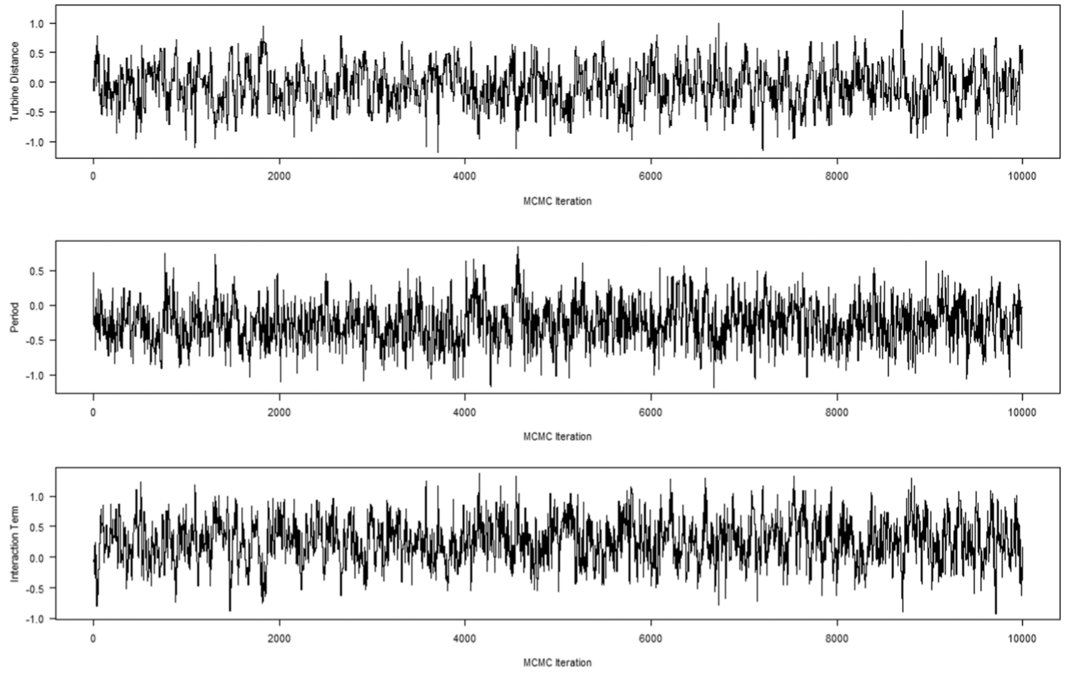

FIGURE A10 Trace plots for regression coefficients in the full data analysis (turbine distance as the covariate) using greater sage-grouse male lek counts from southwest and south-central Wyoming, USA, during 2000–2020. Trace plots show that the parameters converge by 5000 iterations of the MCMC sampler.

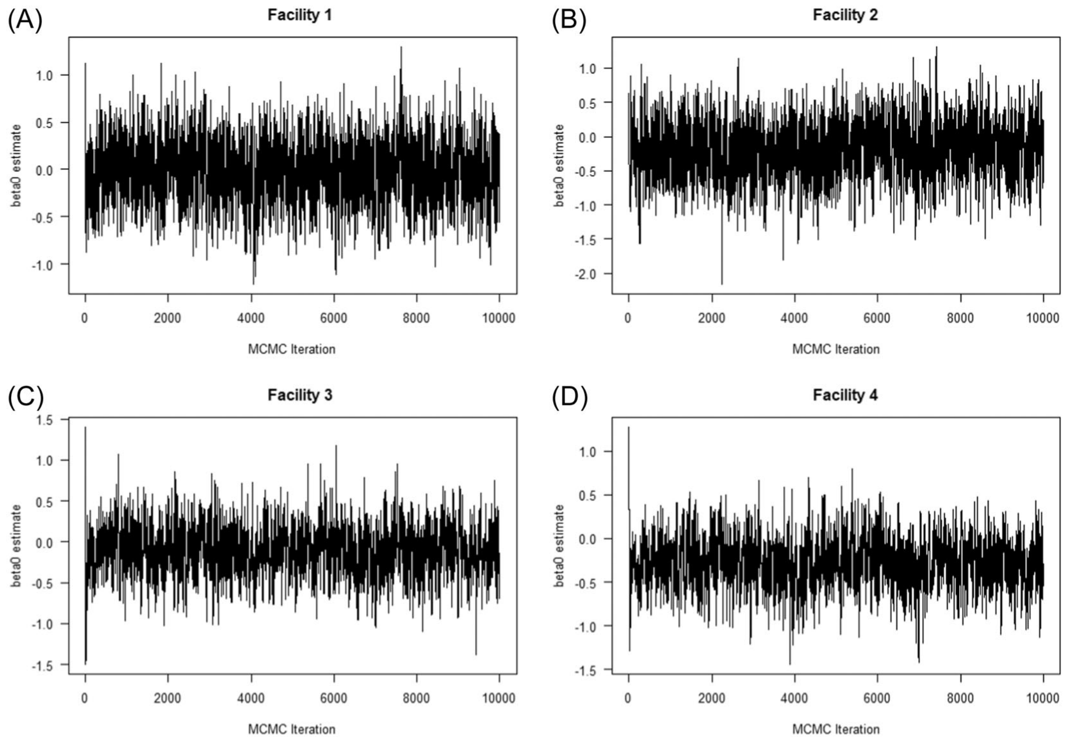

FIGURE A11 Trace plots for a subset of 4 random intercept terms in the subset data analysis with at most 20% missing data per lek (turbine distance as the covariate) using greater sage-grouse male lek counts from southwest and south-central Wyoming, USA, during 2000–2020. Trace plots show that the parameters converge by 5,000 iterations of the MCMC sampler.

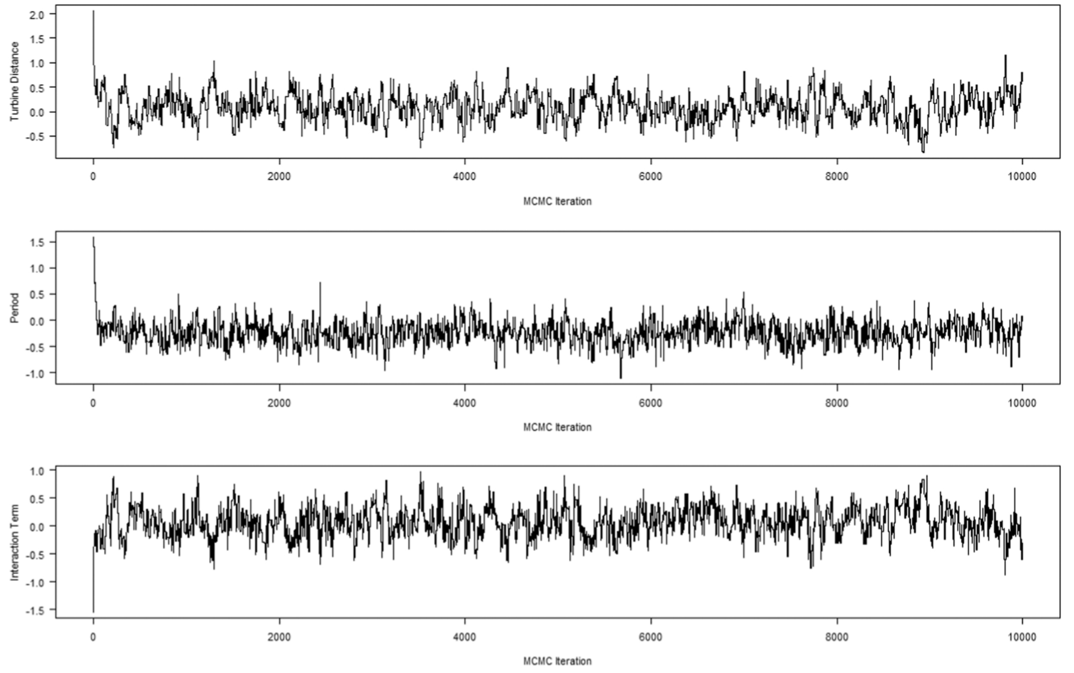

FIGURE A12 Trace plots for the regression coefficients in the subset data analysis with at most 20% missing data per lek (turbine distance as the covariate) using greater sage-grouse male lek counts from southwest and south-central Wyoming, USA, during 2000–2020. Trace plots show that the parameters converge by 5,000 iterations of the MCMC sampler.

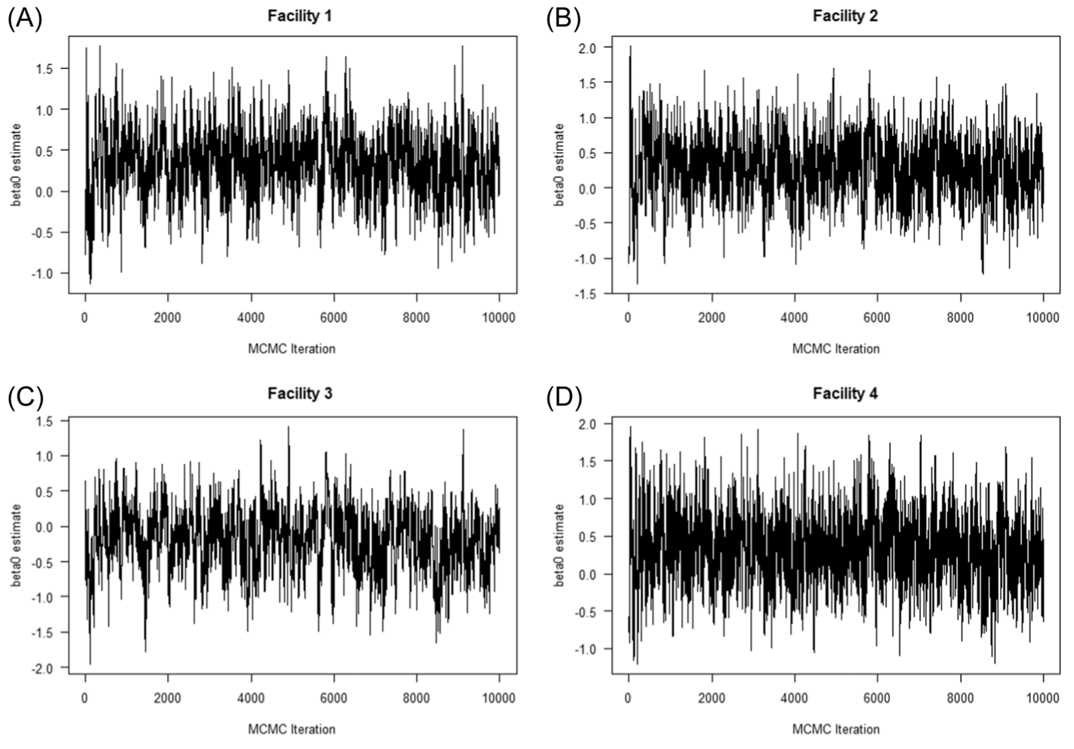

FIGURE A13 Trace plots for a subset of 4 random intercept terms in the complete data analysis (turbine distance as the covariate) using greater sage-grouse male lek counts from southwest and south-central Wyoming, USA, during 2000–2020. Trace plots show that the parameters converge by 5,000 iterations of the MCMC sampler.

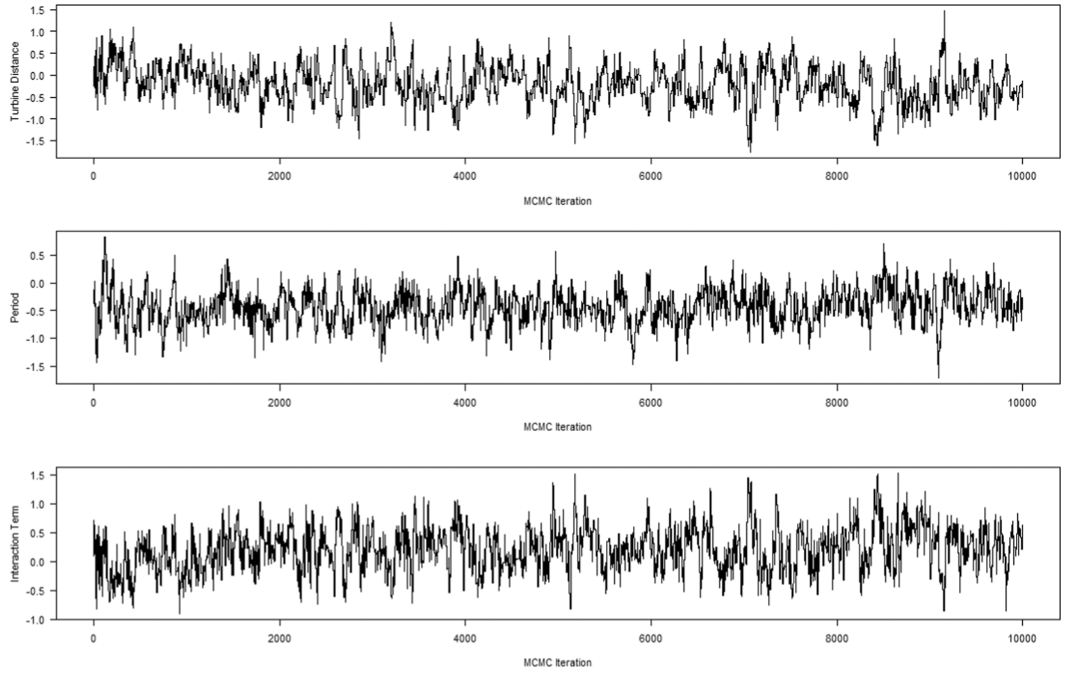

FIGURE A14 Trace plots for the regression coefficients in the complete data analysis (turbine distance as the covariate) using greater sage-grouse male lek counts from southwest and south-central Wyoming, USA, during 2000–2020. Trace plots show that the parameters converge by 5,000 iterations of the MCMC sampler.