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*Original Article*

# Greater Sage-Grouse Male Lek Counts Relative to a Wind Energy Development

**CHAD W. LEBEAU,**[1,2] *Department of Ecosystem Science and Management, University of Wyoming, Dept 3354, 1000 E University Avenue, Laramie, WY 82071, USA*

**JEFFREY L. BECK,** *Department of Ecosystem Science and Management, University of Wyoming, Dept 3354, 1000 E University Avenue, Laramie, WY 82071, USA*

**GREGORY D. JOHNSON,** *Western EcoSystems Technology, Inc., 415 W 17th Street, Suite 200, Cheyenne, WY 82001, USA*

**RYAN M. NIELSON,** *Western EcoSystems Technology, Inc., 415 W 17th Street, Suite 200, Cheyenne, WY 82001, USA*

**MATTHEW J. HOLLORAN,** *Wyoming Wildlife Consultants, LLC, 1612 LaPorte Avenue, Suite 9, Fort Collins, CO 80521, USA*

**KENNETH G. GEROW,** *Department of Statistics, University of Wyoming, Dept 3332, 1000 E University Avenue, Laramie, WY 82071, USA*

**TRENT L. McDONALD,** *Western EcoSystems Technology, Inc., 200 S 2nd Street, Laramie, WY 82070, USA*

**ABSTRACT** Wind energy development is an emerging source of anthropogenic disturbance that could affect greater sage-grouse (*Centrocercus urophasianus*; sage-grouse) populations. Our objective was to determine the response of male sage-grouse attending leks (lek counts) to wind energy development using a before/after–control/treatment study design. We counted males attending each lek within control and treatment areas annually and analyzed peak numbers. We obtained lek count data from 5 treatment and 9 control leks over an 11-year period. We estimated trends in lek counts pre- (2006–2008) and postdevelopment (2009–2016) using a generalized linear mixed negative binomial model. We considered time lags at which the effect of the wind energy development was realized by the male breeding population. Although all lek counts were apparently in decline prior to development and trends on the control and treatment area changed during postdevelopment, we found no negative differences in the relative trends in lek counts between control and treatment areas between pre- and postdevelopment periods. We detected a 56% drop in lek counts at treatment leks relative to control leks assuming the effect of the wind energy development was realized between 2010 and 2011 (i.e., 3 yr postdevelopment). Use of *a posteriori* power analysis estimated similar data sets would have 80% probability of detecting a 28% decrease in the rate of decline of lek counts at treatment leks relative to control leks after development. Our findings suggest males attending leks in close proximity to wind energy development may respond differently compared with leks in close proximity to other forms of anthropogenic features, adding to a growing body of literature regarding the potential effects of energy development on prairie grouse. We recommend additional research and an abundance of caution in designating buffer sizes <1.5 km to avoid measurable effects from wind energy development on males attending leks. © 2017 The Wildlife Society.

**KEY WORDS** *Centrocercus urophasianus*, greater sage-grouse, lek counts, wind energy development, wind turbines.

Wind energy development has increased substantially in prairie habitats with high wind capacity, raising concerns over effects on prairie grouse, including greater sage-grouse (*Centrocercus urophasianus*), sharp-tailed grouse (*Tympanuchus phasianellus*), and lesser (*T. pallidicinctus*) and greater (*T. cupido*) prairie-chicken populations (Kuvlesky et al. 2007, Johnson and Stephens 2011). Direct effects (e.g., collision mortality) on prairie grouse are likely low (Winder et al. 2014*a*), but indirect effects of wind turbines and associated infrastructure such as access roads, substations, and transmission lines may affect spatial and demography responses of prairie grouse species because of tendencies toward avoiding anthropogenic structures and areas with notable human activity (Pruett et al. 2009, Walters et al. 2014).

Trends in greater sage-grouse (sage-grouse) male breeding populations are typically indexed through lek counts (Beck and Braun 1980, Walsh et al. 2004, Garton et al. 2011, Naugle et al. 2011). Lek counts provide an index of male breeding population levels and in many cases, long-term data sets are available for trend analysis (Connelly et al. 2000*b*, Garton et al. 2011). Multiple studies have used lek counts to provide information on male sage-grouse breeding populations in response to disturbances including wildfire and prescribed burning and oil and gas development (Connelly et al. 2000*a*, Holloran 2005, Walker et al. 2007, Harju et al. 2010, Holloran et al. 2010, Hess and Beck 2012, Gregory and Beck 2014).

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[1] *E-mail: cwlebeau@west-inc.com*
[2] *Present address: Western Ecosystems Technology, Inc., 415 W 17th Street, Cheyenne, WY 82001, USA.*

The number of males attending leks has decreased throughout most of the range of sage-grouse over the past few decades (Connelly and Braun 1997, Connelly et al. 2004, Garton et al. 2011). This decline has largely been attributed to anthropogenic influences or landscape changes associated with invasive species such as cheatgrass (*Bromus tectorum*) that fuel large wildfires (Johnson et al. 2011, Naugle et al. 2011, Blomberg et al. 2012, Kirol et al. 2015). Declines in the number of males attending leks (hereafter, male lek attendance) could be related to low male juvenile recruitment, poor female survival, and low productivity as a result of decreased habitat quality (Holloran et al. 2010, Taylor et al. 2011). Lek abandonment or males rejecting leks also has increased throughout much of the sage-grouse range, likely resulting from cumulative negative effects to habitat (Hess and Beck 2012). Lek attendance can be influenced directly through habitat loss and indirectly when male sage-grouse avoid habitat associated with anthropogenic factors such as noise (Blickley et al. 2012).

Wind energy development is an emerging source of anthropogenic disturbance that could affect sage-grouse populations (LeBeau 2012, LeBeau et al. 2014). Few studies have been conducted to evaluate effects of wind energy development on grouse, including sage-grouse. Greater prairie-chicken nest site selection and survival of adult females and nests were not found to be influenced by a commercial wind energy facility in Kansas, USA (McNew et al. 2014, Winder et al. 2014*a*). Greater prairie-chicken lek abandonment documented at this facility was greatest within 8 km of turbines during a 3-year postdevelopment period. Furthermore, rates of change in the maximum number of male prairie-chickens and lek persistence were not influenced by proximity to wind turbines (Winder et al. 2015). However, female greater prairie-chickens avoided wind turbines during the breeding season (Winder et al. 2014*b*). Habitat selection and survival of adult female sage-grouse in close proximity to wind turbines at the Seven Mile Hill Wind Energy Facility (SWEF) in Wyoming, USA, were not affected during 2 years following construction of the site, but a negative effect on nest and brood survival was measured (LeBeau 2012, LeBeau et al. 2014).

Negative effects on sage-grouse fitness parameters from wind energy development may lead to lower male recruitment at leks located in close proximity to wind turbines. We investigated effects of wind energy infrastructure on sage-grouse peak male lek attendance (lek counts) in southeastern Wyoming. We used a before/after–control/treatment study design (Green 1979, McDonald et al. 2000, Morrison et al. 2008) to evaluate whether a newly constructed wind-energy facility was associated with reduced numbers of males attending leks located near the facility, relative to those located farther from the facility. We used sage-grouse lek count data collected during 3 years prior to, and the first 8 years after, development of a wind energy facility.

## STUDY AREA

Our study area was located north of Elk Mountain and Interstate-80 and south of the Shirley Basin in Carbon County, Wyoming, near the town of Hanna (Fig. 1). Land ownership included Bureau of Land Management (22.5%), private (69.5%), and State of Wyoming lands (7.8%). The study area was classified as a semiarid, cold desert with a mean annual precipitation of 26.7 cm and average monthly temperatures ranging from 2.33° C to 13.61° C (WRCC 2014). Shrub-steppe, dominated primarily by Wyoming big sagebrush (*Artemisia tridentata wyomingensis*), was the most common cover type (USGS 2011). Dominant land uses included wind energy development, a surface coal mine near the southwestern edge of the study area (approx. 20 km from the nearest turbines), livestock grazing, and hunting.

Control and treatment areas were included in our study area. The treatment area was situated in the northern portion of the study area and encompassed the SWEF, which consisted of 79 General Electric 1.5-MW wind turbines and approximately 29 km of access roads (Fig. 1). This facility was located north of US Highway 30/287 and south of the Medicine Bow River (Fig. 1); construction began late summer 2008, and the facility became fully operational in December 2008. Elevations in the affected area were from 1,737 m to 2,118 m above sea level. Five occupied sage-grouse leks were located within the treatment area (Fig. 1).

The control area was without wind turbines and adjacent to the SWEF and south of US Highway 30/287 (Fig. 1). The control area contained numerous ridges interspersed with rolling to hilly plains. Elevations were 2,040–2,390 m above sea level. There were 9 occupied sage-grouse leks located within the control, with the closest control lek 6.3 km from the nearest turbine at the SWEF (Fig. 1). Based on telemetry information collected within the overall study area, 5% of all female sage-grouse and 3% of all sage-grouse locations from female sage-grouse captured from either the control or treatment area were documented in the other area (LeBeau 2012).

In addition to the wind energy facility, other anthropogenic features present in the study area included approximately 8 km of paved roads (US Highway 30/287) and 26 km of overhead transmission lines within the treatment area and approximately 50 km of paved roads (Interstate-80, US Highway 30/287, and Wyoming State Highway 72) and 17 km of overhead transmission lines within the control area. Overhead transmission lines and paved roads have existed on the landscape for >10 years. Anthropogenic features added to the study area as a result of constructing the SWEF were wind turbines, associated access roads, and one operation and maintenance building (Fig. 1).

## METHODS

We conducted aerial sage-grouse lek surveys during spring 2008 to detect leks and determine occupancy of historical leks within the study areas (Walsh et al. 2004). We conducted lek searches from fixed-wing aircraft flying parallel transects designed to provide full coverage of the study area. We conducted 3 surveys spaced 7 days apart during peak lekking season from early April through early May. Transects were oriented north–south and separated by approximately 1.0 km. Transects were flown at 91–137 m

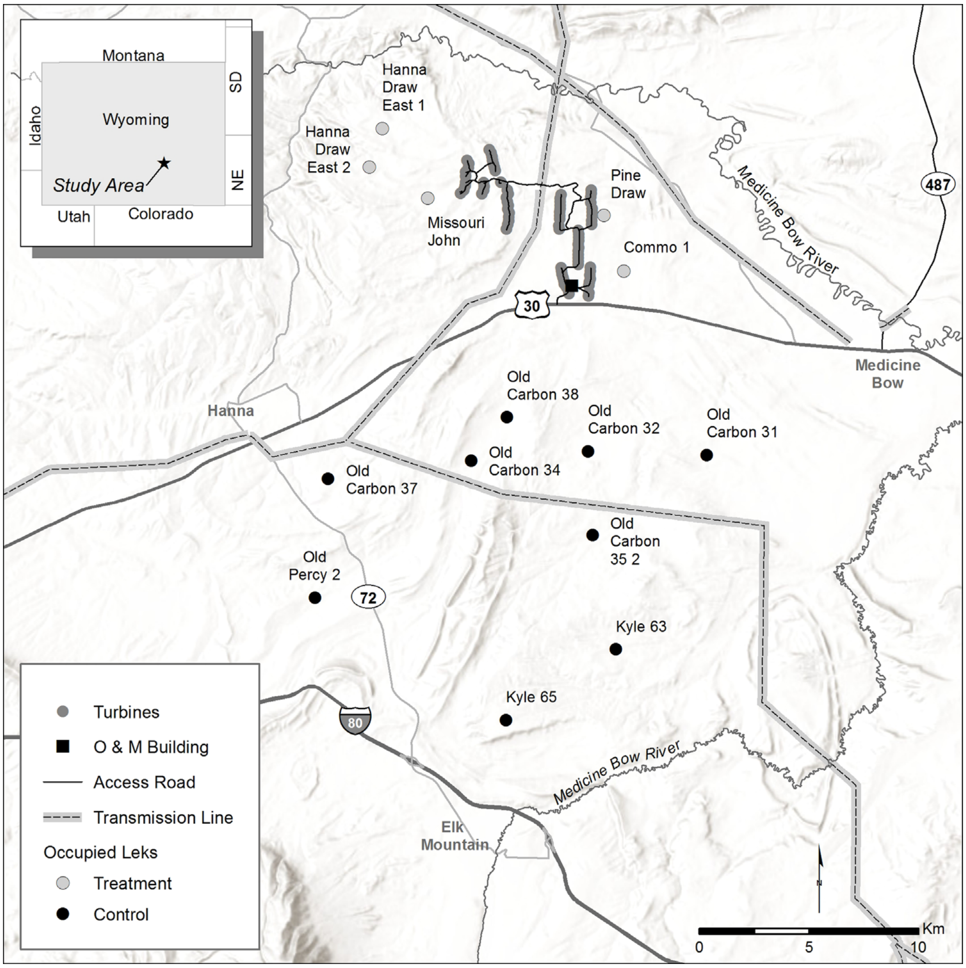

**Figure 1.** Occupied greater sage-grouse lek locations within the treatment and control study areas located in Carbon County, Wyoming, USA, 2006–2016.

above ground level at an approximate speed of 160 km/hr. We recorded Global Positioning System coordinates and approximate numbers of male and female sage-grouse observed at all leks from the air.

We documented the number of males at all historical and new leks identified from aerial searches throughout the treatment ($n = 5$) and control ($n = 9$) areas. Ground surveys conducted in 2006 and 2007 were performed by the Wyoming Game and Fish Department. We conducted ground surveys between 2008 and 2016. We visited each active lek located during aerial surveys and known historical lek locations 3 times each spring to count male sage-grouse attending each lek (Connelly et al. 2003, Holloran 2005). We spaced ground surveys a minimum of 7 days apart and conducted them during the lekking period to capture variability in lek attendance (Connelly et al. 2003). We conducted counts for 15 min in the early morning hours when males were most active. We recorded the maximum number of male sage-grouse, date, and time period of observation. The perimeters of all leks were mapped by traversing the extent of open areas of the lek on foot and recording waypoints on a hand-held Global Positioning System unit so that the geographic lek center could be determined.

## Analytical Methods

Lek counts over the study period were more likely to be auto-correlated than correlated to counts from other monitored leks. We accounted for serial auto-correlation in lek counts at individual leks by considering individual leks as a random effect in a generalized linear mixed-effects negative binomial model (GLMM; McLean et al. 1991, Zuur et al. 2009, Blickley et al. 2012). Fixed effects, such as study area and distance to turbine, were identical across study period for each lek, whereas random effects differed from lek to lek (Gelman 2005).

We evaluated the effect of the SWEF on lek counts by estimating before/after–control/treatment-type fixed effects in the GLMM. The purpose of this analysis was to detect differences in the relative trends and magnitudes of lek counts pre- and postdevelopment of the SWEF. We estimated 4 slopes as fixed effects: 1) predevelopment on control leks; 2) predevelopment on treatment leks; 3) postdevelopment on control leks; and 4) postdevelopment on treatment leks. The difference between predevelopment slopes between control and treatment leks (i.e., fixed-effect slope [1] minus fixed-effect slope [2]) established the baseline difference in slopes. The postdevelopment slope on control leks (slope [3]) allowed for a natural change in the trajectory of lek counts postdevelopment unrelated to SWEF. Finally, the postdevelopment slope at treatment leks (slope [4]) allowed the relative difference between slopes to differ following development of the SWEF. The GLMM we fitted took the form:

$$\begin{aligned} log\left(\mu_{ij}\right) = {} & \beta_0 + \beta_1(SWEF_i) + \beta_2\left(Post_j\right) + \beta_3\left(SWEF_i \times Post_j\right) \\ & + \beta_4\left(Year_j\right) + \beta_5\left(Year_j \times SWEF_i\right) + \beta_6\left(Year_j \times Post_j\right) \\ & + \beta_7\left(Year_j \times SWEF_i \times Post_j\right) + b_{0i} + b_{1i}\left(Year_j\right) + \varepsilon_{ij}, \theta \end{aligned}$$

where $\mu_{ij}$ is the mean maximum male count on lek $i$ in year $j$, $SWEF_i$ is a study-area indicator variable (treatment $[TRT]$ = 1), $Post_j$ is an indicator variable indicating which years follow development of the SWEF (postdevelopment = 1), $Year_j$ is a recoded variable for year of the survey (2006 = 1, 2007 = 2, . . ., 2016 = 11), $b_{0i}$ is the random year intercept for lek $i$, and $b_{1i}$ was the random slope for lek $i$. The random effects, $b_{0i}$ and $b_{1i}$, are assumed to be normally distributed with **0** mean and general (unstructured) covariance matrix. The random or observational part of the GLMM was

$$R_{ij} \sim NegBinomial\left(\mu_{ij} + \varepsilon_{ij}, \boldsymbol{\theta}\right)$$

where the error terms, $\varepsilon_{ij}$, were assumed to be normally distributed with mean **0** and covariance matrix $\boldsymbol{\Sigma}$. In addition to a generic study-area effect quantified by the SWEF study-area indicator (*SWEF*; treatment = 1), we investigated 2 additional quantifications of development effect: a SWEF study-area indicator for leks located within 1.5 km of the SWEF (*SWEFnear*; leks ≤1.5 km = 1) and a continuous distance to turbine (*d_turbine* [km]) covariate.

We used the GLMM to determine whether addition of the SWEF to the landscape was associated with a change in relative trends in lek counts postdevelopment by testing $\beta_7 = 0$ versus the one-sided alternative $\beta_7 < 0$. The parameter $\beta_7$ measured the difference in slope differences between control and treatment lek counts pre- and postdevelopment. For example, suppose the slope at control and treatment leks averaged −3 and −5 males/year during predevelopment, respectively. Both trends are declining during predevelopment, but the decline is greater at treatment leks. The difference between these predevelopment slopes averages −2 males/year. Suppose the slope on control leks increased to an average of 1 male/year postdevelopment. Under the null hypothesis of no effect, the slope on treatment leks would average −1 male/year, which is equal to the slope on control leks postdevelopment (average of 1 male/yr) plus the difference in slopes predevelopment (average of −2 males/yr; in this case $\beta_7 = 0$). The trends are still decreasing at treatment leks postdevelopment, but the difference between control and treatment slopes remains the same pre- and postdevelopment. Now, suppose the actual slope on treatment leks postdevelopment averaged −4 males/year. In this case, $\beta_7 = -3$, the actual slope postdevelopment (average of −4 males/yr) minus the expected slope postdevelopment on treatment lek (−1 male/yr). In this example, the rate of decline postdevelopment increased more than expected based on relative slopes predevelopment (Fig. 2a).

Assuming $\beta_7$ was not statistically different from zero in our GLMM, we determined whether a change in the overall magnitude of lek counts occurred by testing $\beta_3 = 0$. This tested for presence of a pulse disturbance or large drop in lek counts soon after development (Fig. 2b). The previous test of $\beta_7 = 0$ ignored changes in magnitude pre- to postdevelopment. If slopes were within statistical error of having the same relationship pre- and postdevelopment (i.e., $\beta_7 = 0$), the second test involving $\beta_3$ tested for an overall drop in the average lek count postdevelopment.

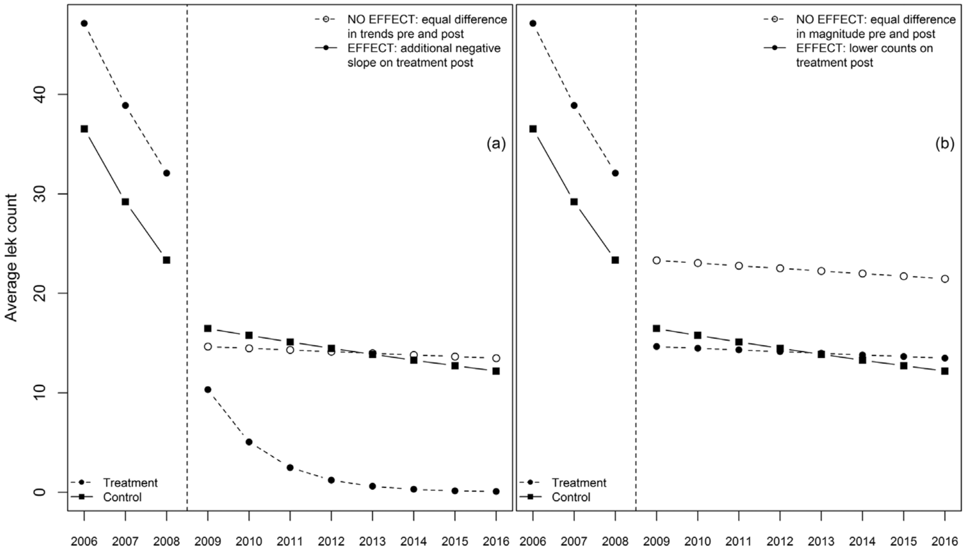

**Figure 2.** Illustration of the effects tested in a generalized linear mixed-effects negative binomial model (GLMM) of the Seven Mile Hill Wind Energy Facility Carbon County, Wyoming, USA, on male sage-grouse attending treatment and control leks assuming the effect of wind development was realized by the male breeding population between 2008 and 2009. The parameter $\beta_7$ measured the difference in slope differences between control and treatment lek counts pre- and postdevelopment (a). Size of the plotted $\beta_7$ effect equates to 28% additional increase in the rate of decrease from the 2008 predevelopment average at treatment leks relative to control leks (a). Assuming $\beta_7$ was not statistically different from zero in our GLMM, we determined whether a change in the overall magnitude of counts occurred by testing $\beta_3 = 0$ (b). Size of the plotted $\beta_3$ effect equates to 27% reduction in the 2008 predevelopment average lek count at treatment leks (b).

The SWEF became operational in December 2008; thus, the first breeding season following development was spring 2009. To estimate potential time lags in the manifestation of potential development effects, we assumed the year at which effects of the SWEF occurred could have been between 2008 and 2009, 2009 and 2010…, and 2014 and 2015, and estimated $\beta_7$ and $\beta_3$ (if $\beta_7$ was not significant) under each assumption. We did not test for a lag effect in years 2015 and 2016 because of the lack of (*Post*) data points associated with this lag (1 yr). This resulted in 7 GLMMs and 7 $\beta_7$ estimates. We applied a Bonferroni correction to protect the experiment-wide significance (experiment-wide $\alpha = 0.10$). Individual coefficient estimates were evaluated at $\alpha = 0.10/7 = 0.014$ level (i.e., 98.6% CI). We considered estimates with confidence intervals that did not contain 0.0 as statistically significant.

We conducted *a posteriori* power analyses to assess the magnitude of additional increases in rate of decline (i.e., magnitude of $\beta_7$) that data sets such as ours could have detected with 80% power. The key features of our data set for determining statistical power were duration, number of leks in each area, and inherent variation around slopes. We conducted the power analyses assuming any effects occurred between 2008 and 2009 (i.e., we did not consider time lag effects) and simulating 500 data sets from models with known $\beta_7$ coefficients. We assumed effects occurred between 2008 and 2009 because precision of $\beta_7$ (and hence power) improves if effects are assumed to occur nearer the center of our monitoring period (i.e., near 2011 and 2012). In 2008–2009, only 3 years of predevelopment data existed, whereas in 2011–2012, 6 years of postdevelopment data existed. We assumed the additional rate of decline (i.e., $\beta_7$) varied in 5% increments from 0% to 30% relative to the 2008–2009 treatment mean. We refitted the GLMM to every generated data set and computed power as the number of correct hypothesis rejections out of the number of models that converged (10 or $<500$ models failed to converge for each value of $\beta_7$). Finally, we plotted power against $\beta_7$ expressed as a percentage of the 2008 average-treatment lek count to estimate the entire power curve.

## RESULTS

Fourteen sage-grouse leks (treatment = 5 and control = 9) were monitored in 2008 and from 2010 to 2016 (Table 1 and Fig. 1). One lek located in the control and 2 leks located in the treatment area were missed during the surveys and not counted in 2008 and 2009, respectively. Two leks located in the treatment area were counted in 2006 and no leks were counted in 2007. One lek located in the control area was not counted in 2006 (Table 1). One new lek (Pine Draw) within the treatment area was identified during aerial lek surveys in 2008.

Data collected from 2009 to 2016 represent the first 8 sage-grouse breeding seasons after the SWEF became operational. Prior to construction in 2008, 3 leks with a combined lek count of 130 males were located within 1.5 km of the SWEF turbines: Missouri John, Pine Draw, and Commo 1 (Table 1). In 2009, the first breeding season after construction, 103 males were counted on these 3 leks (Table 1). No males were observed attending the Pine Draw lek 4 years postdevelopment. However, 5 males were observed on this lek in 2016, 8 years postdevelopment. These 3 leks were included in the *SWEFnear* indicator variable.

Based on the one-sided alternative hypothesis $\beta_7 < 0$, we did not detect an increase in the rate of decline of lek counts on treatment leks or leks $<1.5$ km from turbines postdevelopment

**Table 1.** Maximum counts, yearly averages, and totals of male greater sage-grouse on occupied leks located within the treatment and control study areas, Carbon County, Wyoming, USA, 2006–2016. Entries of "NA" indicate no count was conducted. In our analysis, 2006–2008 were pretreatment and 2009–2016 were posttreatment years.

| | | Year | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Lek name** | **Distance to nearest turbine (km)** | **2006** | **2007** | **2008** | **2009** | **2010** | **2011** | **2012** | **2013** | **2014** | **2015** | **2016** |
| Treatment | | | | | | | | | | | | |
| Commo 1[a] | 1.5 | 36 | NA | 23 | 21 | 18 | 5 | 15 | 13 | 10 | 20 | 17 |
| Hanna Draw East 1 | 4.1 | NA | NA | 32 | NA | 27 | 5 | 11 | 8 | 21 | 39 | 52 |
| Hanna Draw East 2 | 4.3 | NA | NA | 18 | NA | 11 | 2 | 2 | 0 | 0 | 2 | 4 |
| Missouri John[a] | 1.5 | 92 | NA | 74 | 62 | 38 | 20 | 18 | 18 | 11 | 50 | 56 |
| Pine Draw[a] | 0.5 | NA | NA | 33 | 20 | 14 | 6 | 0 | 0 | 0 | 0 | 5 |
| Average | NA | 64 | NA | 36 | 34 | 22 | 8 | 9 | 8 | 8 | 22 | 27 |
| Total | NA | 128 | NA | 180 | 103 | 108 | 38 | 46 | 39 | 42 | 111 | 134 |
| Control | | | | | | | | | | | | |
| Kyle 63 | 16.2 | 87 | 81 | 67 | 68 | 64 | 32 | 19 | 32 | 51 | 59 | 52 |
| Kyle 65 | 19.7 | 16 | 8 | 5 | 8 | 4 | 0 | 2 | 0 | 0 | 1 | 11 |
| Old Carbon 31 | 9.1 | 49 | 17 | 28 | 41 | 28 | 23 | 23 | 26 | 19 | 35 | 38 |
| Old Carbon 32 | 7.1 | 18 | 0 | 9 | 33 | 4 | 20 | 12 | 22 | 27 | 30 | 30 |
| Old Carbon 34 | 8.9 | 44 | 43 | 49 | 49 | 31 | 26 | 20 | 26 | 29 | 53 | 48 |
| Old Carbon 35-2 | 10.9 | 118 | 109 | 111 | 88 | 41 | 55 | 22 | 39 | 40 | 78 | 68 |
| Old Carbon 37 | 13.9 | NA | 57 | 54 | 42 | 28 | 23 | 25 | 30 | 38 | 49 | 43 |
| Old Carbon 38 | 6.3 | 24 | 3 | 10 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Old Percy 2 | 18.1 | 39 | 2 | NA | 31 | 4 | 3 | 0 | 7 | 14 | 16 | 7 |
| Average | NA | 49 | 36 | 42 | 40 | 23 | 20 | 14 | 20 | 24 | 36 | 33 |
| Total | NA | 431 | 348 | 361 | 379 | 224 | 195 | 148 | 193 | 241 | 366 | 297 |

[a] Leks located within 1.5 km of wind turbines at Seven Mile Hill Wind Energy Facility turbines.

**Table 2.** Model coefficients and Bonferroni corrected confidence intervals (98.6% CI) associated with the difference in slope differences between control ($TRT = 0$) and treatment ($TRT = 1$) greater sage-grouse lek counts pre- and postdevelopment ($\beta_7$) and in the overall magnitude of lek counts ($\beta_3$; assuming $\beta_7$ was not significant) using a generalized linear mixed-effects negative binomial model, Carbon County, Wyoming, USA, 2006–2016. We considered 7 time lags when the effects of the wind energy facility were realized by the male breeding population.

| | | *TRT* × *Post* | | *Year* × *TRT* × *Post* | |
|---|---|---|---|---|---|
| **Year of estimated effect** | **Years following development** | **$\beta_3$** | **98.6% CI** | **$\beta_7$** | **98.6% CI** |
| 2008–2009 | 1 | −0.466 | −1.655 to 0.724 | −0.073 | −0.798 to 0.653 |
| 2009–2010 | 2 | 0.069 | −0.9 to 1.037 | 0.049 | −0.381 to 0.478 |
| 2010–2011 | 3 | −0.826 | −1.649 to −0.002 | 0.12 | −0.166 to 0.407 |
| 2011–2012 | 4 | −0.278 | −1.155 to 0.598 | 0.224 | −0.068 to 0.516 |
| 2012–2013 | 5 | | | 0.405 | 0.061 to 0.749 |
| 2013–2014 | 6 | | | 0.582 | 0.063 to 1.102 |
| 2014–2015 | 7 | 0.369 | −0.819 to 1.556 | 0.503 | −0.481 to 1.488 |

(Tables 2 and 3; Fig. 3). Based on testing of *d_turbine*, we did not detect an increase in the rate of decline on leks located closer to turbines than farther away postdevelopment (Table 4). We did estimate a positive difference in relative trends of lek counts between treatment and control leks when we assumed the effect of SWEF occurred between 5 and 6 years postdevelopment (i.e., $\beta_7 > 0$; Table 2 and Fig. 3). This positive difference equated to a 50% and 79% ($[exp(\beta_7) - 1] \times 100$) increase in the rate of change of average lek count at treatment leks relative to control leks 5 and 6 years postdevelopment, respectively (Table 2).

Based on the one-sided alternative hypothesis $\beta_3 < 0$, we detected a significant decrease in the overall magnitude of lek counts at treatment leks when we assumed the effect of the SWEF occurred 3 years postdevelopment (Table 2). Other decreases in magnitude pre- and postdevelopment were not statistically significant (Tables 2–4). Lek counts at treatment leks dropped by 56% relative to that of control leks when we assumed the effect of SWEF occurred 3 years postdevelopment (Table 2; 2011 panel of Fig. 3).

From our *a posteriori* power analyses, we estimated that data sets of similar duration, number of leks, and inherent variation would have 80% power to detect a 28% steeper decline of lek counts on treatment leks relative to control leks postdevelopment (Figs. 2 and 4). Power increases if we assumed the effect of the SWEF to have occurred between 2009 and 2010 (e.g., 2 yr postdevelopment) and we could have detected a smaller decline (i.e., 80% power to detect a 20% steeper decline). In our data set, we observed an increase in the rate of decline postdevelopment assuming the effect of the SWEF to have occurred between 2008 and 2009, meaning our estimated $\beta_7$ was negative (e.g., $\beta_7$ in 2008–2009 equaled −0.073; Table 2) and the additional decline was 2.89% of the 2008 predevelopment average.

# DISCUSSION

We found little or no evidence that the addition of the Seven Mile Hill Wind Energy Facility (SWEF) to the landscape negatively affected lek counts 8 years following development. When we incorporated time lags into our analysis, we detected small positive significant differences in the slopes postdevelopment. The lack of predevelopment data, especially at treatment leks, could have limited our ability to detect significant differences in trends in lek counts assuming no time lags occurred and the effect of the SWEF occurred during the first postdevelopment year. However, if we consider lag effects, our power to detect significant differences in the relative slopes increased and we are confident that we would have been able to detect such negative differences if they existed during the postdevelopment period because of our sampling effort.

We detected a small statistically nonsignificant negative decline postdevelopment assuming the effect of the SWEF occurred during the first postdevelopment year. However, our data set had relatively low power to detect a statistically significant negative decline of this magnitude. Power in our

**Table 3.** Model coefficients and Bonferroni corrected confidence intervals (98.6% CI) associated with the difference in slope differences between greater sage-grouse leks located within 1.5 km of turbines ($SWEFnear = 1$) and leks located beyond 1.5 km of turbines ($SWEFnear = 0$) pre- and postdevelopment ($\beta_7$) and in the overall magnitude of lek counts ($\beta_3$; assuming $\beta_7$ was not significant) using a generalized linear mixed-effects negative binomial model, Carbon County, Wyoming, USA, 2006–2016. We considered 7 time lags when the effects of the wind energy facility were realized by the male breeding population.

| | | *SWEFnear* × *Post* | | *Year* × *SWEFnear* × *PostYear* | |
|---|---|---|---|---|---|
| **Year of estimated effect** | **Years following development** | **$\beta_3$** | **98.6% CI** | **$\beta_7$** | **98.6% CI** |
| 2008–2009 | 1 | −0.22 | −1.564 to 1.124 | −0.08 | −0.837 to 0.678 |
| 2009–2010 | 2 | 0.106 | −0.923 to 1.135 | 0.035 | −0.400 to 0.469 |
| 2010–2011 | 3[a] | | | | |
| 2011–2012 | 4 | −0.17 | −1.181 to 0.84 | 0.091 | −0.239 to 0.421 |
| 2012–2013 | 5 | −0.53 | −1.595 to 0.545 | 0.222 | −0.18 to 0.623 |
| 2013–2014 | 6 | −0.74 | −1.972 to 0.502 | 0.52 | −0.121 to 1.161 |
| 2014–2015 | 7 | 0.262 | −1.146 to 1.671 | 0.383 | −0.794 to 1.56 |

[a] Model did not converge.

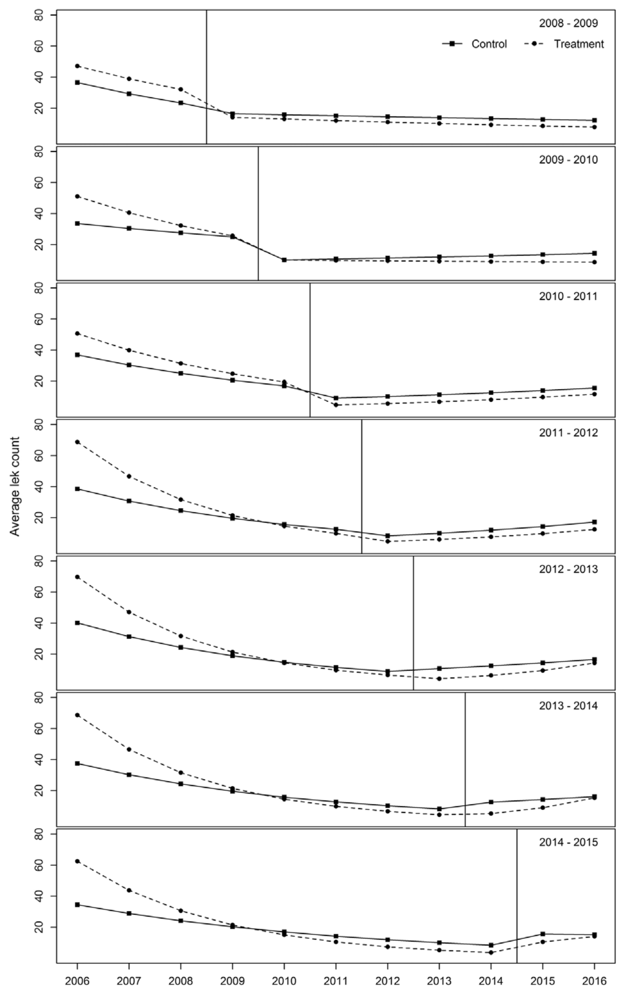

**Figure 3.** Estimated trends in the counts of male greater sage-grouse attending leks within the control and treatment study areas pre- (2006–2008) and postdevelopment (2009–2016) of the Seven Mile Hill Wind Energy Facility, Carbon County, Wyoming, USA, 2006–2016. The estimated year of effect is indicated on each graph as a solid vertical line.

data set increased as we increased the rate of decline and simulated time lag effects. With our data, a 20% increase in the rate of decline would equate to treatment leks declining to an average of <2 males/lek between 2012 and 2016 relative to control leks. Thus, the effect of the SWEF on lek counts at treatment leks would have to be rather large for us to detect assuming the effect of the SWEF occurred between 2008 and 2009. However, our ability to detect smaller differences in the rate of decline increases (>80% chance) if we assume the effect of the SWEF occurred between 2009 and 2010 (i.e., leks would decline to an average of <7 males/lek between 2012 and 2016). From the power analysis, we conclude our data set had a reasonable chance of detecting even relatively small increases in the rate of decline, especially if we assumed lag effects were to occur.

We detected a 56% drop in males attending treatment leks relative to control leks if we assume the effect occurred between 2011 and 2012. This drop in males attending treatment leks 3 years postdevelopment could be attributed to the SWEF and a lag response by males; however, the relative differences in trends between control and treatment leks during this time period were not statistically significant. This decline in males appears to be an isolated event between 2011 and 2012 because no other postdevelopment years experienced a drop in lek counts. The Pine Draw lek decreased from 5 males in 2011 to 0 males in 2012 and this drop was likely the cause of the differences between control and treatment leks during that time period. Counts at the Pine Draw lek appeared to be affected by the presence of turbines because counts were consistently 0 between 2012 and 2015 compared with leks >1.5 km from the nearest turbine, suggesting leks >1.5 km from the nearest turbine were able to persist on the landscape 8 years following development.

The negative influences of infrastructure on male sage-grouse lek attendance documented in several studies were associated with oil and gas development, which suggests the type of infrastructure and confounding factors associated with these infrastructure types (e.g., human presence, predator distributions, habitat suitability, etc.) may differentially affect males attending leks (e.g., Harju et al. 2010, Gregory and Beck 2014). Holloran (2005) assessed peak male lek attendance at 21 sage-grouse leks in southwestern Wyoming from 1999 to 2004 and found that leks located within 5.0 km of oil and gas development had greater annual rates of decline than control leks. Oil and gas density increased 3.6-fold across Wyoming from 1991 to 2011. This progression of oil and gas development was associated with a 24% decline in male lek attendance across the state during this period (Gregory and Beck 2014). Male lek attendance has also been shown to be negatively affected within multiple

**Table 4.** Model coefficients and Bonferroni corrected confidence intervals (98.6% CI) associated with the difference in slope differences for greater sage-grouse lek counts and distance to turbines pre- and postdevelopment ($\beta_7$) and in the overall magnitude of lek counts ($\beta_3$; assuming $\beta_7$ was not significant) using a generalized linear mixed-effects negative binomial model, Carbon County, Wyoming, USA, 2006–2016. We considered 7 time lags when the effects of the wind energy facility were realized by the male breeding population.

| | | ***d_turbine* × *Post*** | | ***Year* × *d_turbine* × *Post*** | |
|---|---|---|---|---|---|
| **Year of estimated effect** | **Years following development** | $\beta_3$ | **98.6% CI** | $\beta_7$ | **98.6% CI** |
| 2008–2009 | 1 | 0.037 | −0.062 to 0.136 | 0.018 | −0.034 to 0.071 |
| 2009–2010 | 2 | −0.02 | −0.091 to 0.056 | 0.004 | −0.024 to 0.033 |
| 2010–2011 | 3 | 0.014 | −0.055 to 0.084 | 0.004 | −0.019 to 0.026 |
| 2011–2012 | 4 | 0.013 | −0.061 to 0.087 | 0.001 | −0.022 to 0.025 |
| 2012–2013 | 5 | 0.05 | −0.027 to 0.127 | −0.01 | −0.038 to 0.018 |
| 2013–2014 | 6 | 0.053 | −0.032 to 0.137 | −0.03 | −0.069 to 0.016 |
| 2014–2015 | 7 | −0.02 | −0.117 to 0.084 | −0.01 | −0.095 to 0.07 |

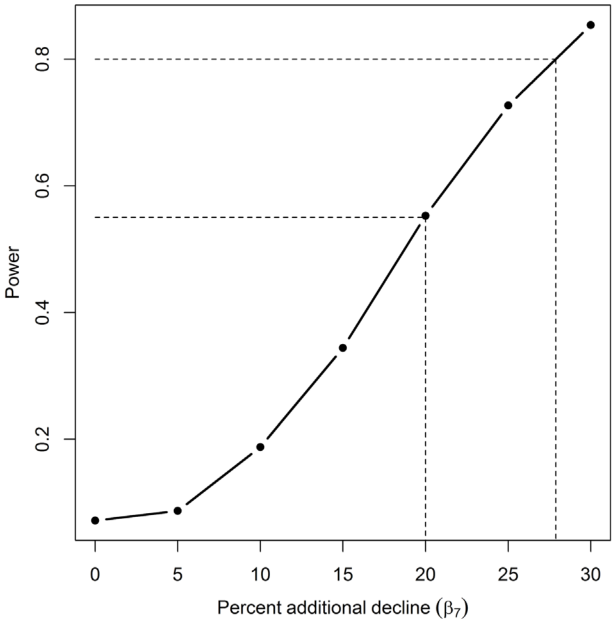

**Figure 4.** Estimated power curve for detecting additional rate of decline of male greater sage-grouse on treatment leks relative to control leks assuming the effect of the Seven Mile Hill Wind Energy Facility occurred between 2008 and 2009, Carbon County, Wyoming, USA, 2006–2016.

distance bands ranging from 0.8 km to 10 km of active wells (Walker et al. 2007, Harju et al. 2010, Hess and Beck 2012, Gregory and Beck 2014). In addition, there are time lags that range from 2 to 10 years (Harju et al. 2010) or 1 to 4 years (Doherty 2008, Gregory and Beck 2014), depending on spatial scale of well pad densities, before discernible effects on male attendance at leks associated with oil and gas development have been detected (Walker et al. 2007, Doherty 2008, Harju et al. 2010, Gregory and Beck 2014). The different types of infrastructure and associated human activity at the SWEF may not have a negative effect on lek counts compared with other types of energy development.

Most research on the response of prairie grouse to wind energy development has been conducted on greater prairie-chickens. Greater prairie-chicken lek abandonment was greatest within 8 km of turbines at a study site in Kansas during a 3-year postdevelopment period (Winder et al. 2015). The probability of greater prairie-chicken lek persistence pre- and postdevelopment at the study site in Kansas was attributed to lek size and habitat classification and not distance to turbine (Winder et al. 2015). Similar to our study, lek persistence did not appear to be influenced by wind turbines, but rather other environmental landscape features. The most logical explanation for leks declining in size and disappearing over time within the control and treatment area was the interaction between survival, fidelity, and male juvenile recruitment (Holloran et al. 2010). The presence of the SWEF may have influenced these interactions at the Pine Draw lek, located 0.5 km from the nearest turbine, but it is unclear what influenced these interactions at the Old Carbon 38 lek located in the control area because land uses did not change over the duration of the study period and this lek was located 6.3 km away from, and out of sight of, the nearest turbine. The declines at these leks could be related to population fluctuations exhibited by most sage-grouse populations regardless of their proximity to energy development, but the lack of male sage-grouse telemetry monitoring limited our ability to speculate on the causes of these declines at these leks.

We collected lek count data across an 11-year time period and at all leks in close proximity to the SWEF, which represented the entire male breeding population that could potentially be affected by this facility. Unlike other development studies, we were restricted to a relatively small development area (i.e., the extent of wind-energy development infrastructure was small (1,256 km$^2$ compared with 30,002 km$^2$; Hess and Beck 2012), and as a result we were limited to a few leks potentially affected by the SWEF. The number of leks was the single largest factor influencing statistical power to detect relatively small changes in trends in this longitudinal data set.

Results of our analysis provide insight into the response of male breeding sage-grouse to wind energy development. However, telemetry information on survival and habitat selection from monitored individuals may provide a more detailed assessment of potential effects of the SWEF on male breeding sage-grouse. Additional monitoring of multiple spatially distributed study sites would provide further information on impacts and cumulative effects of wind energy development on lek counts. Males from other sage-grouse populations may respond differently to wind-energy development infrastructure than this population because of varying degrees of habitat quality across the range of sage-grouse and differences in the size and layout of wind energy facilities.

## MANAGEMENT IMPLICATIONS

Current U.S. Fish and Wildlife Service Land-Based Wind Energy Guidelines do not have specific avoidance measures for prairie grouse for wind energy developers but the Guidelines do suggest effects will be similar to those from other anthropogenic structures (USFWS 2012). Guidelines specific to Wyoming state that wind energy development should not occur within 0.40 km of the perimeter of occupied leks outside of sage-grouse Core Areas and no wind energy development should occur within sage-grouse Core Areas (WY Executive Order 2015-4 2015). We did not observe a negative effect of males attending leks >1.5 km from the nearest turbine. Despite the fact that we failed to reject the hypotheses of no effect, it is possible an effect of the SWEF exists on males attending leks and we failed to detect it (i.e., we may have made a Type II error), and for this reason we recommend an abundance of caution in designating buffer sizes <1.5 km to avoid impacts from wind energy infrastructure on males attending leks.

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