Management and Conservation

Short-Term Impacts of Wind Energy Development on Greater Sage-Grouse Fitness

CHAD W. LEBEAU,[1] *Western EcoSystems Technology, Inc., 415 W. 17th Street, Suite 200, Cheyenne, WY 82001, USA*

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

GREGORY D. JOHNSON, *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*

ABSTRACT Greater sage-grouse (*Centrocercus urophasianus*) are experiencing population declines across much of their current range. Population declines are directly related to changes in greater sage-grouse fitness parameters including nest and brood success, and female survival. Reduced fitness in greater sage-grouse populations has been attributed to a decrease in habitat suitability caused by anthropogenic disturbance factors including energy extraction activities. The increased demand for renewable energy has raised concerns about the impacts of infrastructure associated with wind energy development on greater sage-grouse populations. We hypothesized that greater sage-grouse nest, brood, and adult survival would decrease with increasing proximity to wind energy infrastructure, particularly wind turbines. We monitored 95 nests, 31 broods, and identified 45 mortalities from 116 female greater sage-grouse from 2009 to 2010 at a wind energy facility in south-central Wyoming, USA. We used Cox proportional hazards regression to model nest survival and used the Andersen–Gill survival model to estimate female and brood survival relative to vegetation cover, topography, and distance to wind turbines and other anthropogenic features on the landscape. Results from our survival analysis indicated that the risk of a nest or brood failing decreased by 7.1% and 38.1%, respectively, with every 1.0 km increase in distance from nearest turbine. We detected no variation in female survival relative to wind energy infrastructure. Decreased nest and brood survival was likely the result of increased predation, which may have been a product of anthropogenic development and habitat fragmentation. Future wind energy developments should consider the increased risk of nest and brood failure within habitats of close proximity to turbines. Identifying nesting and brood-rearing habitats within close proximity to proposed wind energy developments is critical when estimating potential impacts to overall population fitness. © 2014 The Wildlife Society.

KEY WORDS *Centrocercus urophasianus*, energy development, fitness, greater sage-grouse, survival, wind energy, wind turbines.

Increasing concern for environmental sustainability and the demand for domestic energy has led to a large expansion of renewable wind energy development in the United States. Wind energy development is increasing in prairie habitats with high wind capacity, which has raised concerns over impacts to prairie grouse species including greater sage-grouse (*Centrocerus urophasianus*; hereafter, sage-grouse), sharp-tailed grouse (*Tympanuchus phasianellus*), and lesser (*T. pallidicinctus*) and greater (*T. cupido*) prairie chickens (Kuvlesky et al. 2007, American Wind Energy Association 2010). Direct impacts to prairie grouse from wind energy developments (e.g., collisions) are likely to be low because these species avoid tall structures and areas with human activities (Pruett et al. 2009*a*, *b*; Naugle et al. 2011). However, wind turbines and associated power transmission lines are likely to indirectly affect prairie grouse through habitat fragmentation and displacement. Although no peer-reviewed, published studies estimate the indirect and direct impacts from wind turbines to prairie grouse species, male lek attendance for forest-dwelling black grouse (*Lyrurus tetrix*) was negatively influenced by wind turbines 5 years after development of a wind energy facility in Austria where male lek attendance decreased and collisions with wind energy infrastructure were documented (Zeiler and Grünschachner-Berger 2009). Managers do not know how prairie grouse will respond to this new form of energy development and studies addressing the potential impacts of wind energy development to prairie grouse, including sage-grouse, are lacking (Johnson and Stephens 2011). Given the large overlap between sage-grouse habitats and areas with high wind energy capacity, a better understanding of the relationship between wind energy development and declining sage-grouse populations is necessary (Aldridge et al. 2008, Becker et al. 2009, Garton et al. 2011).

Although the type and magnitude of activities (i.e., timing and amount of anthropogenic traffic, size, and area of development) associated with oil and gas development differ

from those related to wind energy development, the demographic responses of sage-grouse populations to wind energy development may be similar to oil and gas development. For example, current sage-grouse declines are at least partially explained by lower annual survival of females (Taylor et al. 2012), and in the case of oil and gas development, impacts on females contribute to population-level declines (Holloran 2005). Negative impacts of oil and gas development on nest initiation and success also contribute to population-level declines (Lyon and Anderson 2003, Holloran 2005, Dzialak et al. 2011). Holloran (2005) found that sage-grouse nests were more successful in areas of lower natural gas well densities compared to that of higher density areas. Nests initiated in close proximity to a natural gas well that existed or were installed the previous year were at greater risk of failing than nests initiated farther from natural gas wells (Dzialak et al. 2011). In addition, nest initiation rates were reduced in areas of greater vehicle traffic associated with gas development (Lyon and Anderson 2003). Similar to nesting, impacts from anthropogenic features also influence brood-rearing. Chick mortality was 1.5 times greater in habitats where oil and gas wells were visible within 1 km from brood-rearing sites in southern Alberta (Aldridge and Boyce 2007). In addition, chicks reared in natural gas fields had lower survival probabilities as yearlings compared to those reared outside of gas fields (Holloran et al. 2010). These examples describe some degree of influence by anthropogenic features on sage-grouse fitness and indicate managers should consider similar impacts to sage-grouse populations from wind energy development.

The purpose of our study was to investigate the effect of wind energy infrastructure and associated habitat features on sage-grouse fitness. Specifically, we investigated sage-grouse nest, brood, and female survival relative to wind energy infrastructure, vegetation characteristics, and topographical features. We hypothesized that sage-grouse nest, brood, and female survival would decrease with proximity to infrastructure, specifically turbines, because similar impacts have been documented for sage-grouse inhabiting areas with oil and gas development (Aldridge and Boyce 2007, Holloran et al. 2010, Doherty et al. 2011, Dzialak et al. 2011, Kirol 2012).

STUDY AREA

Our study area, Seven Mile Hill (SMH), was located in Carbon County, Wyoming, USA between the towns of Medicine Bow and Hanna (Fig. 1). The study area was positioned north of Elk Mountain and Interstate-80 and south of the Shirley Basin in south-central Wyoming. Land ownership included Bureau of Land Management (BLM; 22.5%), private (69.5%), and State of Wyoming lands (8.0%). The SMH Wind Energy Facility (SWEF) was situated in the northern portion of the study area. Construction of the SWEF facility began in late summer 2008 and the facility became operational by December 2008. The SWEF consisted of 79-General Electric 1.5-Megawatt (MW) turbines capable of producing 118.5 MW of electricity on
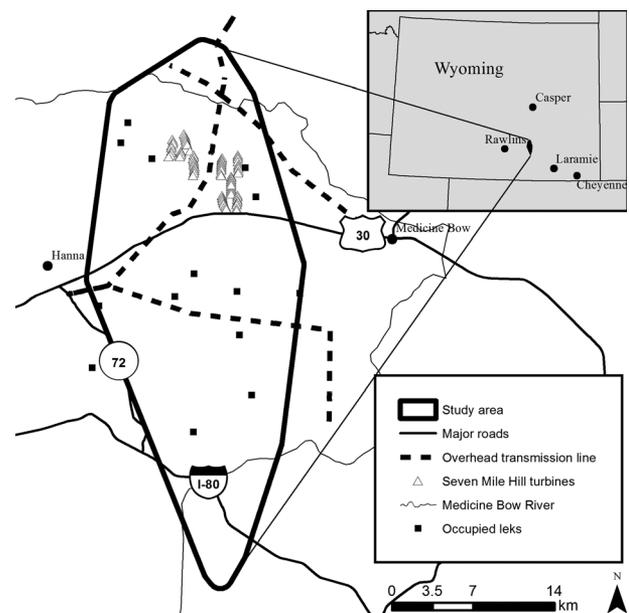
Figure 1. Seven Mile Hill study area in Carbon County, Wyoming, USA and occupied greater sage-grouse leks in 2009 and 2010. The Seven Mile Hill Wind Energy facility consisted of 79, 1.5-MW wind turbines.

an annual basis and approximately 29 km of access roads (Fig. 1). The SMH study area contained approximately 50 km of paved roads (Interstate-80, US HWY 30/287, and State HWY 72) and 43 km of overhead transmission lines. Overhead transmission lines and paved roads have existed on the SMH landscape for >10 years. The only anthropogenic features added to the SMH landscape, as a result of constructing the SWEF, were wind turbines and associated access roads (Fig. 1). Fourteen occupied sage-grouse leks were located within SMH, 3 of which occurred within 1.6 km of turbines (Fig. 1). The average peak number of males attending leks within SMH increased from 27 in 2000 to 52 in 2006 before declining to 22 in 2010.

Climate was classified as a semiarid, cold desert with a mean annual precipitation average of 26.7 cm and average temperatures ranging from $-2.33°$ C to $13.61°$ C (Western Regional Climate Center 2012). Elevations in the study area ranged from 1,737 m to 2,390 m above sea level. Shrub steppe, primarily dominated by Wyoming big sagebrush (*Artemisia tridentata wyomingensis*), was the most common cover type in the study area (U.S. Geological Survey [USGS] 2001). Dominant land uses included wind energy development, a surface coal mine near the southwestern edge of the study area, livestock grazing, and hunting.

METHODS

Field Methods

We captured 116 female sage-grouse by nighttime spotlighting and use of hoop nets (Giesen et al. 1982, Wakkinen et al. 1992) on roosts surrounding leks during the 2009 and 2010 breeding seasons. We attempted to capture sage-grouse at all accessible active lek sites within 16 km of

the SMH wind turbines proportionately to the number of males attending those leks. We aged, weighed (0.1-g precision), acquired blood samples (year 2009), and fitted each captured grouse with a 22-g necklace-mounted very high frequency radio transmitter with a battery life of 666 days (Advanced Telemetry Systems, Incorporated, model A4000, Isanti, MN). Radio transmitters were equipped with mortality censors that were triggered when transmitters were stationary for 8 hours. We released each radio-marked female at the point of capture and marked the location using a hand-held global positioning system (GPS) unit. We gained approval from the Wyoming Game and Fish Department (Chapter 33 permit 572 issued to Western EcoSystems Technology, Inc.) to capture, handle, and monitor female sage-grouse.

We relocated each radio-marked female 3 times each week during the pre-laying and nesting period (Apr through Jun) and at least once each week for brooding and barren (i.e., females that were not nesting or brood-rearing) females from hatch or nest loss through 31 October. We monitored marked sage-grouse primarily from the ground using hand-held receivers and Yagi antennas. We determined sage-grouse locations by triangulation or homing until visibly observed. In addition, we estimated the triangulation error by placing 6 test collars for each technician throughout the project area and estimated the mean telemetry error between the actual and estimated locations. The mean telemetry error rate was incorporated into our modeling efforts. We employed aerial telemetry to locate missing birds throughout the study period.

During the pre-nesting and nesting seasons (late Apr through 15 Jun), we monitored each radio-marked female sage-grouse from a distance >60 m at least every third day. We assumed females were nesting when movements became localized. We located nests using a progressively smaller concentric circle approach by walking circles around the radio signal using the signal strength as an indication of proximity (Holloran and Anderson 2005). Once a nest location was established, we conducted incubation monitoring on an alternate-day schedule to determine nesting fate. We mapped all nest locations using a hand-held GPS. We considered a nest that successfully hatched (i.e., eggs with detached membranes) ≥1 egg to be a successful nesting attempt (Rotella et al. 2004). We considered nests that failed to successfully hatch ≥1 egg either because of predation or abandonment to be failed nesting attempts. We monitored females that were unsuccessful in their first nesting attempt 3 times per week through 15 June to determine possible re-nesting attempts.

To evaluate brood survival, we located radio-marked females that successfully hatched ≥1 egg each week through 35–37 days post-hatch (Walker 2008). We categorized the brood-rearing period as early (hatch through 14 days post-hatch; Thompson et al. 2006) or late (>14 and ≤35–37 days post-hatch; Walker 2008). We considered females to be successful through the early brood-rearing period if ≥1 chick survived to 14 days post-hatch; we established chick presence during this period either through visual confirmation of a live chick or the brooding female's response to field observers (e.g., chick protective behavior exhibited). We determined fledging success (late brood success) for those females who were successful in early brood-rearing by assessing whether a female was brooding chicks through consecutive nighttime spotlight surveys conducted on days 35–37 post-hatch (Walker 2008); females successful in raising late broods were those we confirmed brooding at least 1 chick during the late brood period. We did not assess brood survival among individuals (i.e., marked chicks), but derived survival from flush and nighttime spotlighting of unmarked chicks and in some instances mixed broods. Brood amalgamation may have occurred, but we were concerned with the overall ability of a female to successfully rear at least 1 chick so we did not account for brood mixing in this analysis. We treated instances where a marked female could not be associated with a chick as brood failures.

Landscape Covariates

We developed a suite of covariates to estimate the hazard of nest, brood, and female survival. Anthropogenic features included major roads, transmission lines, and wind turbines (see Fig. 1). We included US HWY 30/287, Wyoming State Highway 72, and Interstate 80 as major roads. We digitized major roads and overhead transmission lines (230 kV wooden H-frame) using aerial photography imagery within ArcMap 10 (Environmental Systems Research Institute, Redlands, CA). We obtained turbine locations from PacifiCorp Energy (Salt Lake City, UT), the operators of the SWEF. Vegetation layers used in the analysis were developed by Homer et al. (2012) and derived using remote-sensed products and a combination of methods to integrate 2.4 m QuickBird, 30-m Landsat TM, and 56-m AWiFS (Advanced Wide Field Sensor) imagery from 2006 to 2007 into the characterization of vegetation components. We considered 4 primary components (percent bare ground, percent herbaceous cover, percent litter, and percent shrub cover) and 4 secondary components (3 types of shrub cover—percent sagebrush [*Artemisia* spp.], percent big sagebrush [*A. tridentata* spp.], and percent Wyoming big sagebrush—and shrub height; Homer et al. 2009, 2012; Table 1). We included the standard deviation of shrub height, total shrub cover, and total sagebrush cover in our modeling. We calculated landscape features, including elevation, slope, and rugged, from a 10-m National Elevation Dataset (USGS, EROS Data Center, Sioux Falls, SD). Rugged captured the variability in slope and aspect into a single measure ranging from 0 (no terrain variation) to 1 (complete terrain variation; Sappington et al. 2007; Table 1).

Survival Analyses

We used Cox proportional hazards models (Cox 1972) to estimate sage-grouse nest survival. We used the Andersen–Gill formulation of the Cox proportional hazards model (Therneau and Grambsch 2000) to estimate brood and female survival (Anderson and Gill 1982). The Anderson–Gill formulation of the Cox model accommodates multiple monitoring intervals by incorporating changes in habitat characteristics at each relocation that represent changes in

Table 1. Explanatory anthropogenic and environmental covariates used in modeling sage-grouse nest, brood, and female survival at the Seven Mile Hill study area, Carbon County Wyoming, USA, 2009 and 2010.

Covariates	Variable description
Anthropogenic infrastructure	
Roads	Distance to nearest major road [WYO HWY 72, US HWY 287/30, and I-80 (km)]
Tline	Distance to nearest overhead transmission line (km)
Turbine	Distance to nearest turbine (km)
Environmental	
Bare ground[a]	Percent bare ground
Big sagebrush[a]	Percent big sagebrush (*Artemisia tridentata* spp.)
Elevation	Altitude above sea level (m)
Herbaceous[a]	Percent herbaceous cover
Litter[a]	Percent litter
Sagebrush[a,b]	Percent sagebrush (*Artemisia* spp.)
Shrub[a,b]	Percent shrub cover
Shrub height[a,b]	Shrub height (0–253 cm)
Slope	Degrees 0–90
Rugged	Variability in slope and aspect (0–1; 1 = complete terrain variation; Sappington et al. 2007)
Wyoming big sagebrush[a]	Percent Wyoming big sagebrush (*Artemisia tridentata wyomingensis*)

[a] Vegetation covariates obtained from Homer et al. (2012).
[b] SD is the standard deviation of these shrub covariates, which we also included in the analysis.

exposure during the brood-rearing and female survival period (Therneau and Grambsch 2000, Johnson et al. 2004).

We assessed nest survival for a 26-day incubation period during the 2009 and 2010 nesting seasons (incubation period lasts 25–29 days; Schroeder et al. 1999). We combined nests observed across the study area into 1 sample to model survival relative to wind energy development. Re-nests can only result from a failed nesting attempt and may not be independent of first nests; thus, we excluded re-nests from analyses. Events or failures occurred when the sage-grouse abandoned its nest or its nest was depredated. We did not include abandoned nests thought to be caused by field observers in the survival analysis because of the potential bias associated with those nests. We estimated nest fate date using the last known monitoring interval as well as the condition of the nest to estimate the event date as well as the type of predator (mammalian or avian). We censored nests that were successful through the 26-day period (Nur et al. 2004). We used Cox proportional hazards to estimate the effects of wind energy infrastructure on nest survival (Nur et al. 2004, Aldridge and Boyce 2007, Liebezeit et al. 2009).

We combined early and late brood-rearing monitoring from both years for modeling survival of broods (Aldridge and Boyce 2007). To determine brood survival, we assessed the presence of chicks with hens at least 2 times during the first 14 days of the brood-rearing period and 1 final time at the end of the brood-rearing period. We used 5 weekly monitoring intervals during the brooding period. The first monitoring interval began directly after a successful hatched nest and monitoring ended on the fifth interval 35–37 days post-hatch. Events or failures occurred when we did not observe chicks or the female did not elicit behaviors indicating she had chicks during any 1 of the checks. The cause of brood failure could not be assessed because individual chicks were not marked. We defined the interval containing the event to be the interval between the last monitoring visit where chick presence was confirmed and the

first visit where chicks were absent. Because of our revisit schedule, events could have occurred during weeks 1, 2, and 5 when we assessed survival. The exact week of the event could not be determined if chicks were absent during week 5 (i.e., brood could have failed during weeks 3, 4, or 5). By assigning the event to week 5 and not week 3, reported overall brood survival rates may be overestimated by at most 10%; however, the relative difference in survival between broods as compared to covariate values is unbiased. We censored broods that were successful and survived the entire monitoring period to week 5 (Nur et al. 2004). We averaged covariates associated with intervals containing 2 or more relocations of the female.

Lastly, we modeled weekly female sage-grouse survival from time of capture to 31 October during both years. We assessed weekly survival for all monitored sage-grouse. Events or mortalities occurred when we confirmed mortality via telemetry. We evaluated the condition of the carcass in an attempt to determine cause of death. We estimated date of mortality by the condition of the carcass and last known monitoring interval. For example, when we discovered a mortality, we reviewed the most recent location where the individual was determined to be alive and either selected the date that was the mid-point between the last 2 locations (i.e., the last alive and dead intervals) or we estimated the date of mortality by assessing the condition of the carcass. We averaged covariates corresponding to individuals that recorded multiple locations within a specified interval.

Model Development

We included an indicator variable for age (adult = 1, yearling = 0) and year (2009 = 1, 2010 = 0) to determine if age or year influenced survival. We calculated average values of each environmental feature at 3 different scales defined by a circle with the radii corresponding to the mean telemetry error rate (0.30 km), the median distance between consecutive year's nests from 2009 to 2010 (0.46 km), and the median distance traveled by brooding females between

monitoring intervals during the brood-rearing period (1.0 km).

We used a forward model selection procedure to identify the effects of wind energy infrastructure on nest, brood, and female survival. We allowed each covariate to compete with each other in a forward selection procedure but did not allow 2 correlated variables ($r \geq |0.60|$) to be included in any 1 model to avoid collinearity. We performed model building using forward variable selection via improvements in adjusted Akaike's Information Criterion for small sample sizes (AIC_c; Burnham and Anderson 2002) using R language for statistical computing (R Development Core Team 2012). For example, the covariate selected first during the model building process for a survival estimate resulted in the lowest AIC_c score among other univariate models. We then added remaining covariates to the first selected covariate and reevaluated the model via AIC_c to see if the additional covariate further reduced the AIC_c score. If the model AIC_c was further reduced, then the model building process continued looking forward (adding covariates) until the AIC_c value could not be further reduced.

We calculated hazards ratios [exp(β)] and 90% hazard ratio confidence intervals to interpret the magnitude and influence of habitat and anthropogenic variables on survival of an individual nest, brood, or female. We considered hazards ratios that included 1 within their 90% confidence interval to be insignificant (alpha level = 0.10). We used survival curves to illustrate the varying degree of risk as a function of the top model covariates (Therneau and Grambsch 2000, Johnson et al. 2004). We used Schoenfeld residuals (Schoenfeld 1982) to assess model fit (Therneau et al. 1990, Grambsch and Therneau 1994, Kleinbaum and Klein 2005). We plotted the ranked Schoenfeld residuals for each covariate and for the top model as a whole against time to inspect the distribution of the residuals (see Figs. S1, S2, and S3, available online at www.onlinelibrary.wiley.com). Lastly, using the top hazard models, we estimated the relative risk of mortality at a resolution (100-m grid cells) that was meaningful to managers and comparable to the scale of habitat layers used in the analysis within a minimum convex polygon around all locations observed during each survival period (Johnson et al. 2004). We used these estimates to visually depict the relative risk of mortality across the study area.

RESULTS

Nest Survival
We located 50 nests in 2009 and 45 nests in 2010. We observed 2 re-nests in 2009 and 5 re-nests in 2010. We estimated nesting propensity, apparent nest success, and nest survival for all first nesting attempts ($n = 48$ [2009] and $n = 40$ [2010]). Nesting propensity, or the percentage of females observed initiating a nesting attempt, was 64.0% in 2009 ($n = 75$ females; 90% CI: 53.9–73.2%) and 48.8% in 2010 ($n = 82$ females; 90% CI: 39.2–58.4%). Nest hatch dates ranged from 26 May to 28 June (mean = 1 Jun) for all assumed first nesting attempts and from 29 June to 2 July (mean = 30 Jun) for all second nesting attempts. Two of the

7 observed re-nests were successful. Apparent nest success (fraction of the found first nesting attempts that successfully hatched ≥ 1 egg) was similar in 2009 (39.6%; $n = 19$; 90% CI: 27.7–52.5%) and 2010 (37.5%; $n = 15$; 90% CI: 24.7–51.7%). Although cause of death could not be determined for all nest failures, we determined 14 (14.7%) were killed by avian predators and 34 (35.8%) were killed by mammalian predators. We documented 16 first attempt nests within 1.6 km of wind turbines at SMH; 4 (25.0%) of these nests were successful but none of the 5 nests closest to turbines were successful.

We used 88 sage-grouse nests in Cox proportional hazards modeling (we removed 7 re-nests from the survival modeling). We estimated the nest survival rate during the 26-day incubation period as 39.7% (90% CI: 31.7–49.7%). The top model ($w_i = 0.51$) relating environmental and anthropogenic features to sage-grouse nest survival included standard deviation of shrub height (cm) within 0.30 km of a nest, distance (km) to nearest turbine, and distance to nearest overhead transmission line (Table 2).

The risk of a nest failing decreased by 17.3% for every 1 cm increase in the standard deviation of shrub height within 0.30 km of a nest (90% CI: 8.7–25.1%; Table 3). The risk of a nest failing increased by 12.4% with every 1.0 km increase in the distance to nearest overhead transmission line (90% CI: 0.3–25.9%; Table 3). Lastly, the risk of a nest failing decreased by 7.1% with every 1.0 km increase in distance from a turbine (90% CI: 2.7–11.3%; Table 3, Fig. 2). Spatially, habitats closer to turbines had higher relative risk of a nest failing than habitats farther from turbines (Fig. 3). Based on examination of the plotted Schoenfeld residuals, we found no evidence of non-proportional hazards for any of the 3 covariates included in the top model, suggesting that nest failures were independent.

Brood Survival
We monitored 31 females with broods during the brood-rearing period ($n = 20$ in 2009 and $n = 11$ in 2010). Early brood-rearing (hatch through 2 weeks post-hatch) success was relatively high during both study years but was greatest in 2009 (95.0%; 90% CI: 78.4–99.7%) compared to 72.7% (90% CI: 43.6–92.1%) in 2010; however, the difference in the means was not statistically different. Of the successful early brood females, 11 broods were successful through the late brood-rearing period (35–37 days post-hatch) in 2009 and 8 were successful in 2010. Apparent late brood-rearing success (fraction of females with broods successfully raising ≥ 1 chick 35–37 days post-hatch) was 18.9% lower in 2009 than in 2010 but was not statistically different (2009 = 61.1%, 90% CI: 39.4–79.5%; 2010 = 80.0%, 90% CI: 49.0–95.6%).

We used 131 locations, 5 monitoring intervals, and 31 broods to model brood survival relative to the landscape covariates. We censored 2 broods and did not included them in modeling, 1 because the brooding female was killed immediately following hatch and 1 because the female could not be found. Twelve broods failed during the brood-rearing period (survival = 83.5%; 90% CI: 69.8–99.8%). The top model ($w_i = 0.92$) relating environmental and anthropogenic

Table 2. Model fit statistics for greater sage-grouse nest, brood, and female survival at the Seven Mile Hill study area, Carbon County, Wyoming, USA, 2009 and 2010. Competing models are listed according to the model best fitting the data and ranked by (ΔAIC$_c$), the difference between the model with the lowest Akaike's Information Criterion for small samples (AIC$_c$) and the AIC$_c$ for the current model. The value of the maximized log-likelihood function (log [L]), the number of estimated parameters (K), and Akaike's weights (w_i) for each model are also presented. Competing models were limited to models with improved AIC$_c$ scores.

Model[a]	log[L]	K	AIC$_c$	ΔAIC$_c$	w_i
Nest survival					
Shrub height SD, turbine, tline	−214.716	3	435.696	0.000	0.513
Shrub height SD, turbine	−216.087	2	436.304	0.608	0.378
Shrub height SD	−218.372	1	438.786	3.090	0.109
Null	−220.583		441.167	5.471	0.032
Brood survival					
Turbine, rugged, shrub	−30.053	3	66.384	0.000	0.917
Turbine, rugged	−33.670	2	71.468	5.085	0.072
Turbine	−36.610	1	75.263	8.879	0.011
Null	−38.300		76.500	10.116	0.006
Female survival					
Roads, tline	−187.313	2	378.750	0.000	0.395
Roads	−188.560	1	379.167	0.417	0.320
Null	−189.707		379.400	0.650	0.285

[a] Shrub height SD is the standard deviation of shrub height within 0.30-km buffer, rugged within 0.46-km buffer, and shrub within 1-km buffer. Tline represents the distance to nearest overhead transmission line.

features to sage-grouse brood survival included distance to nearest turbine (km), rugged (scale = 0.46 km), and percent shrub cover within 1.0 km of a brood location (Table 2).

The relative risk of a brood failing increased approximately 5 fold with every 1-unit increase in rugged within 0.46 km of a brood location (90% CI: 2.1–11.3; Table 3). The risk of a brood failing increased approximately 3 fold with every 1.0% increase in percent shrub cover within 1.0 km of a brood location (90% CI: 1.5–6.2; Table 3). Lastly, the risk of a brood failing decreased by 38.1% with every 1.0 km increase in distance from nearest turbine (90% CI: 18.6–52.9%; Table 3, Figs. 2 and 3). Based on examination of the plotted Schoenfeld residuals, we found no evidence of non-proportional hazards for any of the 3 covariates included in the top model, suggesting that brood failures were independent.

Female Survival
During our study, 45 of 116 (38.8%) radio-marked female sage-grouse died. Similar to nest failures, we could not determine cause of death for all mortalities. Thirteen sage-grouse (28.9%) were killed by avian predators and 16 (35.6%) were killed by mammalian predators. In 2009, we submitted

3 dead radio-collared females that did not exhibit any signs of trauma to the Wyoming State Veterinary Laboratory in Laramie, Wyoming to be examined for the presence of West Nile virus. Two of the 3 (4.4% of all mortalities) female sage-grouse tested positive for West Nile virus.

We used 1,417 locations, 23 monitoring intervals, and 116 female sage-grouse to model weekly female sage-grouse survival. The estimated female survival rate during the summer period was 50.0% (90% CI: 41.0–61.1%). We censored 8 events because they occurred within 2 weeks of capture and may have been related to the capture event. The univariate modeling estimating differences in female survival indicated that capture location (i.e., lek of capture) did not influence female survival (hazard ratio = 0.84; 90% CI: 0.49–1.43). In addition, the age of each female (adult or yearling) did not influence female survival (hazard ratio = 1.3; 90% CI: 0.75–2.22). The set of competing models (i.e., models within 4 AIC$_c$ points) included the null model (Table 2), suggesting none of the covariates we considered explained the variation in female survival within our study. Based on examination of the plotted Schoenfeld residuals, we found no evidence of non-proportional hazards for the 2 covariates included in the top model.

Table 3. Relative risks of sage-grouse nests and broods for each covariate or risk factor included in the top model for the Seven Mile Hill study area in Carbon County, Wyoming, USA, 2009 and 2010.

Covariate[a]	Scale (km)	Estimate	SE	Hazard ratio	Hazard ratio 90% CI Lower	Hazard ratio 90% CI Upper
Nest survival						
Shrub height SD	0.30	−0.190	0.060	0.827	0.749	0.913
Turbine (km)		−0.074	0.028	0.929	0.887	0.973
Tline (km)		0.117	0.069	1.124	1.003	1.259
Brood survival						
Turbine (km)		−0.479	0.167	0.619	0.471	0.814
Rugged	0.46	1.576	0.517	4.834	2.066	11.31
Shrub	1.00	1.108	0.431	3.028	1.490	6.155

[a] Tline represents the distance to nearest overhead transmission line.
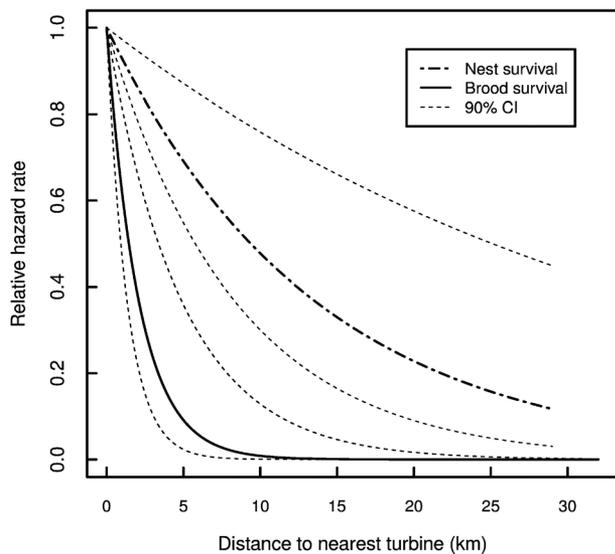
Figure 2. Relative hazard rate of sage-grouse nest and brood survival adjusted for the distance to nearest turbine at the Seven Mile Hill study area, Carbon County, Wyoming, USA, 2009 and 2010. Dotted lines indicate the lower and upper 90% confidence limits.

DISCUSSION

Our study is the first to estimate the short-term impacts of wind energy development on sage-grouse fitness parameters. The survival models we developed detected a greater relative probability of nest and brood failure in habitats within close proximity to turbines. However, the covariates used to model female survival did not detect any variability among individuals, indicating none of the landscape features we examined affected female survival, including distance to

turbine. In addition to distance to nearest turbine, the relative risk of a nest failing within the study area increased in habitats with a lower variability of shrub height and decreased in habitats closer to transmission lines. However, the relationship between nest survival and distance to transmission line was not substantial because of the large 90% confidence intervals. Lastly, the risk of a brood failing increased in habitats with higher rugged and percent shrub cover.

A synthesis of 50 sage-grouse demographic studies determined female survival was the most important fitness parameter that influenced population growth rate and concluded that future management of sage-grouse populations should focus on increasing female survival (Taylor et al. 2012). We did not detect any variability in female survival related to the distance to turbines, which is counter to research conducted in natural gas fields for sage-grouse and lesser prairie-chickens (Hagen 2003, Holloran 2005). At wind energy facilities, each turbine is visited on average 4 times per year for operation and maintenance purposes, whereas approximately 1,825 vehicle trips per year occurred on average at a producing natural gas well (Sawyer et al. 2009, BLM 2012). Reduced human activity within the wind development compared to oil and gas development may disturb sage-grouse less, thus having a smaller effect on female survival (Remington and Braun 1991, Holloran 2005). For example, meso-carnivore mammals and corvids, primary sage-grouse nest predators (Hagen 2011), may be attracted to wind energy developments because of subsidized food resources from deaths of birds by turbines, combined with low levels of human activity, whereas predators that prey on adults (e.g., golden eagles [*Aquila chrysaetos*]) may not. Alternatively, the inability of our models to detect variability in female survival within the SMH study area could be related to the omission of a covariate important for survival from the models. Disease could influence survival rate; however, West Nile Virus accounted for only 4.4% of all mortalities, thus appearing to be isolated incidents that would not affect the overall survival rate within the study area.

We used the best available habitat layers in our nest and brood survival analysis but are aware that some habitat features influential to nest and brood success were omitted. Numerous studies have established the importance of herbaceous understory in sagebrush-dominated habitats for sage-grouse nest and brood success (Connelly et al. 2011). The vegetation covariate layers we used from Homer et al. (2012) did not include some habitat features known to influence nest and brood success (e.g., residual grass cover and height, and forb cover and diversity [see Connelly et al. 2011]). Therefore, we cannot rule out that our nest and brood survival results reflect higher inherent quality nesting and brood-rearing habitats farther from wind turbines. In addition, small brood sample sizes reduced our power to detect variability in brood survival in our study area. However, because of the biology of sage-grouse, our sample size was similar to other brood survival studies (e.g., 35 [Aldridge and Boyce 2007], 33 [Kirol 2012], and 21 [Dahlgren et al. 2010]).
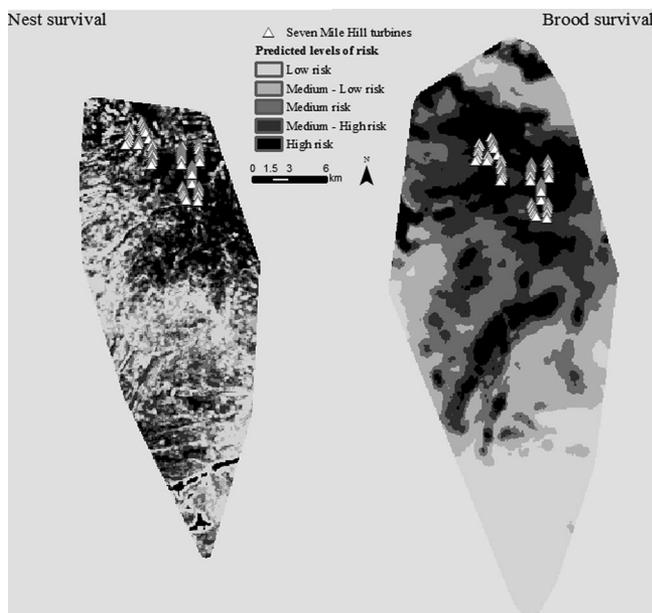
Figure 3. Spatial variation in the predicted relative risk of sage-grouse brood failure and nest failure (low to high) within the Seven Mile Hill study area, Carbon County, Wyoming, USA, 2009 and 2010.

Similar to our results, Kirol (2012) identified an increased risk of nest failure in habitats with low standard deviation of shrub height within habitats characteristic of oil and gas development. However, this may not be due to the influence of development type but rather the ecology of sage-grouse nest site selection. For example, increased variation in shrub height may provide adequate nesting habitat where nests are located in areas of higher shrub heights but are surrounded by habitat that contains lower shrub heights with increased herbaceous cover for foraging. Further development of finer-scaled, site-specific GIS layers may provide a more detailed summary of the influence of standard deviation of shrub height on nest survival.

The lack of other studies investigating impacts from wind energy development to sage-grouse survival limits our ability to make inferences about the cumulative impacts of wind energy development on sage-grouse survival, but we were able to describe some of the short-term impacts that wind energy developments may have on sage-grouse populations. Although available GIS data may have produced some uncertainty in the interpretation of our results, our results demonstrate that wind energy development has short-term implications to sage-grouse populations during nesting and brood-rearing. Our findings also point to the need for further research to identify potential mechanisms that may lead to reduce demographic fitness parameters of sage-grouse in areas near wind turbines. The potential reason for decreased nest and brood survival within habitats in close proximity to turbines in our study is unknown but is likely attributable to increased predation (Coates and Delehany 2010). However, the lack of pre-development data and concurrent predator surveys limit our ability to speculate as to the mechanism (e.g., edge effects or limitation of predatory defense mechanisms) driving predator-prey interactions in the wind development area.

MANAGEMENT IMPLICATIONS

Future wind energy project placement should consider the increased levels of risk to sage-grouse nests and broods within habitats of close proximity to wind turbines. Current United States Fish and Wildlife Service (USFWS) Land-Based Wind Energy Guidelines do not have specific prairie grouse avoidance measures for wind energy developers but do suggest impacts will be similar to those from other anthropogenic structures (USFWS 2012). Guidelines specific to Wyoming suggest wind energy development should not occur within 0.40 km of the perimeter of occupied leks outside of sage-grouse core areas and no development should occur within sage-grouse core areas (Wyoming Game and Fish Department 2010). We did not determine actual thresholds, but placing wind turbines at least 5 km from nesting and brood-rearing habitats should reduce negative influences from wind energy infrastructure in the short-term. These results indicate the current guidelines may be inadequate for future wind energy developments outside of Wyoming sage-grouse core areas. Because most mortalities and failures were attributable to predation, we are confident that decreased probabilities of survival were related

to increased predation risk; but, identifying the direct source of risk was difficult (e.g., increased predator numbers, ecological trap habitats, subsidized predators, compromised defense mechanisms). We recommend that future research consider predator-prey mechanisms by estimating avian and mammal predator density to better understand the impacts of wind energy development on sage-grouse fitness parameters to develop sustainable mitigation measures. We also recommend that future studies investigating fitness consequences to sage-grouse from energy development consider habitat covariates not currently available in GIS including residual grass cover and height and forb cover and diversity.

LITERATURE CITED

Aldridge, C. L., and M. S. Boyce. 2007. Linking occurrence and fitness to persistence: habitat-based approach for endangered greater sage-grouse. Ecological Applications 17:508–526.

Aldridge, C. L., S. E. Nielsen, H. L. Beyer, M. S. Boyce, J. W. Connelly, S. T. Knick, and M. A. Schroeder. 2008. Range-wide patterns of greater sage-grouse persistence. Diversity and Distributions 14:983–994.

American Wind Energy Association. 2010. U.S. projects database. <http://www.awea.org/la_usprojects.cfm>. Accessed 1 Feb 2011.

Anderson, P. K., and R. D. Gill. 1982. Cox's regression model for counting processes: a large sample study. The Annals of Statistics 10:1100–1120.

Becker, J. M., J. D. Tagestad, C. A. Duberstein, and J. L. Downs. 2009. Sage-grouse and wind energy: biology, habits, and potential effects from development. PNNL-18567. Pacific Northwest National Laboratory, Richland, Washington, USA. <http://www.pnl.gov/main/publications/external/technical_reports/PNNL-18567.pdf>. Accessed 1 Dec 2012.

Bureau of Land Management [BLM]. 2012. Proposed plan amendment & final environmental impact statement/final environmental impact report for the Ocotillo Wind Energy Facility. El Centro Field Office, El Centro, California, USA. <http://www.blm.gov/ca/st/en/fo/elcentro/nepa/ocotillo_express_wind.html>. Accessed 14 Dec 2012.

Burnham, K. P., and D. R. Anderson. 2002. Model selection and multimodel inference: a practical information-theoretic approach. Second edition. Springer-Verlag, New York, New York, USA.

Coates, P. S., and D. J. Delehany. 2010. Nest predation of greater sage-grouse in relation to microhabitat factors and predators. Journal of Wildlife Management 74:240–248.

Connelly, J. W., E. T. Rinkes, and C. E. Braun. 2011. Characteristics of greater sage-grouse habitats: a landscape species at micro- and macro-scales. Pages 69–83. in S. T. Knick, and J. W. Connelly, editors. Greater sage-grouse: ecology and conservation of a landscape species and its habitats. Studies in Avian Biology Series. Volume 38. University of California Press, Berkeley, California, USA.

Cox, D. R. 1972. Regression models and life-tables. Journal of the Royal Statistical Society Series B-Statistical Methodology 34:187–220.

Dahlgren, D. K., T. A. Messmer, and D. N. Koons. 2010. Achieving better estimates of greater sage-grouse chick survival in Utah. Journal of Wildlife Management 74:1286–1294.

Doherty, K. E., D. E. Naugle, H. Copeland, A. Pocewiz, and J. Kiesecke. 2011. Energy development and conservation tradeoffs: systematic planning for sage-grouse in their eastern range. Pages 505–517. in S. T. Knick, and J. W. Connelly, editors. Greater sage-grouse: ecology and conservation of a landscape species and its habitats. Studies in Avian Biology Series. Volume 38. University of California Press, Berkeley, California, USA.

Dzialak, M. R., C. V. Olson, S. M. Harju, S. L. Webb, J. P. Mudd, J. B. Winstead, and L. D. Hayden-Wing. 2011. Identifying and prioritizing greater sage-grouse nesting and brood-rearing habitat for conservation in human-modified landscapes. PLoS ONE 6:e26273.

Garton, E. O., J. W. Connelly, J. S. Horne, C. A. Hagen, A. Moser, and M. A. Schroeder. 2011. Greater sage-grouse population dynamics and probability of persistence. Pages 293–381. in S. T. Knick, and J. W. Connelly, editors. Greater sage-grouse: ecology and conservation of a landscape species and its habitats. Studies in Avian Biology Series. Volume 38 University of California Press, Berkeley, California, USA.

Giesen, K. M., T. J. Schoenberg, and C. E. Braun. 1982. Methods for trapping sage grouse in Colorado. Wildlife Society Bulletin 10:224–231.

Grambsch, P. M., and T. M. Therneau. 1994. Proportional hazards test and diagnostics based on weighted residuals. Biometrika 81:515–526.

Hagen, C. A. 2003. A demographic analysis of lesser prairie-chicken populations in southwest Kansas: survival, population viability, and habitat use. Dissertation, Kansas State University, Manhattan, USA.

Hagen, C. A. 2011. Predation on greater sage-grouse: facts, process, and effect. Pages 95–100. in S. T. Knick, and J. W. Connelly, editors. Greater sage-grouse: ecology and conservation of a landscape species and its habitats. Studies in Avian Biology Series. Volume 38 University of California Press, Berkeley, California, USA.

Holloran, M. J. 2005. Greater sage-grouse (Centrocercus urophasianus) population response to natural gas field development in western Wyoming. Dissertation, University of Wyoming, Laramie, USA.

Holloran, M. J., and S. H. Anderson. 2005. Spatial distribution of greater sage-grouse nests in relatively contiguous sagebrush habitats. Condor 107:742–752.

Holloran, M. J., R. C. Kaiser, and W. A. Hubert. 2010. Yearling greater sage-grouse response to energy development in Wyoming. Journal of Wildlife Management 74:65–72.

Homer, C. G., C. L. Aldridge, D. K. Meyer, M. J. Coan, and Z. H. Bowen. 2009. Multiscale sagebrush rangeland habitat modeling in southwest Wyoming. U.S. Geological Survey, Washington, D.C., USA.

Homer, C. G., C. L. Aldridge, D. K. Meyer, and S. J. Schell. 2012. Multi-scale remote sensing sagebrush characterization with regression trees over Wyoming, USA: laying a foundation for monitoring. International Journal of Applied Earth Observation and Geoinformation 14:233–244.

Johnson, C. J., M. S. Boyce, C. C. Schwartz, and M. A. Haroldson. 2004. Modeling survival: application of the Andersen-Gill Model to Yellow-stone grizzly bears. Journal of Wildlife Management 68:966–978.

Johnson, G. D., and S. E. Stephens 2011. Windpower and biofuels: a green dilemma for wildlife conservation. Pages 131–157. in D. E. Naugle, editor. Energy development and wildlife conservation in western North America. Island Press, Washington, D.C., USA.

Kirol, C. P. 2012. Quantifying habitat importance for greater sage-grouse (Centrocercus urophasianus) population persistence in an energy development landscape. Thesis, University of Wyoming, Laramie, USA.

Kleinbaum, D. G., and M. Klein. 2005. Survival analysis, a self-learning text. Second edition. Springer Science + Business Media, Inc., New York, New York, USA.

Kuvlesky, W. P., L. A. Brennan, M. L. Morrison, K. K. Boydston, B. M. Ballard, and F. C. Bryant. 2007. Wind energy development and wildlife challenges and opportunities. Journal of Wildlife Management 71:2487–2498.

Liebezeit, J. R., S. J. Kendall, S. Brown, C. B. Johnson, P. Martin, T. L. McDonald, D. C. Payer, C. L. Rea, A. Streever, A. M. Wildman, and S. Zack. 2009. Influence of human development and predators on nest survival of tundra birds, Arctic Coastal Plain, Alaska. Ecological Applications 19:1628–1644.

Lyon, A. G., and S. H. Anderson. 2003. Potential gas development impacts on sage grouse nest initiation and movement. Wildlife Society Bulletin 31:486–491.

Naugle, K., E. Doherty, B. L. Walker, M. J. Holloran, and H. E. Copeland, 2011. Energy development and greater sage-grouse. Pages 489–505. in S. T. Knick, and J. W. Connelly, editors. Greater sage-grouse: ecology and conservation of a landscape species and its habitats. Studies in Avian Biology Series. Volume 38 University of California Press, Berkeley, California, USA.

Nur, N., A. L. Holmes, and G. R. Geupel. 2004. Use of survival time analysis to analyze nesting success in birds: an example using loggerhead shrikes. Condor 106:457–471.

Pruett, C. L., M. A. Patten, and D. H. Wolfe. 2009a. It's not easy being green: wind energy and a declining grassland bird. Bioscience 59:257–262.

Pruett, C. L., M. A. Patten, and D. H. Wolfe. 2009b. Avoidance behavior by prairie grouse: implications for development of wind energy. Conservation Biology 23:1253–1259.

Remington, T. E., and C. E. Braun. 1991. How surface coal mining affects sage grouse, North Park, Colorado. Proceedings, issues and technology in management of impacted western wildlife. Thorne Ecological Institute 5:128–132.

Rotella, J. J., S. J. Dinsmore, and T. L. Shaffer. 2004. Modeling nest-survival data: a comparison of recently developed methods that can be implemented in MARK and SAS. Animal Biodiversity and Conservation 27:187–205.

Sappington, M. J., K. M. Longshore, and D. B. Thompson. 2007. Quantifying landscape ruggedness for animal habitat analysis: a case study using bighorn sheep in the Mojave Desert. Journal of Wildlife Management 71:1419–1426.

Sawyer, H., M. J. Kauffman, and R. M. Nielson. 2009. Influence of well pad activity on winter habitat selection patterns of mule deer. Journal of Wildlife Management 73:1052–1061.

Schoenfeld, D. 1982. Residuals for the proportional hazards regression model. Biometrika 69:239–241.

Schroeder, M. A., J. R. Young, and C. E. Braun. 1999. Sage grouse (Centrocercus urophasianus). Pages 1–28. in A. Poole, and F. Gill, editors. The birds of North America. The Birds of North America Inc., Philadelphia, Pennsylvania, USA.

Taylor, R. L., B. L. Walker, D. E. Naugle, and L. S. Mills. 2012. Managing multiple vital rates to maximize greater sage-grouse population growth. Journal of Wildlife Management 76:336–347.

Therneau, T. M., and P. M. Grambsch 2000. Modeling survival data: extending the Cox model. Springer-Verlag, New York, New York, USA.

Therneau, T. M., P. M. Grambsch, and T. R. Fleming. 1990. Martingale-based residuals for survival models. Biometrika 77:147–160.

Thompson, K. M., M. J. Holloran, S. J. Slater, J. L. Kuipers, and S. H. Anderson. 2006. Early brood-rearing habitat use and productivity of greater sage-grouse in Wyoming. Western North American Naturalist 66:332–342.

U.S. Fish and Wildlife Service [USFWS]. 2012. Final land-based wind energy guidelines. U.S. Fish and Wildlife Service, Arlington, Virginia, USA.

U.S. Geological Survey [USGS]. 2001. Land use/land cover national land cover database. USGS Headquarters, USGS National Center, Reston, Virginia, USA.

Wakkinen, W. L., K. P. Reese, J. W. Connelly, and R. A. Fischer. 1992. An improved spotlighting technique for capturing sage grouse. Wildlife Society Bulletin 20:425–426.

Walker, B. L. 2008. Greater sage-grouse response to coal-bed natural gas development and West Nile virus in the Powder River Basin, Montana and Wyoming, USA. Dissertation, University of Montana, Missoula, USA.

Western Regional Climate Center. 2012. Medicine Bow, Wyoming (486120). <http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?wy6120>. Accessed 1 Feb 2012.

Wyoming Game and Fish Department. 2010. Wildlife protection recommendations for wind energy development in Wyoming. Wyoming Game and Fish Department, Cheyenne, Wyoming, USA.

Zeiler, H. P., and V. Grünschachner-Berger. 2009. Impact of wind power plants on black grouse, Lyrurus tetrix in Alpine regions. Folia Zoologica 58:173–182.

Associate Editor: Bret Collier.

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article at the publisher's web-site.