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LeBeau, Chad, W, Evaluation of Greater Sage-Grouse Reproductive Habitat and Response to
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The demand for clean renewable energies and tax incentives has prompted a nationwide increase in wind energy development. Renewable energy development is occurring in a wide variety of habitats potentially impacting many species including greater sage-grouse (*Centrocercus urophasianus*). Greater sage-grouse require contiguous intact sagebrush (*Artemisia* spp.) habitats. The addition of wind energy infrastructure to these landscapes may negatively impact population viability. Greater sage-grouse are experiencing range-wide population declines and are currently listed as a candidate species under the Endangered Species Act of 1973. The purpose of my study was to investigate the response of greater sage-grouse to wind energy development. Mine is the first study to document the short-term effects of wind energy infrastructure on greater sage-grouse habitat selection, nest, brood, and female survival, and male lek attendance. I hypothesized that greater sage-grouse would select for habitats farther from wind energy infrastructure, particularly wind turbines, during the nesting, brood-rearing, and summer periods. In addition, I hypothesized that greater sage-grouse nest, brood, and female survival would decline in habitats with close proximity to wind turbines. Lastly, I hypothesized that greater sage-grouse male lek attendance would experience greater declines from pre wind energy development to 4 years post development at leks with close proximity to wind turbines compared to leks farther from turbines.

My study area was located in south-central Wyoming between the towns of Medicine Bow and Hanna and consisted of one study area influenced by wind energy development (Seven

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Mile Hill) and a second study area that was not impacted by wind energy development (Simpson Ridge). I identified 14 leks within both study areas and conducted lek counts at each of these leks from 2008 to 2012. I captured 116 female greater sage-grouse from both study areas from 2009 to 2010. I equipped each female grouse with a VHF necklace-mounted transmitter and monitored them via telemetry during the nesting, brood-rearing, and summer periods within both study areas from 2009 to 2010. I documented greater sage-grouse habitat selection as well as nest and brood-rearing success and female survival. I used binary logistic regression in a use versus availability study design to estimate the odds of habitat selection within both study areas during the nesting, brood-rearing, and summer periods. I used Cox proportional hazards and Andersen-Gill survival models to estimate nest, brood, and female survival relative to wind energy infrastructure. Lastly, I used ratio of means tests and linear mixed effects models to estimate the degree of decline in male lek attendance at leks influenced by wind energy development versus leks with no influence 1 year prior to development to 4 years post development.

Greater sage-grouse did not avoid wind turbines during the nesting and brood-rearing periods, but did select for habitats closer to turbines during the summer season. Greater sage-grouse nest and brood survival decreased in habitats in close proximity to wind turbines, whereas female survival appeared not to be affected by wind turbines. Peak male lek attendance within both study areas experienced significant declines from 1 year pre development to 4 years post development; however, this decline was not attributed to the presence of the wind energy facility.

The results from my study are the first examining the short-term impacts to greater sage-grouse populations from wind energy development. Greater sage-grouse were not avoiding the wind energy development two years following construction and operation of the wind energy facility. This is likely related to high site fidelity inherent in sage-grouse. In addition, more

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suitable habitat may exist closer to turbines at Seven Mile Hill, which may also be driving selection. Fitness parameters including nest and brood survival were reduced in habitats of close proximity to wind turbines and may be the result of increased predation and edge effects associated with the wind energy facility. Lastly, wind energy infrastructure appears not to be affecting male lek attendance 4 years post development; however, time lags are characteristic in greater sage-grouse populations, which may result in impacts not being quantified until 2–10 years following development. Future wind energy developments should identify greater sage-grouse nest and brood-rearing habitats prior to project development to account for the decreased survival in habitats of close proximity to wind turbines. More than 2 years of occurrence data and more than 4 years of male lek attendance data may be necessary to account for the strong site fidelity and time lags present in greater sage-grouse populations.

EVALUATION OF GREATER SAGE-GROUSE REPRODUCTIVE HABITAT AND

RESPONSE TO WIND ENERGY DEVELOPMENT IN SOUTH-CENTRAL, WYOMING

By

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CHAPTER 1

Introduction

WIND ENERGY DEVELOPMENT

Increasing concern for environmental sustainability and the demand for domestic energy have led to investment in renewable energies including biofuels, geothermal, hydropower, solar, and wind in the United States. The United States has adopted a nationwide energy policy focused on renewable energies that states that 20% of all electricity will be provided by wind energy by 2030 (DOE 2008). This initiative has triggered a nationwide increase in wind energy development. In addition, energy demand and tax incentives are encouraging prolific development of wind energy resources, making wind energy the fastest growing renewable energy source.

Wind energy development is occurring across many different landscapes, potentially resulting in habitat fragmentation for numerous wildlife species, ultimately leading to indirect and direct impacts (Kuvlesky et al. 2007). Direct impacts to wildlife species include bird and bat collisions with wind turbine blades or other infrastructure associated with wind energy development (e.g., guy wires, meteorological towers, and power lines). Such impacts to birds and bats are well documented (e.g., Erickson et al. 2001, Johnson et al. 2003). While direct impacts of wind energy development to birds and bats have been well documented, knowledge of indirect impacts is lacking. Indirect impacts potentially resulting from size, noise, and placement of turbines and associated wind energy infrastructure, including roads, transmission lines, and power transfer stations, pose the greatest threat to wildlife (Kuvlesky et al. 2007). The cumulative direct and indirect impacts from wind energy development to wildlife and their

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habitats may contribute to overall declines in productivity and population persistence (WGFD 2009).

Wind energy development is increasing in prairie habitats with high wind capacity (AWEA 2010). This has raised concerns over impacts to prairie grouse species including greater sage-grouse (*Centrocercus urophasianus*), sharp-tailed grouse (*Tympanuchus phasianellus*), and lesser (*T. pallidicinctus*), and greater (T. *cupido*) prairie-chickens (Kuvlesky et al. 2007). Although direct impacts to prairie grouse are likely to be low, indirect impacts from anthropogenic features are likely to occur (Kuvlesky et al. 2007). Pruett et al. (2009*a*) suggest that indirect impacts of wind turbines and associated power transmission lines are likely to impact prairie grouse movement because the species avoid tall structures and areas with human activities. Pruett et al. (2009*b*) determined that lesser and greater prairie-chickens avoided transmission lines and some major roads by at least 100 m in Oklahoma. There few publicly available studies examining the response of prairie grouse species to wind energy development (Johnson and Stephens 2010). Near an operating wind energy facility in Nebraska, prairie-chicken and sharp-tailed grouse lek attendance appeared to be within the range of other non-impacted leks during a 4-yr period (NGPC 2009). In Minnesota, nesting female prairie chickens did not avoid wind turbines when selecting of adequate nesting habitat (Toepfer and Vodehnal 2009). Lastly, black grouse (*Lyrurus tetrix*) lek attendance was negatively impacted by wind turbines 4-yrs after development of a facility in Austria (Zeiler and Grunschachner-Berger 2009).

Little information exists on the impacts of wind energy development on greater sage-grouse (hereafter sage-grouse). However, numerous studies indicate that sage-grouse are influenced by anthropogenic features including energy development (Lyon and Anderson 2003, Holloran 2005, Doherty et al. 2008, Holloran et al. 2010). In addition, the degree of influence

varies by proximity to these features (Holloran 2005, Aldridge and Boyce 2007, Holloran et al. 2010). Holloran (2005) reported that adult female sage-grouse remained in traditional nesting areas regardless of increasing development levels, though yearling females avoided energy infrastructure by nesting farther away from development. Furthermore, Holloran et al. (2010) determined the number of yearling female nests within 950 m of infrastructure was less than expected and the number of nests outside of 950 m was more than expected. 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. In addition, nest initiation rates were reduced in areas of greater vehicle traffic from gas development (Lyon and Anderson 2003).

Similar to nesting parameters, impacts from anthropogenic features also influence brood-rearing parameters. Aldridge and Boyce (2007) reported that chick mortality was 1.5-times higher in habitats where oil and gas wells were visible 1 km from brood-rearing sites. Lastly, male sage-grouse lek attendance rates have been negatively impacted by oil and gas development (Holloran 2005, Walker et al. 2007, Doherty 2008, Harju et al. 2010).

These examples describe some degree of influence by anthropogenic features on sage-grouse distribution and productivity (Holloran 2005, Aldridge and Boyce 2007, Holloran et al. 2010). However, studies addressing the potential impacts of wind energy development to prairie grouse, especially sage-grouse, are lacking.

GREATER SAGE-GROUSE POPULATION TRENDS

Sage-grouse occur in Alberta, California, Colorado, Idaho, Montana, Nevada, North Dakota, Oregon, Saskatchewan, South Dakota, Utah, Washington, and Wyoming, where they occupy about 56% of their historical pre-settlement range (Schroeder et al. 2004). Sage-grouse have been experiencing range-wide population declines, and many monitored populations have been

declining 2% per year since 1965 (Connelly et al. 2004). Garton et al. (2011) predicted that at

least 13% of sage-grouse populations may decline below effective population sizes of 500 within

the next 30 years. Also, Garton et al. (2011) projected that 75% of populations and 29% of the 7

management zones in the United States are likely to decline below effective population sizes of

500 within 100 yrs if current conditions and trends persist.

The decline in sage-grouse populations has been attributed to degradation of sagebrush

habitats (Knick et al. 2003, Connelly et al. 2004, and Aldridge et al. 2008) from disturbance

factors including agricultural conversion (Swenson et al. 1987, Connelly et al. 2004), invasions

of exotic plants leading to increased fire frequencies (Knick et al. 2003, Connelly et al. 2004),

and more recently energy exploitation and extraction (Lyon and Anderson 2003, Holloran 2005,

Holloran et al. 2010, Doherty et al. 2011, Naugle et al. 2011). Sage-grouse are a sagebrush

obligate species (Braun et al. 1977), entirely dependent on healthy continuous sagebrush habitats

for successful reproduction and survival (Schroeder et al. 1999, Connelly et al. 2004).

Fragmentation and degradation of these sagebrush habitats inhibit sage-grouse productivity and

survival, which have long-term impacts on affected sage-grouse populations. Understanding the

current threats and potential new threats to the viability of sage-grouse populations is imperative

to the conservation of this species.

STUDY PURPOSE

The conservation efforts of sage-grouse populations must consider all potential threats that

inhibit population viability. Energy exploitation that includes oil and gas development is

considered a threat to sage-grouse population viability (Lyon and Anderson 2003, Holloran

2005, Holloran et al. 2010, Doherty et al. 2011, Naugle et al. 2011). Energy exploitation in the

form of wind energy may pose similar threats to sage-grouse populations; however, the extent of

these impacts on population viability is unknown. My study was the first study examining the potential short-term impacts to sage-grouse populations from wind energy development. The purpose of my study was to estimate the effects of wind energy infrastructure, particularly wind turbines, on sage-grouse habitat selection patterns, population demographics, and male lek attendance.

STUDY AREA

My study area was located in Carbon County, Wyoming between the towns of Medicine Bow and Hanna (Fig. 1-1). The area was positioned north of Elk Mountain and Interstate-80 and south of the Shirley Basin. Land ownership included Bureau of Land Management (BLM), private, and State of Wyoming lands. Seven Mile Hill (SMH) was situated in the northern portion of my study area, and had an operating wind energy facility. The Seven Mile Hill Wind Energy Facility (SWEF) located within SMH consisting of 79-General Electric 1.5-MW turbines capable of producing 118.5 MW of electricity on an annual basis (Fig. 1-1). Construction of this facility began in late summer of 2008 and the facility became operational by December 2008. The facility was situated north of U.S. Highway 30/287 and south of the Medicine Bow River (Fig. 1-1). Elevations in the northern portion of the study area range from 1,737 to 2,118 m above sea level with the highest point being Seven Mile Hill. Mean annual precipitation averaged 26.7 cm and the area was classified as semiarid, cold desert with average temperatures ranging from -2.33°C to 13.61°C (WRCC 2012). Scrub and shrub, dominated primarily by Wyoming big sagebrush (*Artemisia tridentata wyomingensis*), was the most common cover type in the SMH study area (USGS 2001). There were 5 occupied sage-grouse leks located within the SMH study area (Fig. 1-1).

Simpson Ridge (SR), an area absent of wind turbines, lies adjacent to the SMH wind energy facility, south of U.S. Highway 30/287 (Fig. 1-1). The Simpson Ridge Wind Resource Area (SRWRA) is a proposed wind energy facility and is located within SR (Fig. 1-1). Due to high densities of breeding sage-grouse, most of the SRWRA was within an area mapped by the State of Wyoming as a sage-grouse "Core Population Area" (version 3, (EO) 2010-4, which was updated on June 2, 2011 by Governor Mead's EO 2011-5). Currently, development of this site has been terminated. The SR study area comprised the SRWRA and the surrounding area south of U.S. Highway 30/287. The SR contained numerous ridges interspersed with rolling to hilly plains. Elevations ranged from 2,040–2,390 m above sea level. Simpson Ridge was situated near the base of the Snowy Range Mountains to the south, and south of the Shirley Basin. Climate was classified as a semiarid, cold desert with a mean annual precipitation average of 26.7 cm and the area was classified as semiarid, cold desert with average temperatures ranging from -2.33°C to 13.61°C (WRCC 2012). Land cover classifications indicate that SR was almost entirely comprised of scrub-shrub dominated by Wyoming big sagebrush (USGS 2001). There were 9 occupied sage-grouse leks located within the SR study area (Fig. 1-1).

The SWEF included 79 turbines and approximately 29 km of access roads; however, other anthropogenic features associated with wind energy development occur throughout the entire study area including SR. There were approximately 8 km of paved roads (US HWY 30) and 26 km of overhead transmission lines within the SMH study area. In addition, there were approximately 50 km of paved roads (I-80, US HWY 30, and state HWY 72) and 17 km of overhead transmission lines within the SR study area. The overhead transmission lines and paved roads have existed on the landscape for more than 10 years. The only anthropogenic features

added to the landscape were the SWEF wind turbines and the associated access roads located within SMH (Fig. 1-1).

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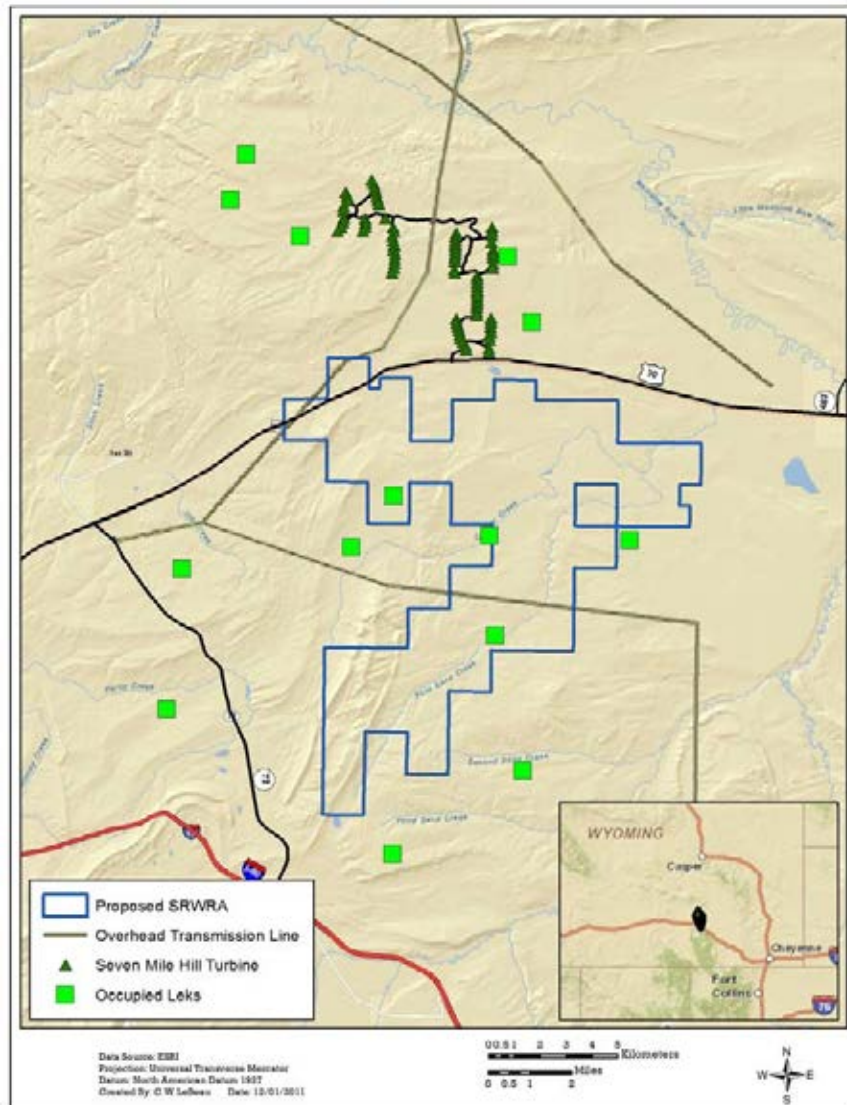
Figure 1-1. Seven Mile Hill and Simpson Ridge study areas located in Carbon County, Wyoming, USA. The Seven Mile Hill Wind Energy facility consisted of 79, 1.5-MW wind turbines. The Simpson Ridge study area comprised of the area within and surrounding the Simpson Ridge Wind Resource Area (SRWRA).

CHAPTER 2

Greater Sage-Grouse Habitat Selection Relative to

Wind Energy Infrastructure in South-Central, Wyoming

In the format for manuscript submittal to the *Journal of Wildlife Management*

ABSTRACT

The degradation of sagebrush habitats within the range of greater sage-grouse (*Centrocercus urophasianus*; hereafter, sage-grouse) has been attributed to a number of environmental and anthropogenic influences including agriculture, large-scale wildfires, and energy extraction. The impacts from energy extraction to sage-grouse populations in the form of oil and gas development have been well documented. The increasing demand for renewable energy has prompted a potential new threat to sage-grouse populations in the form of wind energy development. However, it is unknown if wind turbines and the infrastructure associated with wind energy development will impact the habitat selection patterns of sage-grouse populations. I hypothesized that sage-grouse selected for habitats farther from wind energy infrastructure, particularly wind turbines, during three biologically meaningful periods. In 2009 and 2010, I captured and radio-marked 50 sage-grouse within an existing wind energy facility and 66 within an area not impacted by wind energy development. I monitored the marked sage-grouse via radio-telemetry during the nesting, brood-rearing, and summer periods to document habitat selection. I utilized binary logistic regression to predict the odds of habitat selection within both study areas. I used forward model selection and Akaike's information criterion to identify the best predictive model within both study areas. I validated each top model using K-fold cross validation. Lastly, I created resource selection functions to depict areas of varying levels of habitat selection. The presence of turbines did not influence sage-grouse nest site selection or

brood-rearing habitat selection. However, sage-grouse appeared to select for habitats in close proximity to wind turbines during the summer period. These results may be related to the fact that areas near turbines are comprised of high quality habitats that were used extensively by sage-grouse prior to development of the SMH wind energy facility; however without the collection of pre-development data, it is difficult to speculate the reasons for these selection patterns. The results of my habitat selection modeling did not support my hypothesis that sage-grouse avoid wind turbines during the nesting, brood-rearing, and summer periods. I caution the interpretations of these results because of the strong site fidelity exhibited by sage-grouse and the inherent time lags associated with population-level response to anthropogenic infrastructure as seen in oil and gas developments. However, these results provide valuable insights into the short-term impacts to sage-grouse distribution influenced by wind energy development.

INTRODUCTION

Large home ranges and complex habitat selection patterns are characteristic of many greater sage-grouse (*Centrocercus urophasianus*; hereafter, sage-grouse) populations (e.g., Doherty et al 2008, Atamian et al. 2010, Carpenter et al. 2010). The addition of wind energy infrastructure (hereafter, infrastructure) including turbines, roads, and transmission lines may displace sage-grouse from suitable or desired habitat. From 1984 to 2010, 19 studies examined displacement effects on prairie grouse species from energy development and 12 of these studies were specific to sage-grouse (Hagen 2010). However, none of these studies were specific to the displacement effects of wind energy infrastructure on sage-grouse species.

Displacement impacts similar to those found for sage-grouse from oil and gas development is a growing concern for sage-grouse occupying habitats in close proximity to wind energy development. Some scientists speculate that the skyline created from infrastructure may

displace sage-grouse hundreds of meters or even kilometers from their normal range (USFWS 2003, NWCC 2004). Changing movements may result in selection of poorer quality habitats, ultimately reducing population fitness. If birds are displaced, it is unknown whether in time, local populations may become acclimated to elevated structures. The USFWS argues that placement of tall man-made structures, such as wind turbines, in occupied prairie grouse habitat may result in a decrease in habitat suitability (USFWS 2004). In addition to the displacement from turbines, overhead transmission lines, a type of infrastructure associated with wind energy development, might displace sage-grouse populations. Overhead transmission lines provide perches for avian predators of sage-grouse including ravens (*Corvus corax*) and golden eagles (*Aquila chrysaetos*; Steenhof et al. 1993) and it is assumed that increased predation or indirect impacts from raptors may occur to sage-grouse populations (Ellis 1984, Coates and Delehanty 2010). Although the potential exists for wind turbines to displace greater sage-grouse from occupied habitat, well-designed studies examining the potential impacts of wind turbines on greater sage-grouse are lacking (Johnson and Holloran 2010).

The purpose of my study was to investigate the effect of wind energy infrastructure on sage-grouse distribution and habitat selection patterns. Specifically, I investigated sage-grouse habitat selection during three biologically meaningful periods that included nesting, brood-rearing, and summer within an existing wind energy facility and in comparison to an adjacent, non-developed area. I hypothesized that sage-grouse avoided infrastructure, specifically turbines, when selecting for nesting, brood-rearing, and summer habitats. This information is critical in planning future wind energy development facilities that occur within occupied sage-grouse habitats.

STUDY AREA

My study area included the Seven Mile Hill (SMH) study area, which was influenced by infrastructure, and the non-impacted Simpson Ridge (SR) study area. The SMH and SR study areas were separated by U.S. Highway 30/287; however, the minimum distance between SMH and SR occupied leks was approximately 8.5 km. Sage-grouse movements between study areas were relatively low (5% of all marked sage-grouse [6] and 3% of all locations [64] from sage-grouse captured from one of the 2 study areas were documented in the other study area). Consequently, sage-grouse that were captured on leks north of U.S. Highway 30/287 were included in the SMH analysis area and sage-grouse captured south of U.S. Highway 30/287 were included in the SR analysis area. In addition, the leks on SMH were in closer proximity to turbines than those at SR. Because of the general lack of movement by sage-grouse and the difference in infrastructure between the 2 areas, I considered SMH the impacted area and SR the control. Please refer to Chapter 1 for detailed descriptions of each study area (see Fig. 1-1).

METHODS

I used binary logistic regression to estimate resource selection functions (RSF) within the SR and SMH study areas to identify the odds of female sage-grouse habitat selection as a function of environmental and infrastructure covariates (Manly et al. 2002). I defined habitat selection (i.e., aka resource selection) as the process by which a sage-grouse chooses habitat components to use (Johnson 1980). Logistic regression is widely used and is a valuable tool to estimate resource selection functions, which are commonly used to evaluate wildlife habitat relationships (Johnson et al. 2006, Manly et al 2002). Animals select particular resource units within available habitats to satisfy particular life requirements. The used resource units can be compared to available resource units to estimate resource selection of that animal (Manly et al. 2002). The results of this comparison can be incorporated into an RSF, which is defined as any function that is

proportional to the probability of use by an animal (Manly et al. 1993, 2002). I used RSF's to predict the odds of habitat selection by sage-grouse during the three seasons within both study areas.

Field Methods

I captured 116 female sage-grouse by 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. Initial capture efforts were centered within SR during the first study year (2009) where 50 sage-grouse females were targeted and 25 were targeted within SMH. During the second study season (2010) the target sample size increased to 40 at SMH and 45 at SR. I attempted to capture grouse at all accessible active lek sites within 16 km of the SMH wind turbines proportionately to the number of males attending those leks. I aged, weighed (0.1-g precision), acquired blood samples (year 2009 only), and fitted each captured grouse with a 22-g necklace-mounted radio transmitter with a battery life of 666 days (Advanced Telemetry Systems, Isanti, MN). I then released each radio-marked female grouse at the point of capture and marked the location using a hand held global positioning system (GPS) unit.

I relocated each radio-marked female at least twice each week during the prelaying and nesting period (Apr through Jun); once every week for brooding females during the brood-rearing period (hatch through 15 Aug); and, at least once per week during the summer (Jun through 1 Sep) periods for all barren females (e.g., females that were unsuccessful in producing or raising young or were not currently nesting or raising young). Marked sage-grouse were monitored primarily from the ground using hand-held receivers. I determined sage-grouse locations by triangulation or homing until visibly observed and classified radio-locations as breeding, nesting, brood-rearing, or summer. I estimated triangulation locations by taking two

vectors in the direction of the signal. In addition, I estimated the triangulation error by placing 6 test collars for each technician throughout both project areas and estimated the mean telemetry error between the actual and estimated locations recorded by each technician. The mean error telemetry rate was incorporated into the habitat selection modeling effort. I employed aerial telemetry to locate missing birds throughout the study period.

I determined nesting success for each radio-marked female sage-grouse from long range triangulation at least every third day throughout the nesting season, late April through 15 June. I assumed females were nesting when movements became localized. Nests were located using a progressively smaller concentric circle approached by walking circles around the radio signal using the signal strength as an indication of proximity (Holloran and Anderson 2005). Once I visually confirmed the female in an incubating position, the location of the observer was recorded with a GPS and a photograph was taken of the habitat surrounding the incubating hen. All future monitoring of the nest was made from remote locations (>60 m) using long distance triangulation to minimize potential disturbance. Once a nest location was established, I conducted incubation monitoring on an alternate-day schedule to determine nesting fate. For each nest and re-nest, data were collected on timing of incubation and nest success. All nest locations were mapped using a hand-held GPS. I considered a nest that successfully hatched (i.e., eggs with detached membranes) ≥1 egg to be a successful nesting attempt. Nests that failed to successfully hatch ≥1 egg were considered failed nesting attempts whose fates included predation (avian, mammal, and unknown) and abandoned. Females that were unsuccessful in their first nesting attempt were monitored three times per week to determine possible re-nesting attempts. I monitored females that were unsuccessful in their first or second nesting attempt at least once each week through 1 September in 2009 and 2010.

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I located radio-marked females that successfully hatched ≥1 egg each week through 15 August 2009 and 2010 to evaluate brood-rearing habitat selection. I categorized the brood-rearing period as early (hatch through 14 days post-hatch; Thompson et al. 2006) or late (35 days post-hatch; Walker 2008). Females were considered successful through the early brood-rearing period if ≥1 chick survived to two weeks post-hatch; chick presence during this period was established either through visual confirmation of a live chick or the brooding female's response to the researcher (e.g., chick protective behavior exhibited). I 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 nighttime spotlight surveys conducted on days 35 and 36 post-hatch (Walker 2008). Similar to sage-grouse with unsuccessful nests, sage-grouse that were unsuccessful during either the early or late brood-rearing period were monitored twice each week through 31 August.

GIS Covariates

I developed a suite of covariates to estimate the odds of sage-grouse selecting nest sites, brood-rearing habitat, and summer habitat within both study areas. Major roads included paved highways: U.S. Highway 30/287 traversed east-west separating SR from SMH; Wyoming State Highway 72 traversed north-south through the SR study area; and Interstate 80 traversed east-west south of the SR study area (see Fig. 1-1). The SMH study area included wind turbines and access roads, whereas SR did not. I digitized major roads and overhead transmission lines (230 kV wooden H-frame) using aerial satellite imagery and ArcMap 10 (ESRI 2011). Turbine locations were obtained from PacifCorp, the operators of the Seven Mile Hill Wind Energy Facility.

Environmental covariates included vegetation and topography features within both study areas. Vegetation layers used in my analysis were remote-sensed sagebrush products developed by Homer et al. (2012). This dataset used a combination of methods to integrate 2.4 m QuickBird, 30 m Landsat TM, and 56 m AWiFS (Advanced Wide Field Sensor) imagery into the characterization of four primary continuous field components (percent bare ground, percent herbaceous cover, percent litter, and percent shrub cover) and four secondary components (three subdivisions of shrub cover —percent sagebrush (*Artemisia* spp.), percent big sagebrush (*A. tridentata* spp.), and percent Wyoming big sagebrush (*A. t. wyomingensis*)—and shrub height (Homer et al. 2009, 2012; Table 2-1). Landscape features included elevation, slope, and terrain ruggedness all of which I calculated from a 10 m National Elevation Dataset (USGS, EROS Data Center, Sioux Falls, SD). Terrain ruggedness 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. 2005; Table 2-1).

Model development

I included distance to each infrastructure and each environmental covariate in developing my habitat selection models (Table 2-1). In addition to the linear term for the distance to each anthropogenic feature, I also included the quadratic terms and decay functions (-*exp*[*distance*]/decay distance) because in many instances animals may avoid features up to a certain point, but beyond this point the affect is less realized (Carpenter et al. 2010). Lastly, I included distance to nearest occupied lek as a covariate because sage-grouse are known to select habitats in the vicinity of their leks (Aldridge and Boyce 2007). Also, I included this covariate to account for the spatial correlation between the distance to nearest lek and turbines (i.e., 3 of 5 leks were located within 1.6 km of turbines at SMH).

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I used nest locations and locations obtained during the brood-rearing period (hatch through 35 days post-hatch) and 1 June – 31 August for the summer period to model sage-grouse habitat selection throughout both study areas. The sage-grouse populations within both study areas were non-migratory (movements were <10 km between or among seasonal ranges), utilizing similar habitats during all annual life cycles (Connelly et al. 2000, Fedy et al. 2012). More specifically, sage-grouse may select different habitats between the early brood period and late brood-rearing periods (Connelly et al. 1988, Kirol et al. 2012). The shift in habitats from early to late brood is dependent on the habitat available to the brooding females and chicks. Brood habitat selection during the early brood and late brood period within both study areas was not characterized by multiple habitats as determined in other more migratory populations where brood selection shifts from xeric to more mesic areas (Connelly et al. 1988, Kirol et al. 2012). Thus, to increase sample sizes, I combined early and late brood locations to estimate habitat selection during the entire brood-rearing period (Aldridge and Boyce 2007).

Because there were a limited number of locations (≤20 per season) for each marked sage-grouse, I pooled each individual's data within seasons and across years and employed a Type I study design where habitat selection and availability were estimated at the population level (Thomas and Taylor 2006). However, to estimate precision of final estimated model coefficients, individual grouse were treated as the primary sampling units (Thomas and Taylor 2006) through bootstrapping to estimate confidence intervals (Manly 2007). The form of the RSF used was (Manly et al. 2002),

$$w(x) = \exp(\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k),$$

where $w(x)$ represents the odds of selection, the x's were model covariates and β were coefficients to be estimated.

Defining the scale and amount of available habitat is an important step in modeling habitat selection for any species (Thomas and Taylor 2006). I investigated sage-grouse habitat selection at a landscape level during each of the seasons. It is recommended that the available habitat for a landscape level habitat selection study should be based on the distribution of radio-collared animals (McClean et al. 2008). Subsequently, I created a 100% minimum convex polygon (MCP) surrounding all observed locations within each study area and representative of life stages to define available habitat (Gillies et al. 2006, Carpenter et al. 2010, Kirol 2012). There were no areas within each MCP that were considered not to be available habitat to sage-grouse (i.e., sagebrush rangeland at low-to-moderate relief that did not include trees).

A geographic information system (GIS) was used to randomly generate available locations at 5 times the number of total observed locations per season (Baasch et al. 2009). The average values representing each environmental feature were extracted at 3 different radii scales, the mean telemetry error rate (0.30 km), the median distance between consecutive year's nests from 2009 to 2010 within both study areas (0.46 km), and the median distance traveled between monitoring intervals during the brood-rearing and summer period (1.0 km). The median movement distance was 1.0 km during brood-rearing and 1.6 km during the summer season; however, I used 1.0 km based on findings from previously published sage-grouse habitat selection studies (Aldridge and Boyce 2007, Carpenter et al. 2010).

Prior to model development, I tested whether each pair of continuous covariates were linearly related using Pearson's correlation analysis. Many of the covariates were correlated with one another ($r \geq |0.6|$). Rather than removing correlated covariates, I allowed for all covariates to compete against each other in a modified forward model selection procedure. However, two highly correlated covariates ($r \geq |0.6|$) were not allowed in the same model. The best

approximating model was identified by comparing the Akaike's information criterion (AICc adjusted for small sample sizes; Burnham and Anderson 2002). The forward model selection procedure continued until the AICc score among models did not change or until the model reached a maximum of 5 covariates (Burnham and Anderson 2002). The model having the lowest AICc and a ΔAICc value $\geq$4 from the next approximating model was considered the top model (Burnham and Anderson 2002, Arnold 2010). To address model uncertainty in competing models, I model averaged across the 90% confidence set of competing models to estimate the final parameters of the top model to produce more robust estimates (Burnham and Anderson 2002, Arnold 2010).

I used a 90% CI to test levels of confidence in my parameter estimates (alpha level = 0.10). Parameter estimate CI's not containing 0.0 were considered statistically different. Confidence intervals for each coefficient were estimated using a bootstrapping technique where the used locations were randomly sampled with replacement and the final model or modeled averaged estimates was refit to the new sample of used locations and the original available locations (Manly et al. 2002, Manly 2007). I used 1,000 bootstrap iterations to identify the lower and upper confidence limits for each estimate. The value at the 5th percentile of the 1,000 estimates represented the lower limit of a 90% confidence limit and the value at the 95th percentile represented the upper confidence limit (i.e., the "percentile method"; McDonald et al. 2006). I created marginal effects plots using the estimated parameters and their associated CI's from the top model in each period and study area to show the marginal effect of selected variables. I calculated odds ratios [(exp(β_0)-1)*100] from coefficients in the final RSF models and used these to interpret the effect and magnitude of each covariate on sage-grouse habitat selection (McDonald et al. 2006). Odds ratios describe the estimated percent change in odds of

selection for a 1-unit change in a predictor variable. Odds ratios were not calculated for covariates with both linear and quadratic effects because odds ratios for quadratic effects depend on values of other variables. Negative odds ratios indicated a decrease in the odds of selection and positive odds ratios indicated an increase.

After estimating the final model for each period and study area, I predicted odds of selection across both study areas. I placed a 100 m x 100 m grid on the landscape within each MCP to make the predictive maps. I extracted habitat covariates associated with each grid cell based on the representative scale of each covariate included in the top logistic regression models. These values represented the various covariates measured at each habitat unit or grid cell. Lastly, I calculated RSF values and placed them into 5 quantile bins to represent progressively selected habitats.

I validated the top models using a K-fold cross-validation process (Boyce et al. 2002) to assess how well the top models performed among a set of apportioned data. I randomly allocated the used locations into 5 equal-sized groups. Leaving out one set of used data (K; testing), I re-estimated the coefficients in the top models using the available locations and the K-1 groups (training) of used locations. The re-estimated model was then used to make predictions to the available locations and used locations from group K. I binned all predictions into 10 classes of equal size using percentiles, and the number of used points in each class was compared to the class rank (1 = lowest, 10 = highest predicted odds of selection) using a Spearman's rank correlation coefficient. This process was repeated for each of K = 5 groups of used locations. The Spearman's rank correlation coefficients (r_s) were averaged to test how well the top model performed on the set of apportioned data.

RESULTS

I recorded 2,659 locations (SMH, $n = 1,063$; SR, $n = 1,596$) from 116 female sage-grouse (SMH, $n = 50$, SR, $n = 66$) during the two study years and during all life stages. Sage-grouse habitat selection was generally concentrated around leks (i.e., within an average of 2.6 km of a lek) within both study areas, especially during the nesting and brood-rearing periods. Sage-grouse captured within SR tended to have a greater distribution compared to sage-grouse captured at SMH; however, leks within SR had a larger distribution than the leks within SMH.

Nest Site Selection

I used 94 identified nest locations (SMH, $n = 42$; SR, $n = 52$) in my nesting habitat selection analysis. One nest of a female captured at SR was observed within SMH, but was not included in the habitat selection analysis because I did not consider that female to be influenced by wind energy development.

Nest site selection within both study areas differed and included multiple environmental and anthropogenic covariates. The top model for SMH included percent shrub and herbaceous cover, elevation, and distance to nearest lek and major road. There was some model uncertainty between the top two models within SMH (i.e., <4 ΔAICc), thus the final parameters were estimated by model averaging the top two models (Table 2-2). The SR model included only 2 covariates: shrub height (cm) and distance to nearest transmission line and was ≥ 4 ΔAICc from the next approximating model (Table 2-2). Distance to nearest turbine was not in the top SMH nest site selection model and adding distance to nearest turbine to the top SMH model did not improve model fit (ΔAIC$c = 2.10$) or have a significant slope ($\beta = -0.04$; 90% CI: -0.32–0.24).

The estimated odds of sage-grouse nest site selection within SMH was 81.6% (90% CI: 38.9–159.6%) higher with every 1.0% increase in shrub cover within a 0.30 km radii (Table 2-3; Fig. 2-1). In addition, the odds of selecting a nest site within SMH was 39.2% lower for every

1.0 km increase from nearest occupied lek (90% CI: 27.9–56.1%; Table 2-3; Fig. 2-1). Nest site selection increased by 16.4% with every 1.0 km increase in distance to a major road (90% CI: 4.0–29.5%; Table 2-3; Fig. 2-1). Nest site selection increased by 2.1% with every 1.0 m increase in elevation (90% CI: 1.2–3.3%; Table 2-3; Fig. 2-1). Lastly, percent herbaceous cover was included in the top model; however, the estimated parameter was not significant (90% CI: -2.1–51.1%; Table 2-3; Fig. 2-1).

Shrub height and distance to transmission line were included in the top SR model. The estimated odds of selection increased by approximately 10.1% for every 1 cm increase in shrub height within a 0.30 km radii, but decreased by approximately 15.3% for every 1.0 km increase in distance from nearest transmission line (90% CI: 5.0–16.2% and 7.9–23.4%, respectively; Table 2-3, Fig. 2-2).

Nest site selection was highest in the western portion of the SMH study area and highest in the area surrounding the overhead transmission lines at SR (Fig. 2-3; Fig. 2-4). Lastly, the 5-fold validation method used for the top model for each study area indicated that the SMH top model had good overall predictive ability (average r_s = 0.67); however, the predictive ability for the SR top model was lower (average r_s = 0.49), but still better than random chance.

Brood-rearing Habitat Selection

I included 347 early and late brood-rearing locations (SMH, n = 139; SR, n = 209) from 30 brooding females (SMH, n =13; SR, n = 17) in the brood-rearing habitat selection analysis. Habitat and anthropogenic covariates included in the top models differed between both study areas; however, percent bare ground and herbaceous cover were in the top models for each study area. The quadratic form of distance to nearest overhead transmission line, elevation, and percent shrub cover were included in the top SMH brood-rearing model (Table 2-4). The next best

approximating model observed at both study areas was greater than approximately 4 ΔAICc

values from the top model (Table 2-4). Similar to SMH, distance to nearest overhead

transmission line was also included in the SR top model; however, it retained its linear form.

Distance to major road and percent litter cover were also included in the top SR model. I

experienced some model uncertainty with the top two models being ≤4 ΔAICc from each other

thus I model averaged these two competing models to estimate the final models (Table 2-4).

Distance to nearest turbine, was not included in the top model for SMH; however, it did compete

with all other covariates during the forward model selection procedure. Adding distance to

nearest turbine to the top model within SMH did not improve model fit (i.e., $\Delta AICc = 0.63$; $\beta =$

0.12; 90% CI: -0.39 to 0.61).

The estimated odds of sage-grouse selecting brood-rearing habitat within SMH increased

as distance from nearest overhead transmission line increased up to 4.7 km (90% CI: 2.2–18.5

km, then declined (Table 2-5; Fig. 2-5). Brood-rearing habitat selection decreased by

approximately 13.1% for every 1.0% increase in percent bare ground within a 0.46 km radii

(90% CI: 8.6–17.5%; Table 2-5; Fig. 2-5). In addition, brood-rearing habitat selection increased

by 96.5% and 52.7% for every 1.0% increase in percent herbaceous and shrub cover within a 1.0

km radius (90% CI: 27.8–260.0% and 1.1–158.0%), respectively (Table 2-5; Fig. 2-5).

The SR brood-rearing data supported a model that included distance to nearest

transmission line and major road and percent herbaceous cover; however, substantial variability

of these covariates, indicated by the inclusion of 0.0 within the CI's, existed across individual

birds (Table 2-5; Fig. 2-6). The estimated odds of selecting brood-rearing habitat within SR

decreased by 3.3% for every 1.0% increase in percent bare ground cover within 0.30 km (90%

CI: 1.1–5.6%; Table 2-6; Fig. 2-6). However, brood-rearing habitat selection increased by 11.4%

for every 1.0% increase in percent litter within 0.46 km (90% CI: 2.0–20.7%; Table 2-5; Fig. 2-6).

Habitats west and east of the wind turbines at SMH had the highest odds of habitat selection during the brood-rearing season (Fig. 2-7). Habitats surrounding the overhead transmission line and in the center of SR were estimated as having the highest probability of brood-rearing habitat selection (Fig. 2-8). Lastly, the 5-fold cross-validation for the top models within the SMH and SR study areas indicated that the final top models had overall good predictive abilities (average $r_s = 0.94$ and $r_s = 0.74$, respectively).

Summer Habitat Selection

I included 1,961 summer locations (SMH, $n = 796$; SR, $n = 1,165$) from all female sage-grouse (SMH, $n = 66$; SR, $n = 50$) in the summer habitat selection analysis. The distance to major roads, distance to nearest occupied lek, and percent bare ground formed the top models for each study area. Distance to nearest turbine and elevation were additional covariates included in the SMH top model. Percent herbaceous cover and Wyoming big sagebrush cover were also included in the SR top model. The next approximating model observed at both study areas was greater than approximately 40 ΔAICc values from the top model (Table 2-6).

The estimated odds of selecting summer habitat within SMH decreased by approximately 26.5% for every 1.0 km increase in distance from nearest occupied lek and by 22.4% for every 1.0 km increase in distance to nearest turbine (90% CI: 15.0– 38.7% and 10.7–33.3%, respectively; Table 2-7, Fig. 2-9). Summer habitat selection increased by 17.1% for every 1.0 km increase in distance from nearest major road (90% CI: 7.3–29.0%; Table 2-7; Fig. 2-9). In addition, summer habitat selection decreased by 7.3% for every 1.0% increase in percent bare ground cover within 0.30 km (90% CI: 5.4–9.4%; Table 2-7, Fig. 2-9). Lastly, summer habitat

selection increased by 0.76% for every 1 m increase in elevation (90% CI: 0.3–1.3%; Table 2-7, Fig. 2-9).

Similar to SMH, the odds of selecting summer habitat within SR decreased by approximately 22.5% for every 1.0 km increase in distance from nearest occupied lek and by 12.9% for every 1.0% increase in percent bare ground cover within 1.0 km (90% CI: 10.4–35.3 and 8.0–17.6%, respectively; Table 2-7, Fig. 2-10). In addition, summer habitat selection increased as distance to nearest major road increased up to 8.7 km (90% CI: 1.2–32.0 km), then declined (Fig. 2-10). Lastly, summer habitat selection decreased by 13.4% with every 1.0% increase in percent herbaceous cover and increased by 34.2% with every 1.0% increase in Wyoming big sagebrush cover within 1.0 km (90% CI: 4.0–23.1and 7.3–78.4%, respectively; Table 2-7; Fig. 2-10).

Similar to nest and brood occurrence, the odds of summer habitat selection was highest within habitats west and east of the wind turbines at SMH; however much of these habitats occurred in close proximity to turbines (Fig. 2-11). In addition, summer habitats with the highest odds of selection occurred throughout much of the area within SR; however, most of this habitat occurred within the center of the study area in close proximity to occupied leks (Fig. 2-12). Lastly, the 5-fold cross-validation method used on the top models within the SMH and SR study areas indicated that the final top models had overall strong predictive abilities (average $r_s = 0.88$ and average $r_s = 0.91$, respectively).

DISCUSSION

The proximity to wind turbines did not influence nest site or brood-rearing habitat selection, but the odds of summer selection increased in habitats closer to wind turbines. In addition, the top models without distance to nearest turbines (i.e., habitat covariates only) experienced some

variability between study areas suggesting the control area used in my analysis may not have been an adequate control. If SR was a true control for SMH then I would expect to see consistent models and consistent effects of individual environmental covariates among the study areas. Because this was not realized in my analysis, I have to caution the effectiveness of SR being a true control area for SMH. The inadequacy of the SR as being a true control to SMH may be attributed to the limitations of the vegetation covariates used in my analysis. The vegetation covariates were obtained from remotely sensed data and subsequently may be subject to high variability in some of the estimates. I was limited to remote sensed data and many of these covariates were linearly correlated. Expanding the covariates included in my analysis to include habitat data from different sources might explain some of the model variability.

Another potential bias in my study was the lack of pre-development data to accurately describe the habitat selection patterns of sage-grouse prior to the addition of wind energy infrastructure. Knowledge of the selection patterns prior to development provides researchers a baseline measurement to compare future selection patterns post development. Having the knowledge of pre-development data would also better validate SR as being a true control for SMH. For example, there may be some variability in the habitat selection patterns between study areas, but this may be attributed to sage-grouse being displaced from higher quality habitats to poorer quality habitats within SMH. Future studies evaluating the effects of wind energy on sage-grouse habitat selection patterns should consider multiple years of pre-development data to fully understand the potential changes in habitat selection patterns. In addition, multiple studies that account for the effects of spatial variation among different sage-grouse populations will be necessary to fully understand the extent of the potential impacts to sage-grouse from wind energy development.

Nest Site Selection

Few similarities existed between the top models of nest site selection within SMH and SR. Percent shrub cover was an important predictor within SMH; similarly shrub height was important within the SR study area. Shrub components have also been an important predictor for nest site selection for sage-grouse in other studies (Holloran and Anderson 2005, Hagen et al. 2007, Doherty et al. 2010). Sage-grouse selected for nest sites closer to occupied leks and avoided major roads within SMH. In addition, sage-grouse selected for nesting habitat closer to transmission lines within SR.

Sage-grouse are known to avoid habitats influenced by anthropogenic features (Lyon and Anderson 2003, Holloran et al. 2010). The transmission lines within the SR study area have existed for over 10 yrs and the quality of the habitat surrounding these transmission lines may outweigh the potential risk to sage-grouse from perching raptors (Ellis 1984). In addition, the selection closer to transmission lines may be attributed to the extent of available habitat used in my analysis (Fig. 2-3, Fig. 2-4). I further explored this relationship with a post hoc analysis where I reduced the available habitat to include the area within a 75% fixed kernel home range (Worton 1989). After re-estimating the final model using only the used and random locations within the modified available habitat, I observed a similar effect for shrub height and distance to nearest transmission line as in the original model, suggesting that the habitat I considered to be available using a 100% MCP sufficiently characterized habitat for the nest site selection.

Distance to turbine was not included in the SMH top model for nest site selection and when added to the top model it did not improve model fit (i.e., slope coefficients were not significant at the 90% CI level and AICc scores did not improve). Sage-grouse selecting nesting sites seem to be uninfluenced by the presence of turbines within SMH.

The differences between the SMH and SR study areas could be related to the suite of covariates used in my analysis. The predictive power indicated by the K-fold validation was the lowest for nest site selection further suggesting the covariates used in my analysis may not have been sufficient at estimating the variability of nest site selection between both study areas. Nest site selection was estimated at a larger landscape-level scale where habitat covariates were measured remotely. The landscape-level scale is important for identifying priority nesting habitats but selection patterns can be strongly influenced with the knowledge of local-scale habitat variables that cannot currently be mapped in GIS (Doherty et al. 2010). Also, generation of different covariates may be useful to better estimate the variation in nest site selection between the two study areas.

Brood-rearing Habitat selection

Similar to nest site selection, brood-rearing habitat selection top models were different between SMH and SR. Specifically, sage-grouse within SMH selected for brood-rearing habitats farther away from transmission lines. However, much of the habitat surrounding the transmission lines located within the SMH study area was mostly comprised of a greater percent bare ground, which is not characteristic of sage-grouse brood-rearing habitats (Connelly et al. 2000, Aldridge and Boyce 2007) and percent bare ground was represented as a negative effect in the top brood-rearing selection model (i.e., odds of selection increased in habitats with less bare ground). Distance to nearest transmission line was included in the top brood-rearing model for SR; however there was substantial variability across individual birds. Similarly, herbaceous cover was included within both the SR and SMH top models, but herbaceous cover within SR had high variability at predicting the odds of occurrence.

The selection pattern within SMH was consistent with other sage-grouse studies where brooding areas consistently have higher grass or herbaceous cover (Holloran 1999, Thompson et al. 2006, Hagen et al. 2007). However, brooding sage-grouse in both study areas avoided habitats that consisted of a higher percentage of bare ground and selected for habitats that consisted of a higher percentage of shrub cover (SMH) and litter (SR). Broods selected habitats with greater sagebrush cover in southeastern Alberta (Aldridge and Boyce 2007), across Wyoming (Thompson et al. 2006), and south-central Wyoming (Kirol et al. 2012), which was consistent with the SR and SMH study areas. Distance to nearest turbines was not included in the SMH top model for brood-rearing habitat selection and when added to the top model it did not improve model fit (i.e., slope coefficients were not significant at the 90% CI and AIC_c scores did not improve).

Summer Habitat Selection

Unlike the SR and SMH nest and brood-rearing habitat selection models, similarities existed among the top covariates included in the SMH and SR female summer habitat selection models. The probability of females selecting habitats in the summer increased as distance to nearest lek decreased, percent bare ground decreased, and as distance to nearest major roads increased within both study areas. Distance to nearest lek was included in the modeling because sage-grouse activity during all life stages was relatively close to each lek. It was also included to account for the spatial autocorrelation experienced at SMH where the proximity of leks to turbines may mask the effects of turbines on habitat selection.

Distance to nearest turbine was included in the top SMH summer habitat selection model, but its affect on the odds of selection was different from what was hypothesized. Sage-grouse in the SMH appeared to be selecting for habitats closer to turbines. This could be the result of

strong site fidelity associated with sage-grouse populations (Fischer et al. 1993, Holloran and Anderson 2005). In this case, sage-grouse likely selected habitats closer to turbines prior to construction of the facility and continued to use these habitats 2-yrs post construction. However, the lack of pre-construction data necessary to confirm this relationship limits the interpretation that sage-grouse selected habitats closer to turbines because they used these habitats prior to development.

The results of habitat selection studies are largely a product of defining available habitat. I defined available habitat as the extent of all sage-grouse locations where outlying locations may have a strong influence on selection patterns. I used a post hoc analysis to test whether the selection pattern associated with turbines was a product of my definition of available habitat. I reduced the available habitat to encompass a 75% fixed kernel home range of all summer locations at SMH (Worton 1989). Reapplication of the final model estimated to the home range available habitat showed a similar relationship to the original estimated coefficients where selection increased in habitats closer to turbines; however, this estimate was not significant at the 90% CI level. In addition, there was a similar affect on distance to nearest occupied lek as the original estimate, but it too was insignificant at the 90% CI level. This suggests that selection occurring at a more local scale may not be influenced by turbines or lek locations during the summer period. The post hoc analysis investigating different levels of habitat selection showed some variability in selection patterns suggesting future habitat selection studies investigating the response of wind energy development should consider multiple levels of selection.

The complex life cycles and time lags attributed to sage-grouse populations (Harju et al. 2010, Holloran et al. 2010) make it difficult to conclude or speculate on the cumulative impacts from wind energy infrastructure on sage-grouse habitat selection from my research, which

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covered 2 yrs following wind energy development. Additional years of monitoring as well as multiple studies investigating these relationships are needed to fully understand the long term impacts of wind energy infrastructure on sage-grouse populations. However, the results from my study provide insight into the early effects of wind energy infrastructure on sage-grouse nesting, brood-rearing, and female summer habitat selection.

MANAGEMENT IMPLICATIONS

Understanding the potential impacts to sage-grouse populations from wind energy development is an important step towards landscape level sage-grouse population management. Information on the influence of wind energy developments on sage-grouse is limited due to the lack of studies. My study is the first study investigating the potential relationship that may exist between sage-grouse and wind energy. Future study efforts should focus on collecting sage-grouse habitat selection data in a before and after control treatment study design to fully understand these relationships. In addition, multiple studies at multiple locations are necessary for future wind developments to occur in sage-grouse occupied habitats. For example, Fedy et al. 2012, described the movements of monitored sage-grouse in Wyoming and discovered there was high variability across study sites suggesting selection and suitable habitat varies depending on individual landscapes. The relatively small movements from nesting areas to summer areas within my study area (average = 4.3 km) suggest that sage-grouse were using habitats that were in close proximity to leks compared to other sage-grouse populations where they exhibit large average interseasonal movements ranging from (3.8–14.4 km; Fedy et al. 2012). Because leks within the SMH study area were in close proximity to the SMH turbines and interseasonal movements were relatively small, sage-grouse in SMH might be influenced by wind turbines for a longer period of time compared to populations that exhibit larger seasonal movements. These

conditions suggest the need to monitor the response of different sage-grouse populations to wind energy development. Further exploration of the productivity parameters including nest success, brood-rearing success, and survival associated with these habitats is necessary to fully understand the potential long-term impacts of wind energy development on sage-grouse habitat selection and the response of sage-grouse populations to wind energy development.

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Table 2-1. Explanatory anthropogenic and environmental covariates used in model selection for sage-grouse nest site, brood-rearing, and summer habitat selection at the Seven Mile Hill and Simpson Ridge study areas, Carbon County Wyoming, USA, 2009 and 2010 (Homer et al. 2012).

Covariate	Covariate description
Anthropogenic Infrastructure	
dist_major_rds	Distance to nearest major road (WYO HWY 72, US HWY 287/30, and I-80)^2; km
dist_major_rds^2	Distance to nearest major road (WYO HWY 72, US HWY 287/30, and I-80)^2; km
dist_tline	Distance to nearest overhead transmission line; 230 kV wooden H-frame; km
dist_tline^2	Quadratic term for distance to nearest overhead transmission line (km)^2
dist_turbine	Distance to nearest turbine (km)
dist_turbine^2	Quadratic term for distance to nearest turbine (km)^2
Environmental	
Bare ground†	Percent bare ground
Big_sagebrush†	Percent big sagebrush (*Artemisia tridentata* spp.) cover
Elevation	Altitude above sea level (m)
Herbaceous†	Percent herbaceous cover
Litter†	Percent litter
Sagebrush †	Percent sagebrush (*Artemisia* spp.) cover
Shrub†	Percent shrub cover
Shrub_hgt†	Shrub height (0–253 cm)
Slope	Degrees 0-90
Terrain ruggedness	Variability in slope and aspect (0-1; 1 = complete terrain variation; Sappington et al. 2009)
Wyoming big sagebrush †	Percent Wyoming big sagebrush (*Artemisia tridentata wyomingensis*) cover

†Vegetation covariates obtained from Homer et al. 2012.

Table 2-2. Model fit statistics for greater sage-grouse nest site selection at the Seven Mile Hill and Simpson Ridge study areas, Carbon County, Wyoming, USA, 2009 and 2010. Models are listed according to the model best fitting the data and ranked by (ΔAICc), the difference between the model with the lowest Akaike's Information Criterion for small samples (AICc) and the AICc 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.

Model	log[L]	K	AICc	ΔAICc	w_i
Seven Mile Hill					
shrub300, lek_dist, herbaceous300, elevation460, dist_major_rds	-86.4	6	185.8	0.00	0.75
shrub300, lek_dist, herbaceous300, elevation460	-88.7	5	188.2	2.33	0.23
shrub300, lek_dist, herbaceous300	-94.3	4	197.1	11.22	0.00
shrub300, lek_dist	-98.4	3	203.0	17.13	0.00
shrub300	-103.9	2	211.8	26.00	0.00
Simpson Ridge					
shrub_hgt300, dist_tline	-130.6	3	267.4	0.00	0.97
shrub_hgt300	-135.1	2	274.2	6.87	0.03

Table 2-3. Odds ratios, slope coefficients, and 90% confidence intervals (CI) in the sage-grouse top nest site selection model for the Seven Mile Hill and Simpson Ridge study areas in Carbon County, Wyoming, USA, 2009 and 2010. Odds ratios measure the multiplicative change in odds of selection when a covariate changes by 1 unit, assuming all other covariates remain constant.

Description	Coefficient	90% CI		Odds Ratio (%)	90% CI (%)	
		Lower	Upper		Lower	Upper
Seven Mile Hill						
(Intercept)	-51.6					
Shrub	0.60	0.33	0.95	81.6	38.9	159.6
lek_dist	-0.50	-0.82	-0.33	-39.2	-56.1	-27.9
Herbaceous	0.22	-0.02	0.41	24.2	-2.1	51.1
Elevation	0.02	0.01	0.03	2.1	1.2	3.3
dist_major_rds	0.15	0.04	0.26	16.4	4.0	29.5
Simpson Ridge						
(Intercept)	-3.4					
shrub_hgt	0.10	0.05	0.15	10.1	5.0	16.2
dist_tline	-0.17	-0.27	-0.08	-15.3	-23.4	-7.9

Table 2-4. Model fit statistics for greater sage-grouse brood selection at the Seven Mile Hill and Simpson Ridge study areas, Carbon County, Wyoming, USA, 2009 and 2010. Models are listed according to the model best fitting the data and ranked by (ΔAICc), the difference between the model with the lowest Akaike's Information Criterion for small samples (AICc) and the AICc 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.

Model	log[L]	K	AICc	ΔAICc	w_i
Seven Mile Hill					
dist_tline, dist_tline^2, bare ground460, herbaceous1000, elevation1000, shrub1000	-309.9	7	635.1	0.00	0.91
dist_tline, dist_tline^2, bare ground460, herbaceous1000, elevation1000	-313.5	6	640.0	4.92	0.08
dist_tline, dist_tline^2, bare ground460, herbaceous1000	-316.9	5	644.5	9.45	0.01
dist_tline, dist_tline^2, bare ground460	-323.4	4	655.3	20.22	0.00
dist_tline, dist_tline^2	-343.4	3	693.1	57.99	0.00
Simpson Ridge					
dist_tline, litter460, dist_major_rds, herbaceous1000, bare ground300	-518.4	6	1049.8	0.00	0.81
dist_tline, litter460, dist_major_rds, herbaceous1000	-521.1	5	1052.9	3.15	0.17
dist_tline, litter460, dist_major_rds	-524.2	4	1056.9	7.06	0.02
dist_tline, litter460	-527.4	3	1061.0	11.19	0.00
dist_tline	-530.9	2	1065.9	16.08	0.00

Table 2-5. Odds ratios, slope coefficients, and 90% confidence intervals (CI) for covariates in the sage-grouse top brood-rearing selection model for the Seven Mile Hill and Simpson Ridge study areas in Carbon County, Wyoming, USA, 2009 and 2010. Odds ratios measure the multiplicative change in odds of selection when a covariate changes by 1 unit, assuming all other covariates remain constant. Odds ratios were not calculated for covariates involved with a quadratic effect because they were dependent on values of other covariates.

Description	Coefficient	90% CI		Odds Ratio (%)	90% CI (%)	
		Lower	Upper		Lower	Upper
Seven Mile Hill						
(Intercept)	19.3					
dist_tline	1.12	NA	NA	NA	NA	NA
dist_tline^2	-0.12	-0.25	-0.03	NA	NA	NA
Bare ground	-0.14	-0.19	-0.09	-13.1	-17.5	-8.6
Herbaceous	0.68	0.25	1.28	96.5	27.8	260
Elevation	-0.01	-0.02	0.00	-1.1	-2.28	-0.14
Shrub	0.42	0.01	0.95	52.7	1.1	158
Simpson Ridge						
(Intercept)	-1.0					
dist_tline	-0.12	-0.39	0.07	-11.0	-32.1	7.4
Litter	0.11	0.02	0.19	11.4	2.0	20.7
dist_major_rd	0.09	-0.05	0.28	9.2	-4.4	33.0
Herbaceous	-0.09	-0.28	0.01	-9.0	-24.6	1.1
Bare ground	-0.03	-0.06	-0.01	-3.3	-5.6	-1.1

Table 2-6. Model fit statistics for greater sage-grouse summer selection at the Seven Mile Hill and Simpson Ridge study areas, Carbon County, Wyoming, USA, 2009 and 2010. Models are listed according to the model best fitting the data and ranked by (ΔAICc), the difference between the model with the lowest Akaike's Information Criterion for small samples (AICc) and the AICc 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.

Model	log[L]	K	AICc	ΔAICc	w_i
Seven Mile Hill					
lek_dist, bare ground300, dist_major_rds, dist_turbine, elevation1000	-1880.4	7	3774.1	0.00	1.00
lek_dist, bare ground300, dist_major_rds, dist_turbine	-1915.1	6	3841.0	66.9	0.00
lek_dist, bare ground300, dist_major_rds,	-1959.0	5	3926.7	152.6	0.00
lek_dist, bare ground300	-1983.4	3	3973.4	199.3	0.00
lek_dist	-2045.0	2	4094.3	320.3	0.00
Simpson Ridge					
lek_dist, bare ground1000, dist_major_rds, dist_major_rds^2, herbaceous1000, Wyoming_sagebrush1000	-2625.4	7	5266.1	0.00	1.00
lek_dist, bare ground1000, dist_major_rds, dist_major_rds^2, herbaceous1000	-2648.2	6	5309.3	43.2	0.00
lek_dist, bare ground1000, dist_major_rds, dist_major_rds^2	-2688.7	5	5388.6	122.6	0.00
lek_dist, bare ground1000	-2780.3	3	5567.2	301.1	0.00
lek_dist	-2963.4	2	5931.1	665.0	0.00

Table 2-7. Odds ratios, slope coefficients, and 90% confidence intervals (CI) for covariates in the sage-grouse top summer selection model for the Seven Mile Hill and Simpson Ridge study areas in Carbon County, Wyoming, USA, 2009 and 2010. Odds ratios measure the multiplicative change in odds of selection when a covariate changes by 1 unit, assuming all other covariates remain constant. Odds ratios were not calculated for covariates involved with a quadratic effect because they were dependent on values of other covariates.

Description	Coefficient	90% CI		Odds Ratio (%)	90% CI (%)	
		Lower	Upper		Lower	Upper
Seven Mile Hill						
(Intercept)	-11.9					
lek_dist	-0.31	-0.49	-0.16	-26.5	-38.7	-15.0
bare ground	-0.08	-0.10	-0.06	-7.3	-9.4	-5.4
dist_major_rds	0.16	0.07	0.26	17.1	7.3	29.0
dist_turbine	-0.25	-0.41	-0.11	-22.4	-33.3	-10.7
elevation	0.01	0.00	0.01	0.76	0.27	1.3
Simpson Ridge						
(Intercept)	5.63					
lek_dist	-0.25	-0.43	-0.11	-22.5	-35.3	-10.4
bare ground	-0.14	-0.19	-0.08	-12.9	-17.6	-8.0
dist_major_rds	0.40	NA	NA	NA	NA	NA
dist_ major_rds^2	-0.02	-0.05	0.00	NA	NA	NA
herbaceous	-0.14	-0.26	-0.04	-13.4	-23.1	-4.0
wygenis	0.29	0.07	0.58	34.2	7.3	78.4
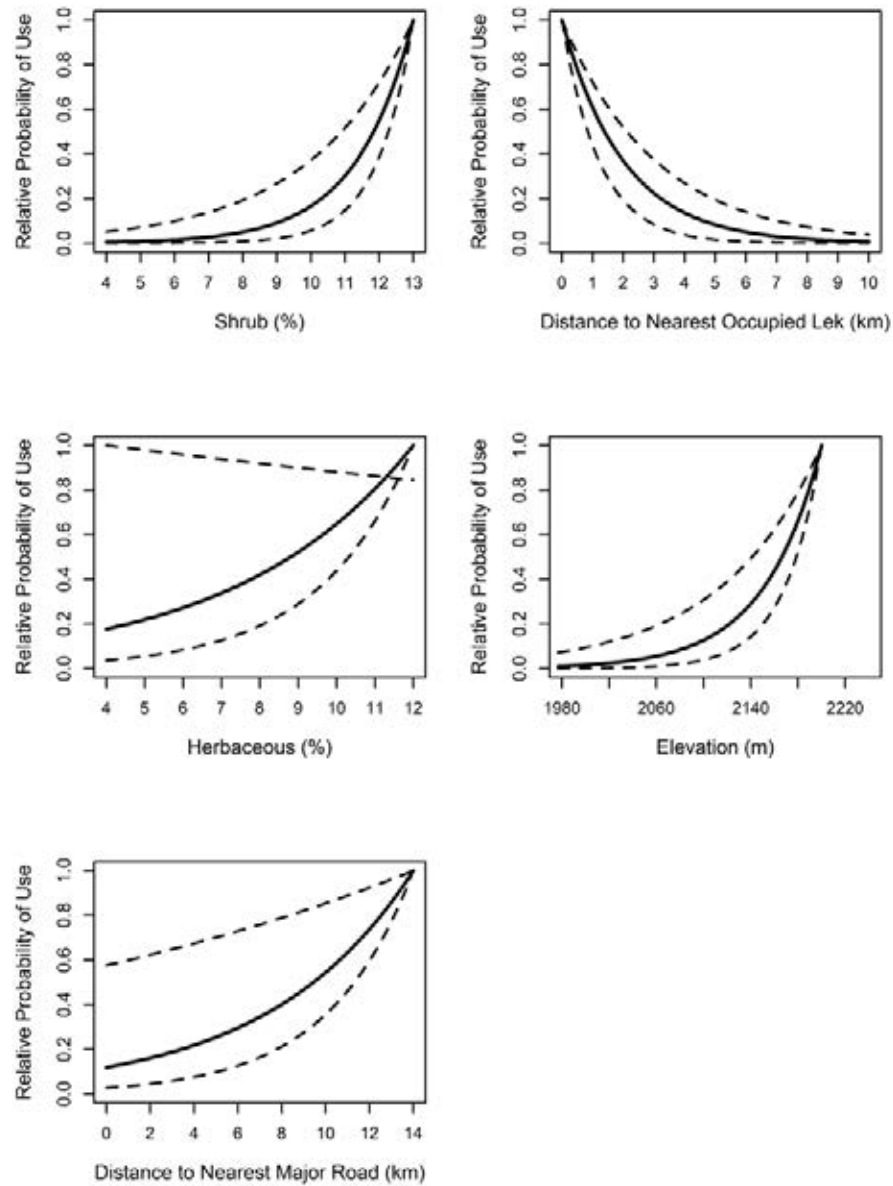
Figure 2-1. Odds ratios or relative probability of sage-grouse nest site selection and 90% confidence intervals (dashed lines) within the Seven Mile Hill study area as a function of top model covariates, Carbon County, Wyoming, USA, 2009 and 2010. All other covariates in the best approximating model were held constant at their mean value. Overlapping confidence limits indicate a non-significant estimate.
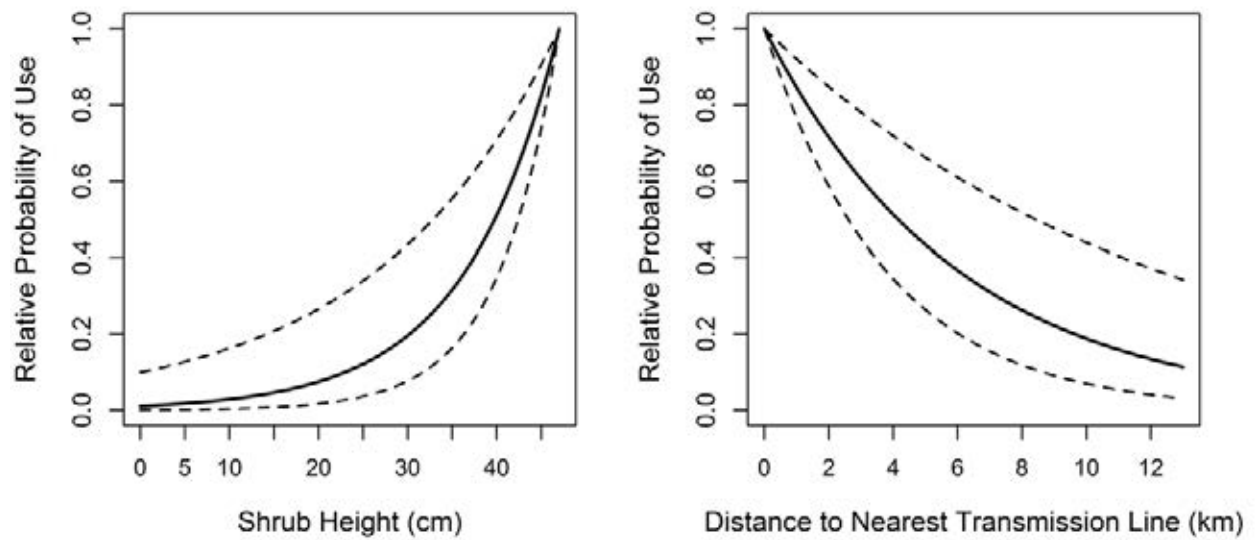
Figure 2-2. Odds ratios or relative probability of sage-grouse nest site occurrence and 90% confidence intervals (dashed lines) within the Simpson Ridge study area as a function of top model covariates, Carbon County, Wyoming, USA, 2009 and 2010. All other covariates in the best approximating model were held constant at their mean value.
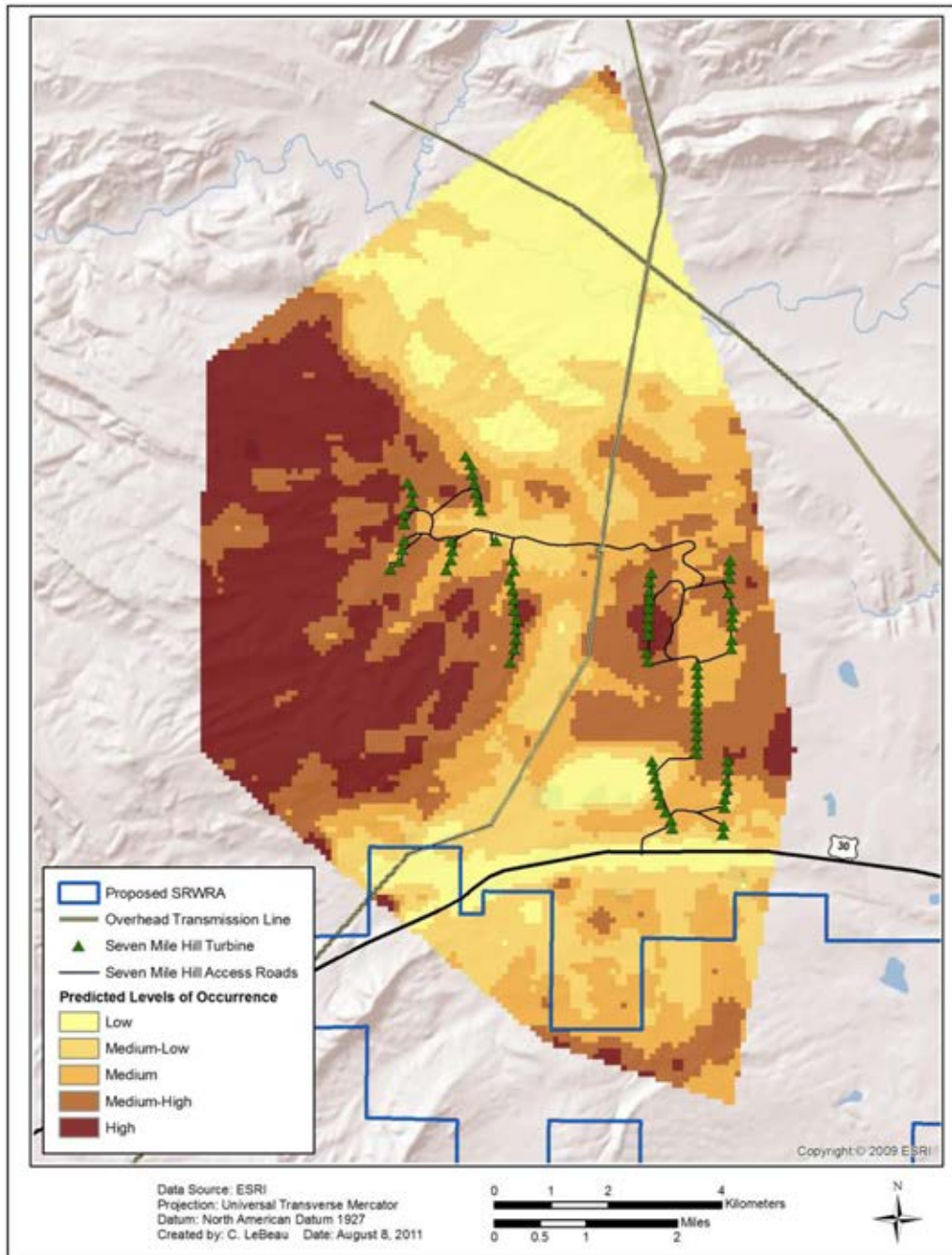
Figure 2-3. Predicted nesting habitat used within a 129 km^2 minimum convex polygon by sage-grouse within the Seven Mile Hill study area, Carbon County, Wyoming, USA, 2009 and 2010.
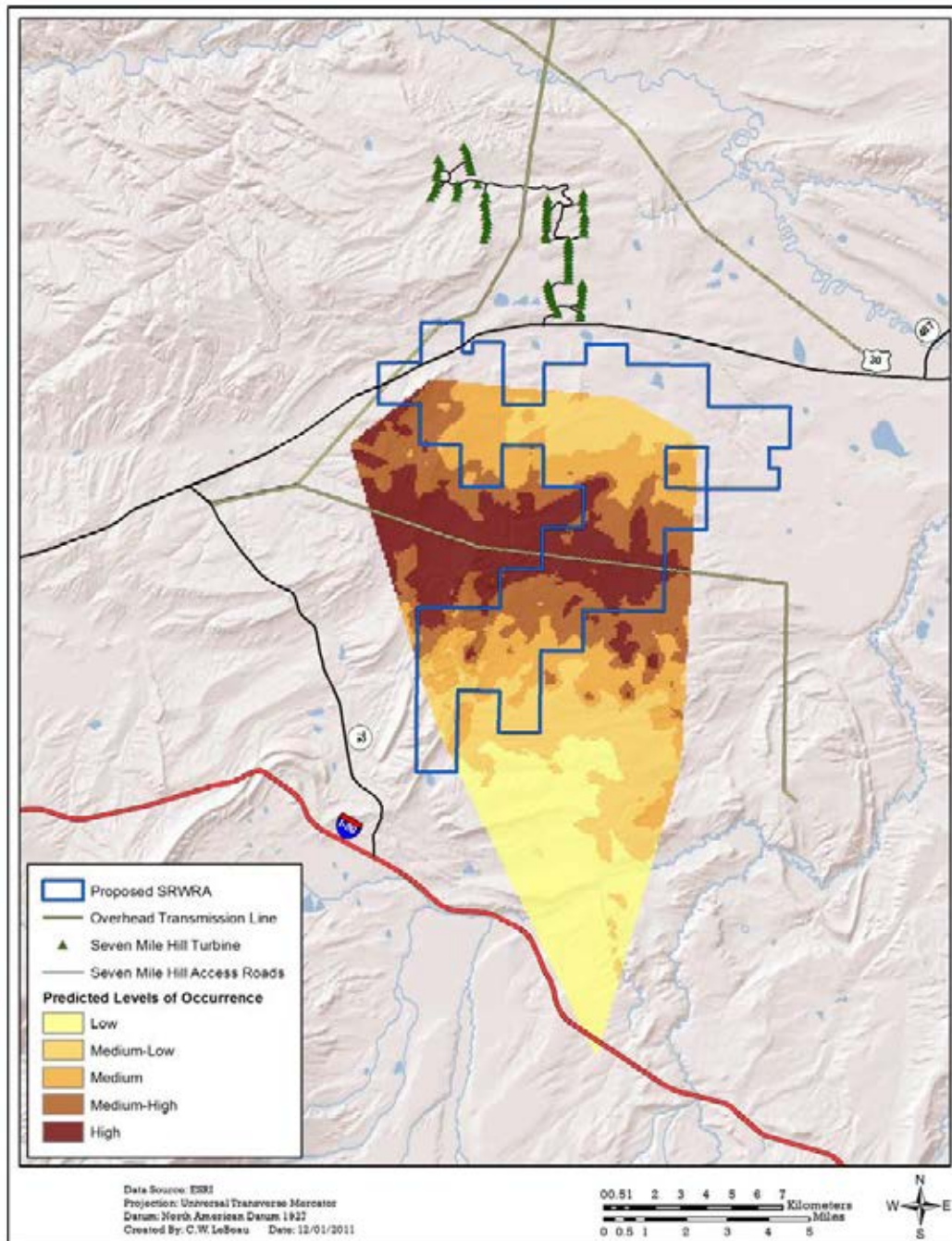
Figure 2-4. Predicted nesting habitat used within a 217 km^2 minimum convex polygon by sage-grouse

within the Simpson Ridge Study area, Carbon County, Wyoming, USA, 2009 and 2010.
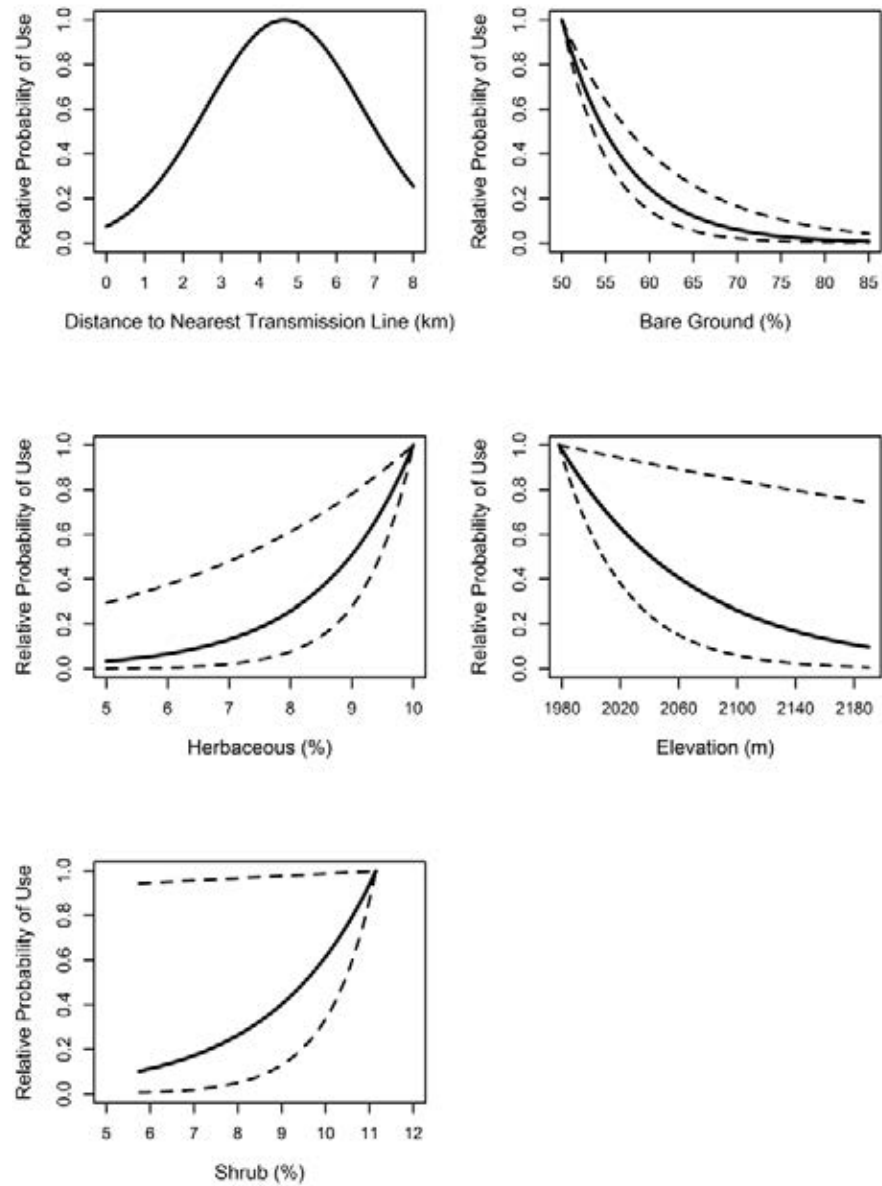
Figure 2-5. Odds ratios or relative probability of sage-grouse brood-rearing selection and 90% confidence intervals (dashed lines) within the Seven Mile Hill study area as a function of top model covariates, Carbon County, Wyoming, USA, 2009 and 2010. Confidence intervals were not calculated for distance to transmission line because confidence intervals for quadratic effects depend on values of other covariates.
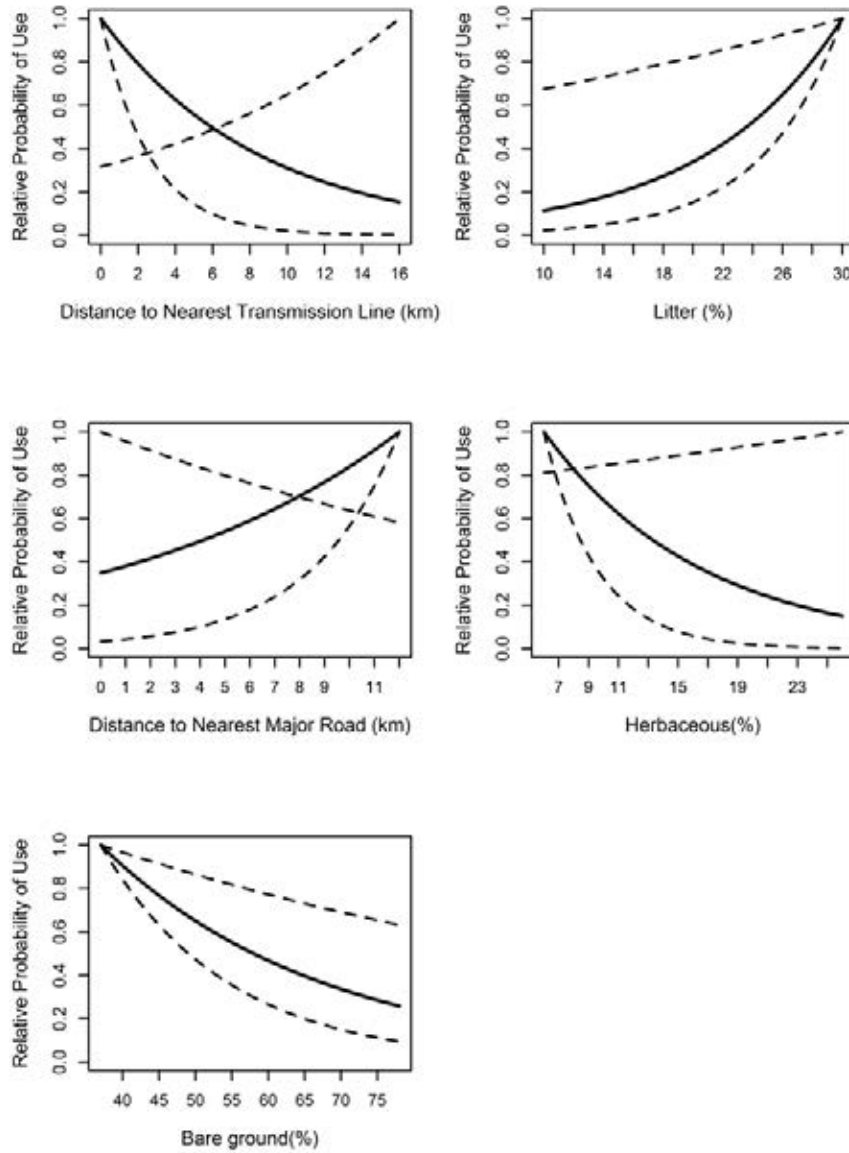
Figure 2-6. Odds ratios or relative probability of sage-grouse brood-rearing occurrence and 90% confidence intervals (dashed lines) within the Simpson Ridge study area as a function of top model covariates, Carbon County, Wyoming, USA, 2009 and 2010. All other covariates in the best approximating model were held constant at their mean value. Overlapping confidence limits indicate a non-significant estimate.
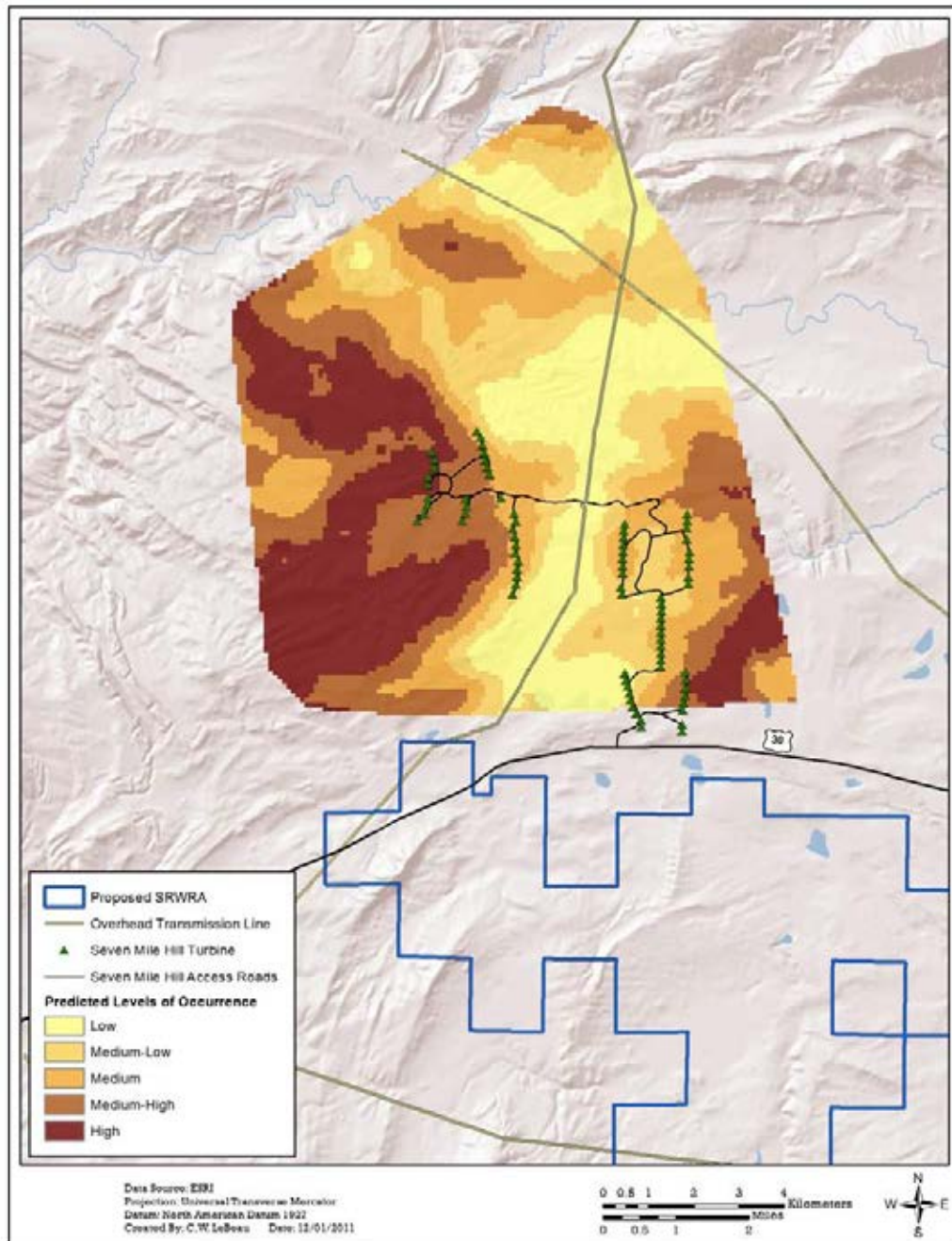
Figure 2-7. Predicted brood-rearing habitat used within a 126 km^2 minimum convex polygon by sage-grouse within the Seven Mile Hill study area, Carbon County, Wyoming, USA, 2009 and 2010.
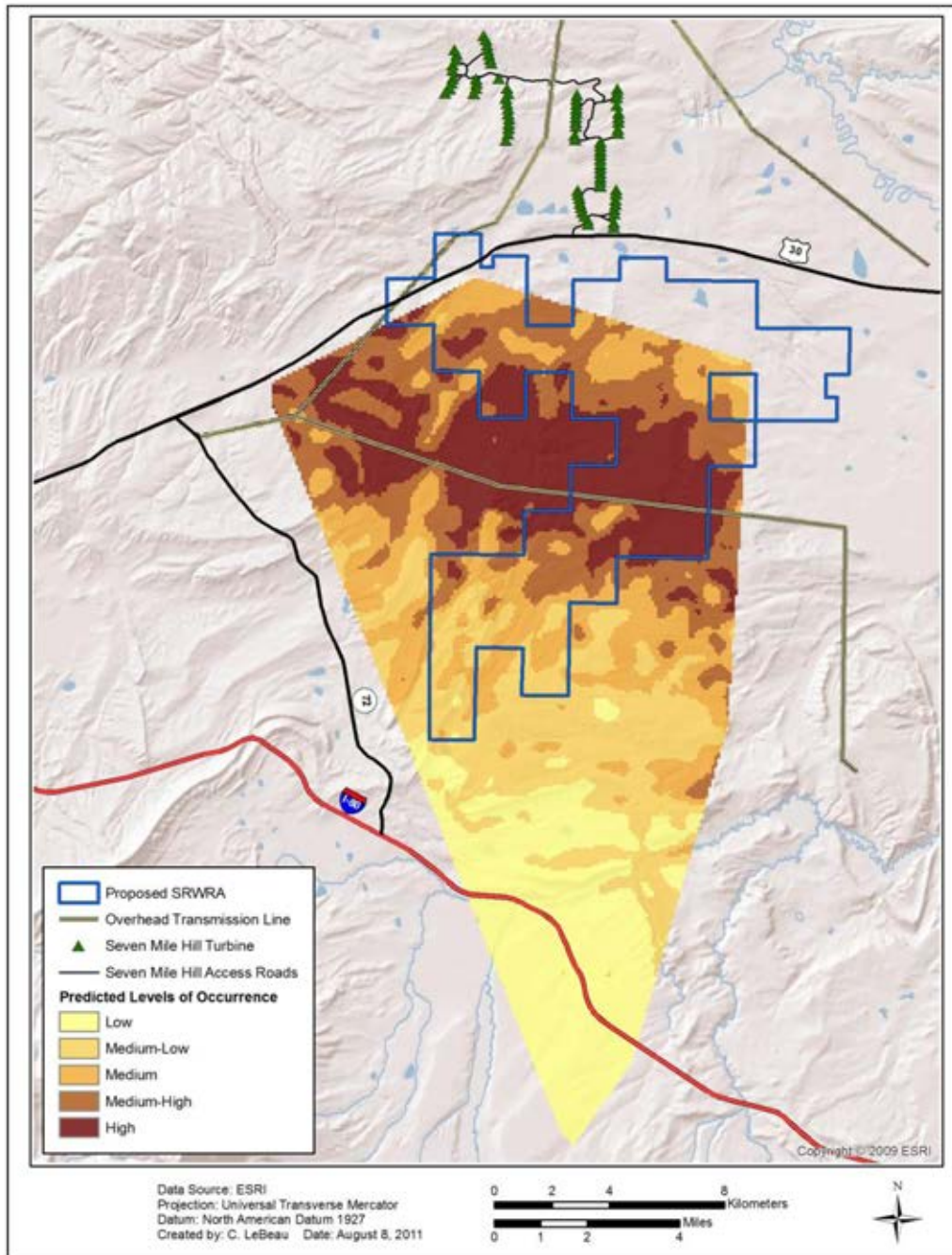
Figure 2-8. Predicted brood-rearing habitat used within a 650 km^2 minimum convex polygon by sage-grouse within the Simpson Ridge study area, Carbon County, Wyoming, USA, 2009 and 2010.
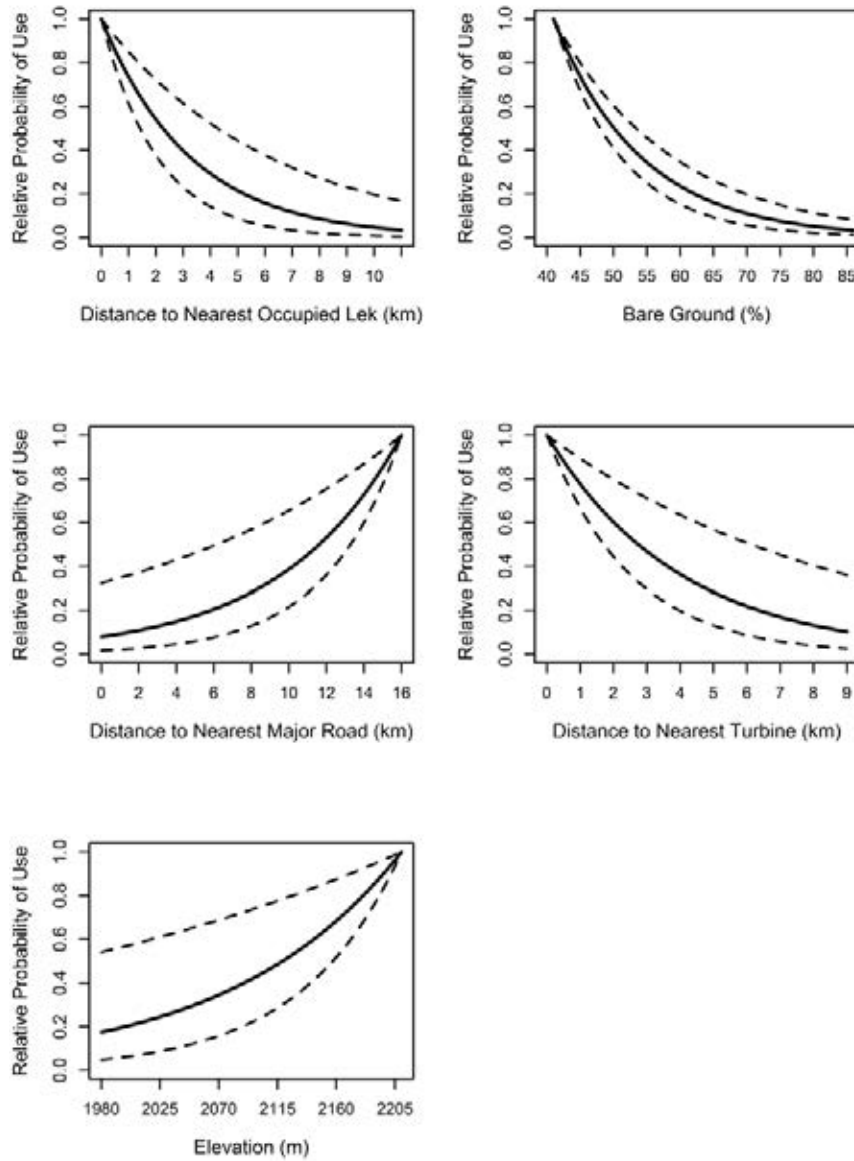
Figure 2-9. Odds ratios or relative probability of female sage-grouse summer occurrence and 90% confidence intervals (dashed lines) within the Seven Mile Hill study area as a function of top model covariates, Carbon County, Wyoming, USA, 2009 and 2010. All other covariates in the best approximating model were held constant at their mean value.
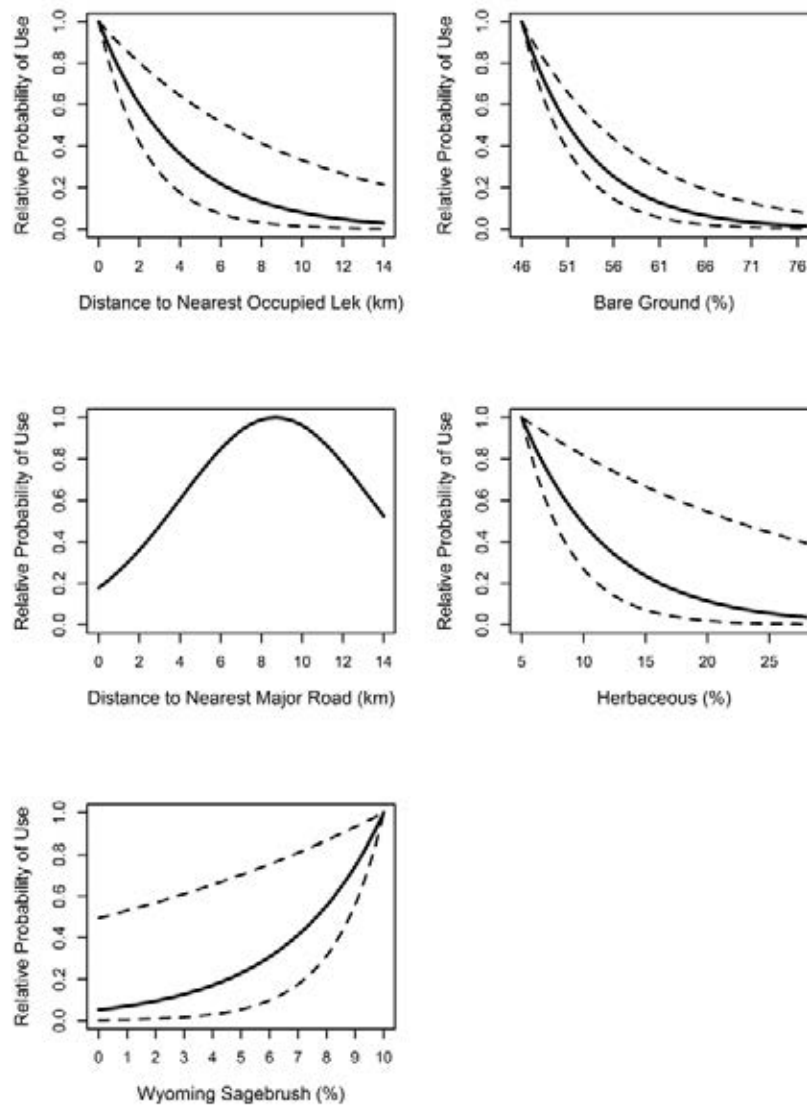
Figure 2-10. Odds ratios or relative probability of female sage-grouse summer occurrence and 90% confidence intervals (dashed lines) within the Simpson Ridge study area as a function of top model covariates, Carbon County, Wyoming, USA, 2009 and 2010. All other covariates in the best approximating model were held constant at their mean value. Confidence intervals were not calculated for distance to major road because confidence intervals for quadratic effects depend on values of other covariates.
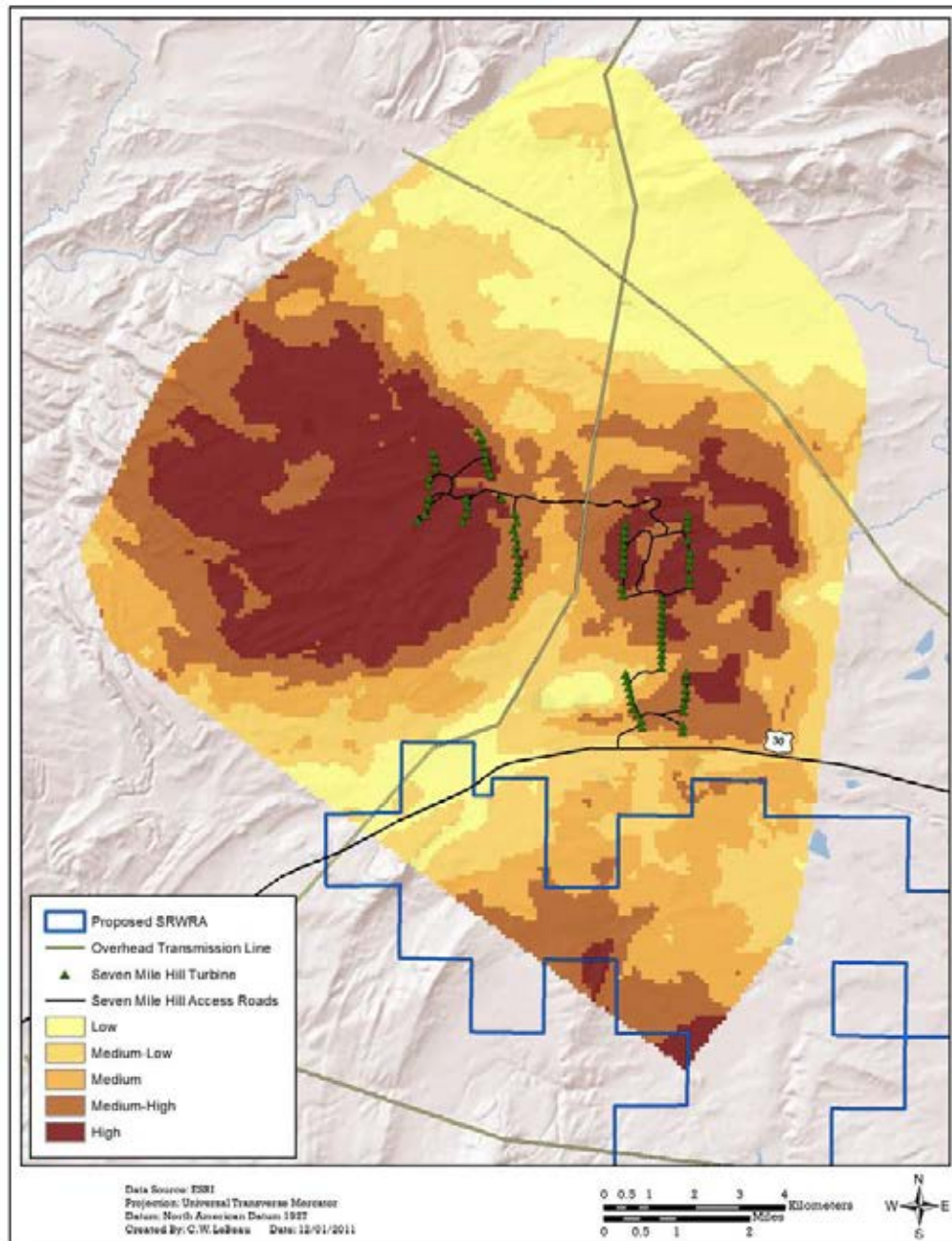
Figure 2-11. Predicted summer habitat used within a 243 km^2 minimum convex polygon by sage-grouse within the Seven Mile Hill study area, Carbon County, Wyoming, USA, 2009 and 2010.
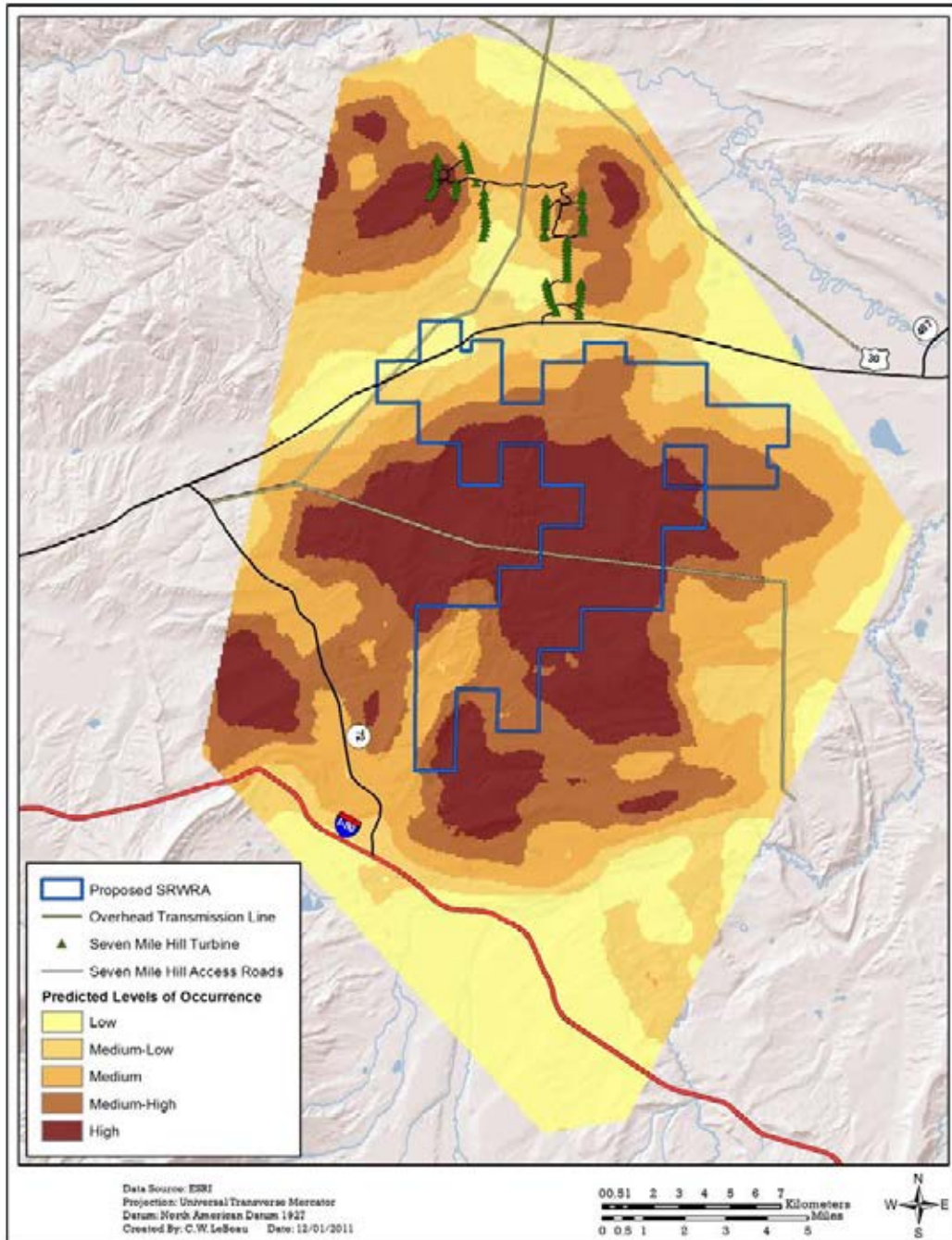
Figure 2-12. Predicted summer habitat used within a 751 km^2 minimum convex polygon by sage-grouse within the Simpson Ridge study area, Carbon County, Wyoming, USA, 2009 and 2010.

CHAPTER 3

Greater Sage-grouse Fitness Parameters Associated

with Wind Energy Development

In the format for manuscript submittal to the *Journal of Wildlife Management*

ABSTRACT

Greater sage-grouse (*Centrocercus urophasianus*) are experiencing population declines in much

their current range. Population declines are directly related to changes in greater sage-grouse

fitness parameters including nest success, brood success, and female survival. The overall fitness

of an individual ultimately determines if the individual is contributing to the viability of a

population. Reduced fitness leads to population declines because of the lack of the individual's

contribution to the population. Reduced fitness in greater sage-grouse populations have been

attributed to a decrease in habitat suitability caused by invasive plant species, increased

predation, and energy extraction activities. More recently, the increased demand for clean

renewable energy has raised concerns about the impacts to greater sage-grouse fitness parameters

in habitats occupied by wind turbines. However, little is known about these potential impacts and

mine is the first study to estimate short-term impacts from wind energy development on greater

sage-grouse fitness parameters. I hypothesized greater sage-grouse fitness parameters decreased

with increasing proximity to wind energy infrastructure particularly wind turbines. I identified 88

nests from 2009 to 2010 within the Simpson Ridge and Seven Mile Hill study areas. In addition,

I monitored 31 females during the brood-rearing period to assess brood survival. Lastly, I

identified 45 mortalities of adult females within both study areas. I utilized Cox proportional

hazard regression to model nest survival and used the Andersen and Gill survival model to

estimate female survival and brood survival relative to wind turbines. I used forward model

selection and Akaike's information criterion to determine optimal models for each fitness parameter. I used Schoenfeld residuals to test for non-proportional hazards in the top model. The results from the survival time analysis indicated the risk of a brood or nest failing increased within habitats of close proximity to wind turbines. In addition, I detected no variation in female survival relative to wind infrastructure. Future wind energy development should consider the increased risk of brood and nest failure within habitats of close proximity to turbines. Identifying nesting and brood-rearing habitats within close proximity to wind energy developments is critical when estimating potential impacts to overall population fitness.

INTRODUCTION

The population demographics of greater sage-grouse (*Centrocercus urophasianus*; hereafter sage-grouse) are unique among upland game bird species (Connelly et al. 2011). Sage-grouse have relatively low reproductive rates (Connelly et al. 2000); low winter mortality (Wik 2002, Zablan 2003), high annual survival (Holloran 1999), and many populations are migratory (Connelly et al. 1988, 2000, Schroeder et al. 1999; Fedy et al. 2012). These demographics are variable among subpopulations across the species' range due to changes in environmental gradients and anthropogenic influences (Connelly et al. 2011).

Nest success is an important vital rate of sage-grouse populations and can be used to assess trends in population productivity. Nest success is defined as the probability of a nest hatching one or more eggs successfully (Rotella et al. 2004). Poor nest success has often been related to sage-grouse population declines (Crawford and Lutz 1985, Gregg et al. 1994, Schroeder et al. 1999). The average nest success rate for sage-grouse in 29 studies using radio-telemetry was 46% (range: 15–86%), and was widely dependent on region, habitat conditions, and study design (Connelly et al. 2011). Nest success also differs from unaltered habitats (61%

of studies reported ≥50% and 22% of studies reported <40% overall nest success) to altered habitats (17% of studies reported ≥50% and 42% of studies reported <40% overall nest success; Connelly et al. 2011).

Peak egg-laying and incubation occurs from March through mid-June, with renesting lasting into early July (Gregg 2006, Schroeder et al. 1999). Mean sage-grouse clutch size ranges from 6.3 to 9.1 eggs (Schroeder et al. 1999). Female sage-grouse exhibit high fidelity to nesting areas (Holloran and Anderson 2005, Fischer et al. 1993). They are known to nest on average 2.1 km from undisturbed leks of capture and 4.1 km from disturbed leks of capture in southwestern Wyoming (Lyon and Anderson 2003). In Wyoming, nests that are not located in close proximity to other nests and situated closest to leks tend to be more successful (Holloran and Anderson 2005). Nest propensity is variable across the species range averaging 78% (Connelly et al. 2011). Furthermore, adult females tend to have higher nest initiation rates than yearlings (Connelly et al. 2004) and female sage-grouse may renest (mean: 30% in the western portion of the species range) following their failed first nesting attempt (Connelly et al. 2011).

In addition to nesting success, early and late brood success is a key parameter in assessing sage-grouse population demographics because juvenile survival impacts overall population productivity (Crawford et al. 2004, Connelly et al. 2011). Beck et al. (2006) provided estimates that indicate juvenile survival equals adult survival after 10 weeks of age, suggesting that nesting and early brood-rearing success are critical drivers of population change. I defined early brood success as the proportion of broods that survived 14 days post hatch (Thompson et al. 2006) and late brood success as the proportion of broods that survived 35 days post hatch (Walker 2008).

Sage-grouse chick survival during the early brood period (18 days post hatch) has been estimated to be 44% in southeastern Oregon and northern Nevada (Rebholz 2007), and 39% through day 28 in south-central Oregon and northern Nevada (Gregg 2006). Chick survival during the late brood period (35 days post hatch) has been estimated to be 33–50% in northeastern Wyoming and southeastern Montana (Walker 2008) and 76.2% (40 days post hatch) in southeastern Wyoming (Kirol 2012). Early brood activity occurs in the vicinity of nesting locations (mean distance from nest in southwestern Wyoming was 1.1 km; Lyon 2000), with the habitat characterized as having a healthy sagebrush (*Artemisia* spp.) overstory and herbaceous understory containing insects critical to chick survival (Johnson and Boyce 1990). When landscapes become desiccated around midsummer, brooding hens often migrate 5-82 km from early brood-rearing habitat (Klebenow and Gray 1968, Wallestad 1971, Connelly et al. 1988, Fisher et al. 1997) to more forb rich habitat, usually higher in elevation where pockets of moisture still remain (Klebenow 1969). These brooding habitats are widely variable and in many cases are dependent on yearly weather conditions (Patterson 1952, Dalke et al. 1963, Connelly et al. 1988, Gregg et al. 1993, Wallestad 1971).

Sage-grouse declines are at least partially explained by lower annual survival of female sage-grouse and in the case of oil and gas development, the impacts to survival result in population-level declines (Holloran 2005). Sage-grouse are characterized as having high annual survival compared to other upland game birds. Annual survival rates of adult female sage-grouse in Wyoming were estimated to be 48–78% (Holloran 1999, 2005). Seasonal survival is variable for both male and female sage-grouse, but is highest during the winter (88–100%; Wik 2002, Beck et al. 2006) and lowest during the spring (57%, March-June; Connelly et al. 2000), summer, and fall (Connelly et al. 2000, Wik 2002).

The purpose of my study was to investigate the affect of wind energy infrastructure on sage-grouse fitness parameters. Specifically, I investigated sage-grouse nest, brood, and female survival in relation to wind energy infrastructure including turbines, roads, and transmission lines. I hypothesized that sage-grouse nest, brood, and female survival decreased as proximity to infrastructure, specifically turbines, increased. This information is critical to provide for use in planning future wind energy development sites that occur within occupied sage-grouse habitats.

STUDY AREA

My study area was consistent with Chapters 1 and 2 in this thesis. Observed nests, brood locations, and mortality locations were combined between years and study areas for my survival analysis (see Fig. 1-1).

METHODS

Field Methods

I captured 116 female sage-grouse by 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. Initial capture efforts were centered within SR during the first study year (2009) where 50 sage-grouse females were targeted and 25 were targeted within SMH. During the second study season (2010) the target sample size increased to 40 at SMH and 45 at SR. I attempted to capture grouse at all accessible active lek sites within 16 km of the SMH wind turbines proportionately to the number of males attending those leks. I aged, weighed (0.1-g precision), acquired blood samples (year 2009), and fitted each captured grouse with a 22-g necklace-mounted radio transmitter with a battery life of 666 days (Advanced Telemetry Systems, Isanti, MN). I then released each radio-marked female grouse at the point of capture and marked the location using a hand held global positioning system (GPS) unit.

I relocated each radio-marked female at least twice each week during the prelaying and nesting period (Apr through Jun); once every week for brooding females during the brood-rearing period (hatch through 15 Aug); and, at least once per week during the summer (Jun through 1 Nov) periods for all barren females (i.e., females that were unsuccessful in producing or raising young or were not currently nesting or raising young). Marked sage-grouse were monitored primarily from the ground using hand-held receivers. I determined sage-grouse locations by triangulation or homing until visibly observed and classified radio-locations as breeding, nesting, brood-rearing, or summer. Triangulation locations were estimated by taking two vectors in the direction of the signal. In addition, I estimated the triangulation error by placing 6 test collars for each technician throughout both project areas and estimated the mean telemetry error between the actual and estimated locations. The mean error telemetry rate was incorporated into the habitat selection modeling effort. I employed aerial telemetry to locate missing birds throughout the study period.

I determined nesting success for each radio-marked female sage-grouse from long range triangulation at least every third day throughout the nesting season, late April through 15 June. I assumed females were nesting when movements became localized. Nests were located using a progressively smaller concentric circle approached by walking circles around the radio signal using the signal strength as an indication of proximity (Holloran and Anderson 2005). Once I visually confirmed the female in an incubating position, the location of the observer was recorded with a GPS and a photograph was taken of the habitat surrounding the incubating hen. All future monitoring of the nest was made from remote locations (>60 m) using long distance triangulation to minimize potential disturbance. Once a nest location was established, I conducted incubation monitoring on an alternate-day schedule to determine nesting fate. For

each nest and re-nest, I collected data on timing of incubation and nest success. All nest locations were mapped using a hand-held GPS. A nest that successfully hatched (i.e., eggs with detached membranes) ≥1 egg was considered a successful nesting attempt. Nests that failed to successfully hatch ≥1 egg were considered failed nesting attempts whose fates included predation (avian, mammal, and unknown) and abandoned. Females that were unsuccessful in their first nesting attempt were monitored three times per week to determine possible re-nesting attempts. Females that were unsuccessful in their first or second nesting attempt were monitored twice each week through 1 November in 2009 and 2010.

I located radio-marked females that successfully hatched ≥1 egg each week through 15 August 2009 and 2010 to evaluate brood-rearing habitat selection. I categorized the brood-rearing period as early (hatch through 14 days post-hatch; Thompson et al. 2006) or late (35 days post-hatch; Walker 2008). Females were considered successful through the early brood-rearing period if ≥1 chick survived to two weeks post-hatch; chick presence during this period was established either through visual confirmation of a live chick or the brooding female's response to the researcher (e.g., chick protective behavior exhibited). I 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 nighttime spotlight surveys conducted on days 35 and 36 post-hatch (Walker 2008). Similar to sage-grouse with unsuccessful nests, sage-grouse that were unsuccessful during either the early or late brood-rearing period were monitored twice each week through 31 August.

GIS Covariates

I developed a suite of covariates to estimate the variability in nest, brood, and female survival within both study areas. Anthropogenic features included major roads, transmission lines, and

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turbines. Major roads included paved highways: U.S. Highway 30/287 traversed east-west

separating SR from SMH; Wyoming State Highway 72 traversed north-south through the SR

study area; and Interstate 80 traversed east-west south of the SR study area (see Fig. 1-1). The

SMH study area included wind turbines and access roads whereas the SR did not. Major roads

and overhead transmission lines were digitized using aerial satellite imagery and ArcMap 10

(ESRI 2011). Turbine locations were obtained from PacifCorp, the operators of the SMH Wind

Energy Facility.

　　　　Environmental covariates I considered included vegetation and topographic features

within both study areas. Vegetation layers used in the analysis were remote sensed sagebrush

products developed by Homer et al. (2012). This dataset used a combination of methods to

integrate 2.4 m QuickBird, 30 m Landsat TM, and 56 m AWiFS (Advanced Wide Field Sensor)

imagery into the characterization of four primary continuous field components (percent bare

ground, percent herbaceous cover, percent litter, and percent shrub cover) and four secondary

components (three subdivisions of shrub cover —percent sagebrush (*Artemisia* spp.), percent big

sagebrush (*A. tridentata* spp.), and percent Wyoming big sagebrush (*A. t. wyomingensis*)—and

shrub height, using regression classification (Homer et al. 2009, 2012; Table 3-1). Landscape

features included elevation, slope, and terrain ruggedness all of which were calculated from a 10

m National Elevation Dataset (USGS, EROS Data Center, Sioux Falls, SD). Terrain ruggedness

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. 2005; Table 3-1).

Survival Parameters

The most common method used to estimate nest survivorship is the Mayfield method (Mayfield

1961, 1975, Burhans et al. 2002, Liebeziet and George 2002, Nur et al. 2004); however, this

method cannot be used to statistically model nest failure in relation to a set of quantitative covariates or measure the joint effects of covariates (Johnson 1979, Nur et al. 2004). A more commonly used method to relate survival to a set of covariates is to use survival time analysis or more specifically, Cox proportional hazard models (Cox 1972). Cox proportional hazard models examine the relationship of multiple explanatory variables to the probability of nest, brood, and female survival for each individual (Therneau and Grambsch 2000). The Cox proportional hazard assumes that each covariate associated with each individual is equal to the average value of that covariate for the entire sample population and the events for the individuals are independent of each other. Violating this assumption creates non-proportional hazards. The Cox proportional hazard models produces risk ratios or hazard ratios that can be used to compare the effects of different levels of a particular covariate of interest (i.e., distance to nearest turbine) on the risk of failure (i.e., nest, brood, and female death). I used survival time analysis to estimate the effects of wind energy infrastructure on nest, brood, and female survival.

I assessed nest survival during the 26 day incubation period during the 2009 and 2010 nesting seasons (Schroeder et al. 1999, Aldridge and Boyce 2007). Nests observed within both study areas were combined into one sample. Re-nests are a result of failed nesting attempts and including re-nests assumes the bird is the sampling unit and not individual nests; therefore, re-nests were excluded from estimates of apparent nest success and survival. Events or failures occurred when the sage-grouse abandoned its nest or its nest was depredated. Abandoned nests thought to be caused by the researcher were not included in the survival analysis because of the potential biased associated with that nest. I 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). Nests that were successful through the 26 day period

were censored (Nur et al. 2004). I 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).

In addition to nest survival, I estimated brood survival within both study areas. Female sage-grouse successfully hatching at least 1 egg during the nesting season were monitored at least once each week from time of hatch to 35 days post hatch; however, to determine brood survival I assessed the presence of chicks with hens at least 2 times during the first 14 days of the brood-rearing period and one final time at the end of the 35 day brood-rearing period. All early and late brood-rearing locations from both study areas and years were combined and included in the survival modeling. Events or failures occurred when no chicks were observed or the female did not act as if she had chicks during either one of the checks. I estimated the fate date using the last monitoring interval where chick survival was assessed. Broods that were successful through the 35 day period were censored (Nur et al. 2004). I used weekly monitoring intervals during this period to assess brood survival. The first monitoring interval began directly after a successful hatched nest and ended 37 days post hatch (Walker 2008). Intervals that recorded multiple observations were grouped and their corresponding covariates were averaged.

Lastly, I modeled female sage-grouse survival from time of capture to 31 October during both years. Female sage-grouse were monitored at least once each week during this period, thus I assessed weekly survival for all monitored sage-grouse. Events or mortalities occurred when I confirmed mortality via telemetry. I estimated fate date by the condition of the carcass and last known monitoring interval. I grouped intervals that recorded multiple observations and averaged their corresponding covariates.

Model Development

I estimated nest survival using Cox proportional hazards (Cox 1972); however, I used the

Anderson-Gill model (A-G; Anderson and Gill 1982), a formulation of the Cox proportional

hazards model, to model brood and female survival. The A-G model accommodates left and right

censored observations, continuous and categorical covariates that may vary during monitoring,

and discontinuous intervals of risk, which are the product of missed observations or

measurements (Therneau and Grambsch 2000, Johnson et al. 2004). The A-G model uses a

counting process style of data input where each subject is represented as a series of observations

with time intervals (i.e., sage-grouse brood location during a single monitoring interval). This

allowed me to incorporate varying degrees of habitat units used throughout the interval of risk.

I used a forward model selection procedure to identify the effects of wind energy

infrastructure on nest, brood, and female survival. Because many of my covariates were

correlated ($r \geq |6|$), I allowed for each covariate to compete with each other in a forward selection

procedure. However, I did not allow two correlated variables to be included in any one model. I

included an indicator variable for which study area the sage-grouse was captured from (SMH=1,

SR= 0) and the age of the sage-grouse (adult = 1, juvenile = 0) to determine if age or study area

was influencing survival. In addition, the average values representing each environmental feature

were extracted at 3 different radii scales, the mean telemetry error rate (0.30 km), the median

distance between consecutive year's nests from 2009 to 2010 within both study areas (0.46 km),

and the median distance traveled between monitoring intervals during the brood-rearing and

summer period (1.0 km). The median movement distance was 1.0 km during brood-rearing and

1.6 km during the summer season; however, I used 1.0 km based on findings from previously

published sage-grouse habitat selection studies (Aldridge and Boyce 2007, Carpenter et al.

2010). Kirol (2012) found the SD of shrub height to be an important predictor of nest survival in

south-central Wyoming; subsequently I included the SD of shrub height, shrub, and sagebrush in my modeling procedure.

I identified the best approximating model by comparing the adjusted Akaike's Information Criterion (AICc; Burnham and Anderson 2002) values between models to identify the model with the lowest AICc value. The top model was identified to be at least 4 ΔAICc values from the next approximating model (Arnold 2010). I model averaged across the 90% confidence set of competing models to estimate the final parameters of the top model to produce more robust estimates and to address model uncertainty in competing models (Burnham and Anderson 2002, Arnold 2010). I calculated hazard ratios and 90% hazard ratio confidence intervals to interpret the magnitude of habitat and anthropogenic variables on an individual nest, brood, or female sage-grouse's daily or weekly hazard during the nesting, brooding-rearing, and female survival periods. Estimates that included 0.0 within their 90% confidence interval were considered insignificant (alpha level = 0.10). I used survival curves to illustrate the varying degree of risk as a function of the top model covariates (Johnson et al. 2004, Therneau and Grambsch 2000). I applied the coefficients generated from the top survival model to a logistic regression equation to predict the odds of survival from 2009 through 2010 at both study areas (Johnson et al. 2004).

Lastly, I used Schoenfeld residuals (Schoenfeld 1982) to assess model fit (Therneau et al. 1990). Scoring Schoenfeld residuals can be a powerful technique to test for non-proportional hazards for continuous variables (Grambsch and Therneau 1994). Schoenfeld residuals for each covariate in the top model are defined for every individual that has a failure event (Kleinbaum and Klein 2005). For the proportional hazard assumption to hold true, the Schoenfeld residuals for a particular covariate would not be related to survival time. I ranked the Schoenfeld residuals

for each covariate in the order of event failures (i.e., the individual with the first event gets a value of 1, and so on; Kleinbaum and Klein 2005). I 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. I fitted a line to the residuals to test for a nonzero slope. A nonzero slope indicated heterogeneity in the residuals thus, rejecting the null hypothesis that the correlation between the Schoenfeld residuals and survival time was zero. Rejection of the null hypothesis indicates that the proportional hazard assumption was violated.

RESULTS

Nest Survival

I located 95 nests in 2009 and 2010 (SR, $n = 53$; SMH, $n = 42$). During both study years, nesting propensity, the number of females observed initiating a nesting attempt, ranged from 59.4% (90% CI: 43.3–74.0%) to 77.3% (90% CI: 58.0–90.6%) within both study areas. SR had more nests during both study years compared to SMH; however, SMH had 6 re-nest attempts compared to 1 re-nest attempt at SR.

Two of the 6 observed re-nests within SMH were successful and the 1 re-nest observed within SR was unsuccessful. Nest success was similar in 2009 and 2010 within both study areas, ranging from 41.9% to 42.9% at SR and from 31.6% to 35.3% at SMH. Overall, nest success at SR (42.3%; 90% CI: 30.7–54.6%, $n = 52$) was higher than at SMH (33.3%; 90% CI: 20.5–48.3%, $n = 36$); however, the difference in the means was not statistically different. 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.

During the 2009 and 2010 monitoring seasons, 16 first nesting attempt nests were initiated within 1.6 km of wind turbines at SMH; the five nests closest to turbines were located

137 m, 231 m, 248 m, 257 m, and 333 m from the nearest turbine. Four of the 16 nests (25.0%) within 1.6 km of turbines were successful, but none of the 5 nests closest to turbines were successful.

The proximity of the observed nests to each infrastructure feature varied throughout the study area. The mean distance to major roads and SMH turbines was greater for all successful nests (6.5 km [90% CI: 5.5–7.4 km] and 8.3 km [90% CI: 6.3–10.2 km], respectively) compared to failed nests (5.6 km [90% CI: 5.1–6.2 km] and 6.6 km [90% CI: 5.4–7.9 km], respectively); however, these differences were not statistically different.

Model Fit.—Eighty-eight sage-grouse nests were used in Cox proportional hazard modeling. The median duration of failed nesting attempts was estimated at 12 days. Results of the univariate model estimating differences in survival among study areas indicated that study area did not influence nest survival (hazard ratio = 1.2, 90% CI: 0.76–1.9). Three models including environmental and anthropogenic covariates were within 2.5 ΔAICc of each other. I model averaged the three competing models to estimate the final parameters for the top model (Burnham and Anderson 2002; Table 3-2). The top model relating environmental and anthropogenic features to sage-grouse nest survival included the standard deviation of shrub height (cm) within 0.30 km of a nest and distances (km) to nearest turbine and nearest overhead transmission line (Table 3-2).

The risk or the odds of a nest failing increased by 11.1% [(exp(β_0)-1)*100] with every 1.0 km increase in the distance to nearest overhead transmission line (90% CI: 10.1–12.1%; Table 3-3; Fig. 3-1). The risk of a nest failing decreased by 14.4% for every 1 cm increase in the SD of shrub height (cm) within 0.30 km of a nest (90% CI: 13.1–15.8%; Table 3-3; Fig. 3-1). Similarly, the risk of a nest failing decreased by 6.2% as distance from turbine increased by 1 km

(90% CI: 5.9–6.5%). More specifically, as distance increased from turbines, the risk of failure decreased by 17.5% ($e^{3(-0.064)}$) at 3.0 km to 47.3% at 10.0 km ($e^{10(-0.064)}$) from the nearest turbine (Table 3-3; Fig. 3-1).

A sage-grouse nest with poor survival would be located in habitats with higher levels of risk. These habitats would consist of a lower standard deviation (SD) of shrub height (5.6 cm, value at the 25th percentile) within 0.30 km, farther from an overhead transmission line (4.9 km, 75th percentile), and closer to turbines (2.0 km, 25th percentile; Fig. 3-2). Habitats with good survival would consist of a higher SD of shrub height (8.8 cm, 75th percentile) within 0.30 km, closer to overhead transmission lines (1.3 km, 25th percentile), and farther from turbines (11 km, 75th percentile; Fig. 3-2). The Cox proportional hazard model predicted a mean survival rate of 45.6% (SE = 0.084; 90% CI: 31.8–59.4%) for nests located in poor habitat conditions and 81.5% (SE = 0.053; 90% CI: 72.7–90.2%) for nests located in more favorable habitat conditions (Fig. 3-2). Spatially, habitats closer to turbines had higher odds of a nest failing than habitats farther from turbines (Fig. 3-3). Lastly, there was no evidence of non-proportional hazards for any of the 3 covariates included in the top model (*P* ranged from 0.22 [turbine] to 0.65 [SD of shrub height]) suggesting that nest failures were independent of each other. In addition, a global test was also calculated for the model as a whole and it too showed no evidence of non-proportional hazards (*P* = 0.60).

Brood Survival

Thirty-one females were monitored during the brood-rearing period in 2009 and 2010 (SMH *n* = 13; SR *n* = 18). Early brood-rearing success was relatively high during both study years, ranging from 92.3% in 2009 and 66.7% in 2010 (SR) to 100% in 2009 and 2010 (SMH). Of the successful early brood females, 11 broods were successful through the late brood-rearing period

in 2009 (9 within SR and 2 within SMH) and 8 were successful in 2010 (4 within SR and 4 within SMH). Late brood-rearing success was similar during both study years (2009 = 61.1%; 90% CI: 39.4–79.5%; 2010 = 80.0%; 95% CI: 49.0–95.6%). In addition, over the 2-year period, late brood-rearing success was 22% greater in the SR study area than in SMH (SMH = 54.5%; 90% CI: 27.8–79.2%, $n = 11$; SR =76.5, 90% CI: 53.6–91.0%, $n = 17$); however there was no statistical difference in the means. The total number of chicks observed ranged from 11 (2009 SMH) to 36 (2010 SR) chicks per study area and year. Brood size (the number of chicks observed per successful late brood-rearing female) ranged from 3.3 chicks/female (SMH 2010) to 5.5 chicks/female (SMH 2009). During both study years, productivity (number of chicks per female in the marked sample) was greater within SR than within SMH (0.18; 90% CI: 0.05–0.32).

Model Fit.—Two broods were censored due to an immediate mortality or the marked female was no longer trackable. Results of the univariate model estimating differences in survival among study areas indicated that broods located within the SMH study area were 2.9-times more likely to fail than broods within SR (hazard ratio = 2.9; 90% CI: 1.1–7.6). The top model ($\Delta AICc = 5.08$) relating environmental and anthropogenic features to sage-grouse brood survival included distance to nearest turbine (km), terrain ruggedness (scale = 0.46 km), and the percent shrub cover within 1.0 km of a brood location (Table 3-2). The next best approximating model differed by ≥ 5 Δ AICc from the top ranked model (Burnhman and Anderson 2002, Arnold 2010).

The risk or odds of a brood failing increased approximately 5 fold with every 1-unit increase in terrain ruggedness within 0.46 km of a brood location (hazard ratio = 4.8; 90% CI: 2.1–11.3; Table 3-3; Fig. 3-4). 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 (hazard ratio = 3.0; 90% CI: 1.5–6.2; Table 3-4; Fig. 3-4). Lastly, the risk of a brood failing decreased by 38.1% with every 1.0 km increase in distance from nearest turbine (hazard ratio = 0.619; 90% CI: 18.6–52.9%; Table 3-3; Fig. 3-4). More specifically, while holding other covariates constant, the effect of a 0.50 km increase in distance to nearest turbine decreased the risk of brood failure by 21.3%. As distance increased from turbine, the relative risk of failure decreased from 76.2% at 3 km to 97.8% at 8 km from the nearest turbine (Fig. 3-4). Spatially, habitats closer to turbines had higher odds of a brood failing than habitats farther from turbines (Fig. 3-5). Lastly, there was no evidence of non-proportional hazards for any of the 3 covariates included in the top model (P ranged from 0.29 [rugged460] to 0.80 [turbine]) suggesting that brood failures were independent of each other. In addition, a global test calculated for the model as a whole showed no evidence of non-proportional hazards ($P = 0.20$).

Female Survival

During the study, 45 of 116 (38.8%) radio-marked birds died. I recorded 31 mortalities in SR (15 in 2009 and 16 in 2010) and 14 within SMH (5 in 2009 and 9 in 2010). Although cause of death could not be determined for all mortalities, 13 were determined to be killed by avian predators and 16 were determined to be killed by mammalian predators. In 2009, 3 dead radio-collared females that did not exhibit any signs of trauma were submitted to the Wyoming State Veterinary Lab in Laramie, Wyoming to be examined for the presence of West Nile virus. Two of the 3 female sage-grouse tested positive for West Nile virus and all were located within the SR study area. The median distance of mortality locations to each infrastructure feature varied from 4.0 km (overhead transmission line), to 6.7 km (major roads), to 8.7 km (turbine). The mean female

survival rate at SMH was 28.0% (90% CI: 18.1–40.4%) compared to 47.0% (90% CI: 36.5–57.7%) at SR.

Model Fit.–A total of 1,417 locations, 23 monitoring intervals, and 45 mortalities were used to model female sage-grouse survival. Eight mortality events were censored because they occurred within 2 weeks of capture. The univariate model estimating differences in female survival among study areas indicated that study area (SMH vs. SR) did not influence female survival (hazard ratio = 0.84; 90% CI: -0.73–0.36). Adult females were 1.3-times more likely to die than juvenile females (hazard ratio = 1.3; 90% CI: 0.75–2.2). I experienced some model uncertainty and modeled averaged the 95% confidence set of top models (Table 3-2).The top model (ΔAICc = 0.55) relating environmental and anthropogenic features to female survival included distance (km) to nearest major road and overhead transmission line (Table 3-2). However, this model (AICc = 378.9) was not more explanatory (within 4 AICc points) than the null model (AICc = 379.3), suggesting none of the predictors I used were adequate to explain the variation in survival within my study (Table 3-2). However, the risk of female mortality during the survival period increased by 21.0% with every 1.0 km increase in distance from major roads (90% CI: 16.4–24.9%; Table 3-3, Fig. 3-6). Similarly, the risk of mortality increased by 9.4% with every 1.0 km increase in distance from transmission line (90% CI: 8.5–10.2%; Table 3-3, Fig. 3-6). Spatially, habitats closer to transmission lines had a higher odds of survival than habitats farther from transmission lines (Fig. 3-7). There was no evidence of non-proportional hazards for any of the 2 covariates included in the top model (P = 0.86 for major roads and P = 0.81 for overhead transmission line) suggesting that summer mortalities were independent of each other. In addition, a global test was also calculated for the model as a whole and it too showed no evidence of non-proportional hazards (P = 0.95).

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DISCUSSION

I investigated the potential influence of wind energy development 2 yrs post development, particularly wind turbine influences on sage-grouse nests, broods, and female survival because these parameters have the greatest effect on sage-grouse population growth (Taylor et al. 2012). More specifically, female survival and brood survival, in that order, have the greatest effect on sage-grouse population growth rate (Taylor et al. 2012). I hypothesized that risk of failure increased for nests and broods that were in close proximity to turbines. In addition, I hypothesized that the risk of female mortality increased as proximity to turbines decreased. I determined that the risk of sage-grouse nest and brood failure increased as proximity to turbines increased using Cox proportional hazards and the Andersen-Gill formulation of Cox proportional hazards. Overall female survival was not influenced by proximity to turbines or any other landscape habitat feature used in the analysis; however, female survival was highest around transmission lines throughout the study area.

The reason for the decreased nest and brood survival within habitats in close proximity to turbines is unknown but may be attributed to increased predation (Coates and Delhanty 2010) due to the presence of human development and edge effects (Batary and Baldi 2004). The lack of concurrent predator monitoring makes it difficult to speculate why there is a decrease in survival closer to turbines. The incorporation of different covariates (i.e., predator densities, noise, and detailed weather data) may further explain the variation in survival among sage-grouse occurring in habitats with close proximity to wind energy.

Nest success within SMH (33.3%) was similar to other sage-grouse studies that reported nest success in other habitats influenced by other forms of energy development (<40%; Connelly et al. 2011). Nest success at SR (42.3%) was slightly higher than at SMH (33.3%), but not as

high as the majority of studies in unaltered habitats (11 of 18 [61%] of studies reported $\geq 50\%$; Connelly et al. 2011).

Survival time analysis or Cox proportional hazard modeling is becoming a widely used and effective tool to predict nest survivorship in avian species (Liebezeit et al. 2009, Nur et al. 2004, Kirol 2012). Survival time analysis has been incorporated into sage-grouse studies as an effective modeling procedure aimed at identifying risky habitats and specific covariates influencing nest and brood survival (Aldridge and Boyce 2007, Moynahan et al. 2007, Herman-Brunson et al. 2009, Kolada et al. 2009). Logistic regression (Holloran et al. 2005) and the Mayfield method (Mayfield 1961, 1975) are also two other common methods for estimating nest survivorship; however they have some limitations. Logistic regression is commonly used when analyzing nest success in avian species (Holloran et al. 2005, Nur et al. 2004); however, it may be inefficient and in some cases may introduce bias into the analyses because nests with uncertain fates must be excluded from the analysis (Manolis et al. 2000). The Mayfield method (Mayfield 1961, 1975) is the most common method at estimating nest survivorship in avian studies; however, it is met with several restrictive and unrealistic assumptions including nest failure is constant over time, homogeneity of failure probability, and independence of outcome among nests (Dinsmore et al. 2002, Nur et al. 2004). Unlike logistic regression and the Mayfield method, survival time analysis accounts for these assumptions.

The results of my nest survival time analysis indicated that nest survival within both study areas was influenced by proximity to turbines and the variation in shrub height. The risk of nest failure increased as proximity to turbines decreased and as the variation in shrub height decreased. Similar sage-grouse nest survival studies indicated that the risk of nest failure was positively influenced by greater shrub cover, higher grass height, grass cover, and greater

variation in the Normalized Difference Vegetation Index (NDVI; Aldridge and Boyce 2007, Moynahan et al. 2007, Herman-Brunson et al. 2009, Kolada et al. 2009). Only one of these studies included covariates explaining the influence of energy development on sage-grouse nest survival; however it was not significant at predicting nest survival (Aldridge and Boyce 2007). My models predicting nest survival provide good predictive power and insight into the spatial variation of nest survival in relation to wind energy development, particularly wind turbines.

Another important fitness parameter that I modeled was brood survival. I used a formulation of Cox proportional hazards model (Andersen-Gill) to estimate brood survival within both study areas. The A-G model incorporates time-varying covariates when predicting survivorship. Aldridge and Boyce (2007) utilized Cox proportional hazards to model chick survival to 56 days. Similarly, Gregg and Crawford (2009) modeled chick survival to 28 days with the Cox model. Cox proportional hazards are appropriate for estimating survival because there are no time varying covariates (i.e., nest covariates are constant during the incubation period or monitoring interval). Cox proportional hazards model can model brood survival (Aldridge and Boyce 2007, Gregg and Crawford 2009); however, this methodology does not allow for time-dependent covariates that may vary in magnitude with time. The Cox proportional hazard model assumes that left or right censored observations are represented over the entire monitoring interval. Thus, it does not take into account the multiple habitats a sage-grouse potentially uses during the brood-rearing period. The A-G formulation of the Cox model accommodates multiple monitoring intervals and subsequently accounts for multiple habitat characteristics represented during the brood-rearing survival period (Therneau and Grambsch 2000).

The results of my brood survival analysis indicated that the risk of a brood failing increased as proximity to turbines increased, as terrain ruggedness increased, and percent shrub cover increased. Of the studies that utilized Cox survival model, brood survival was positively correlated with grass cover (Gregg and Crawford 2009), risk of failure increased in habitats with higher visible oil and gas well density within 1.0 km, and failure increased in habitats with higher CTI (soil moisture index; Aldridge and Boyce 2007).

Lastly, estimating adult female survival is useful in understanding animal population trends because it compares the cumulative effects of environmental conditions or anthropogenic influences to the overall persistence of the population or the growth rate (λ). Sage-grouse declines are at least partially explained by lower annual survival of female sage-grouse and in the case of oil and gas development, the impacts to survival result in population-level declines (Holloran 2005).

I used the A-G model to estimate female survival in summer in relation to wind energy infrastructure. The top model did not differ from the null model suggesting the covariates I measured within both study areas did not detect any variability in survival across the landscape. However, the risk of mortality decreased in habitats with close proximity to transmission lines and major roads. Similar to my study, Moynahan et al. (2006) found no support for inclusion of landscape-level habitat variables in modeling monthly annual survival rates of sage-grouse in Montana.

MANAGEMENT IMPLICATIONS

Mine is the first study to evaluate short term effects of wind energy infrastructure, specifically turbines, on sage-grouse fitness parameters. The presence of turbines negatively impacted sage-grouse nest and brood survival, whereas the presence of turbines did not appear to be affecting

female survival. Future wind energy project placement should consider the increased levels of risk to sage-grouse broods and nests within habitats of close proximity to wind turbines. Although I did not determine actual thresholds, increased levels of risk to these fitness parameters appeared to increase up to 5.0 km from turbines. Identifying nesting and brood-rearing habitats prior to construction and operation of wind energy facilities will provide valuable information as to the possible affect of the facility on sage-grouse nest and brood survival. Furthermore, placing wind turbines at least 5 km from nesting and brood-rearing habitat should reduce negative influences from wind energy infrastructure on sage-grouse nest and brood survival.

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Table 3-1. Explanatory anthropogenic and environmental covariates used in modeling of sage-grouse nest, brood, and female survival at the Seven Mile Hill and Simpson Ridge study areas, Carbon County Wyoming, USA, 2009 and 2010.

Covariates	Variable description
Anthropogenic infrastructure	
dist_major_rds	Distance to nearest major road [WYO HWY 72, US HWY 287/30, and I-80 (km)]
dist_tline	Distance to nearest overhead transmission line (km)
dist_turbine	Distance to nearest turbine (km)
Environmental	
Bare ground†	Percent bare ground
Big sagebrush†	Percent big sagebrush (*Artemisia tridentata* spp.)
Elevation	Altitude above sea level (m)
Herbaceous†	Percent herbaceous cover
Litter†	Percent litter
Sagebrush†*	Percent sagebrush (*Artemisia* spp.)
Shrub†*	Percent shrub cover
Shrub_hgt†*	Shrub height (0–253 cm)
Slope	Degrees 0-90
Terrain ruggedness	Variability in slope and aspect (0-1; 1 = complete terrain variation; Sappington et al. 2009)
Wyoming big sagebrush†	Percent Wyoming big sagebrush (*Artemisia tridentata wyomingensis*)

*Also included is the standard deviation of these covariates.

†Vegetation covariates obtained from Homer et al. 2012.

Table 3-2. Model fit statistics for greater sage-grouse nest, brood, and survival at the Seven Mile Hill and Simpson Ridge study areas, Carbon County, Wyoming, USA, 2009 and 2010. Models are listed according to the model best fitting the data and ranked by (Δ AICc), the difference between the model with the lowest Akaike's Information Criterion for small samples (AICc) and the AICc 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.

Model	log[L]	K	AICc	Δ AICc	w_i
Nest Survival					
sd_shrub_hgt, dist_turbine, dist_tline	-213.3	4	433.1	0.00	0.44
sd_shrub_hgt, dist_turbine	-214.4	3	433.1	0.1	0.43
sd_shrub_hgt	-216.7	2	435.6	2.5	0.13
null	-218.7	1	437.4	4.3	0.05
Brood Survival					
dist_turbine, terrain ruggedness, shrub	-30.1	4	66.6	0.00	0.91
dist_turbine, terrain ruggedness	-33.7	3	71.6	5.0	0.07
dist_turbine	-36.6	2	75.4	8.8	0.01
null	-38.3	1	76.5	10.0	0.01
Female Survival					
dist_major_rds, dist_tline	-187.3	3	378.9	0.00	0.55
dist_major_rds	-188.6	2	379.3	0.37	0.45
null	-189.7	1	379.4	0.69	0.28

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

Covariate	Scale (km)	Estimate	SE	Hazard Ratio [*exp*(Estimate)]	Hazard Ratio 90% CI Lower	Upper
Nest Survival						
sd_shrub_hgt	0.30	-0.16	-0.01	0.86	0.84	0.87
dist_turbine	NA	-0.06	-0.01	0.94	0.94	0.94
dist_tline	NA	0.11	0.01	1.11	1.10	1.12
Brood Survival						
dist_turbine	NA	-0.48	0.17	0.62	0.47	0.81
Terrain ruggedness	0.46	1.6	0.52	4.83	2.07	11.3
Shrub	1.0	1.1	0.43	3.03	1.49	6.16
Survival						
dist_major_rds	NA	0.19	0.02	1.21	1.16	1.25
dist_tline	NA	0.09	0.01	1.09	1.09	1.10
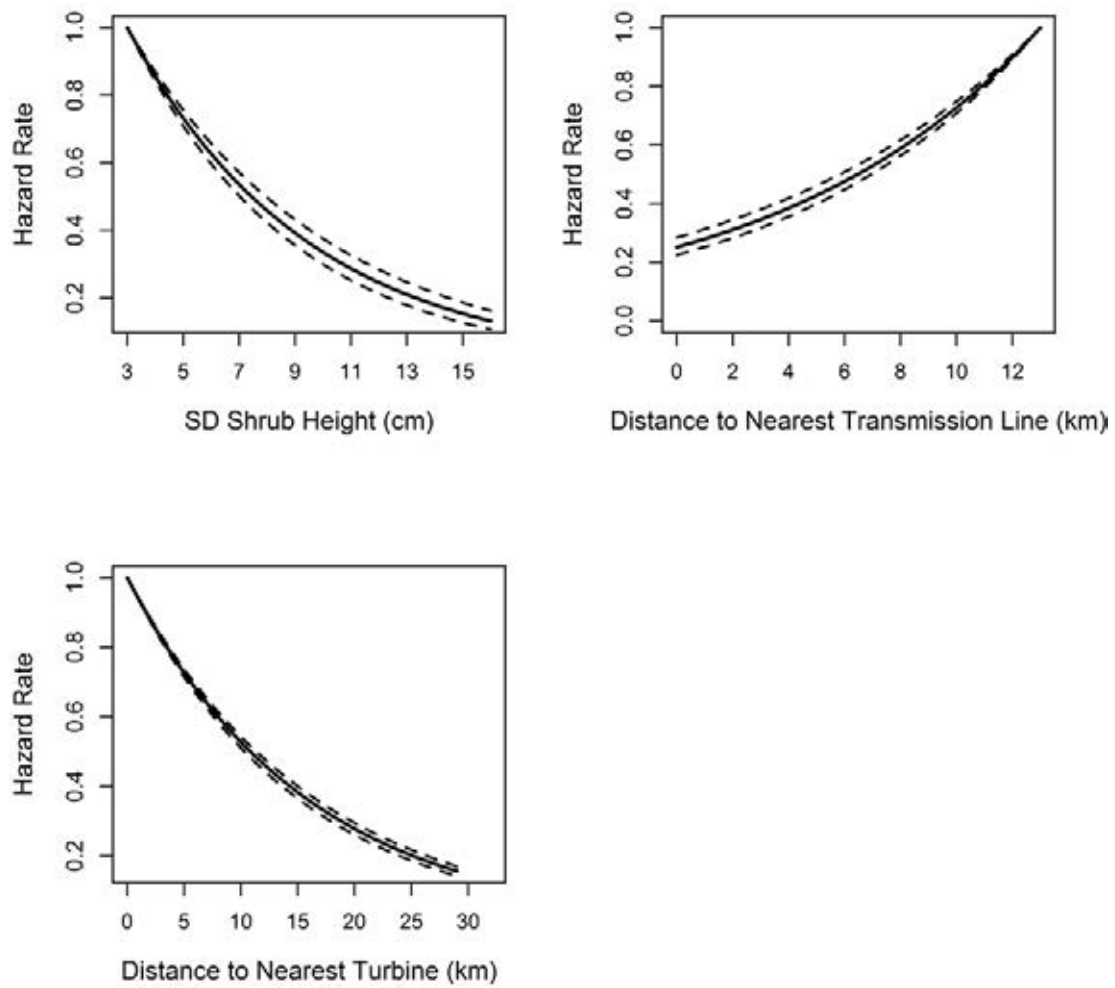
Figure 3-1. Relative hazard rate of nest survival adjusted for the SD of shrub height within 0.30 km, and the distance to nearest turbine and transmission line at the Simpson Ridge and Seven Mile Hill study areas, Carbon County, Wyoming, USA, 2009 and 2010. Dashed lines indicate the lower and upper 90% confidence limits.

Figure 3-2. Expected nest survival and 90% confidence intervals for nests located in higher risk habitats (closer to turbines, further from transmission lines, and higher SD of shrub height within 0.30 km; poor nest survival) and for nests located in lower risk habitats (good nest survival) within the Simpson Ridge and Seven Mile Hill study areas Carbon County, Wyoming, USA, 2009 and 2010.

Figure 3-3. Spatial variation in the predicted relative risk of sage-grouse nest failure (low – high) within the Seven Mile Hill and Simpson Ridge study areas, Carbon County, Wyoming, USA, 2009 and 2010.
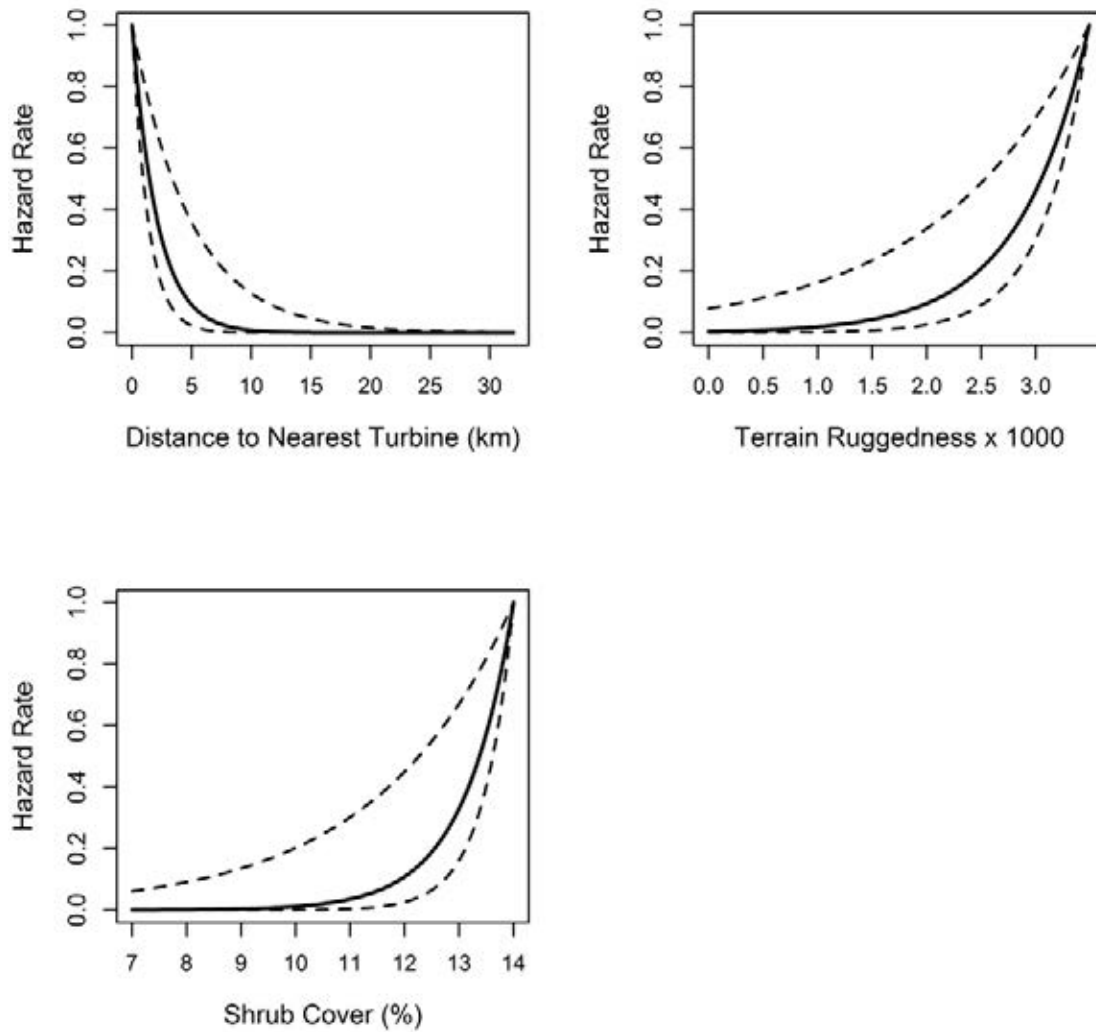
Figure 3-4. Relative hazard rate of brood survival adjusted for distance to nearest turbine, terrain ruggedness, and percent shrub cover at the Simpson Ridge and Seven Mile Hill study areas, Carbon County, Wyoming, USA, 2009 and 2010. Dashed lines indicate the lower and upper 90% confidence limits.
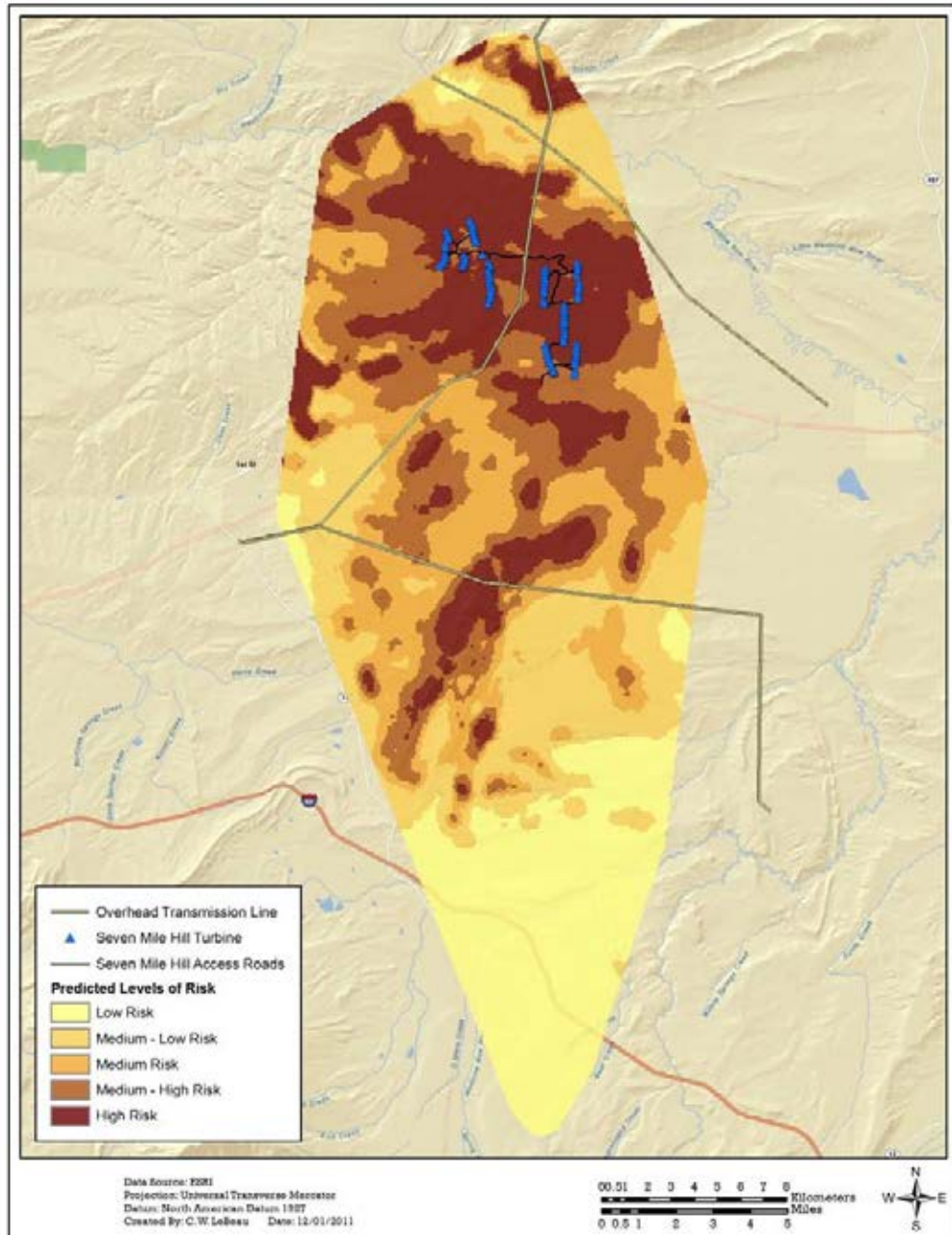
Figure 3-5. Spatial variation in the predicted relative risk of sage-grouse brood failure (low – high) within

the Seven Mile Hill and Simpson Ridge study areas, Carbon County, Wyoming, USA, 2009 and 2010.

Figure 3-6. Relative hazard rate of female survival adjusted for the distance to nearest major road and distance to nearest overhead transmission line at the Simpson Ridge and Seven Mile Hill study areas, Carbon County, Wyoming, USA, 2009 and 2010. Dashed lines indicate the lower and upper 90% confidence limits.
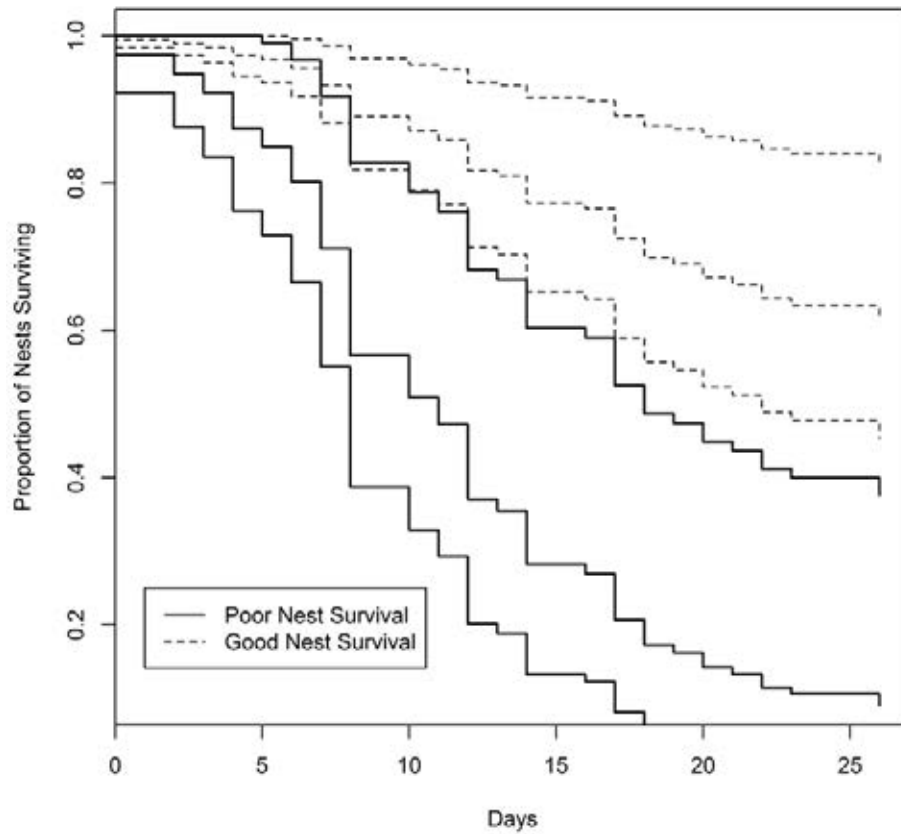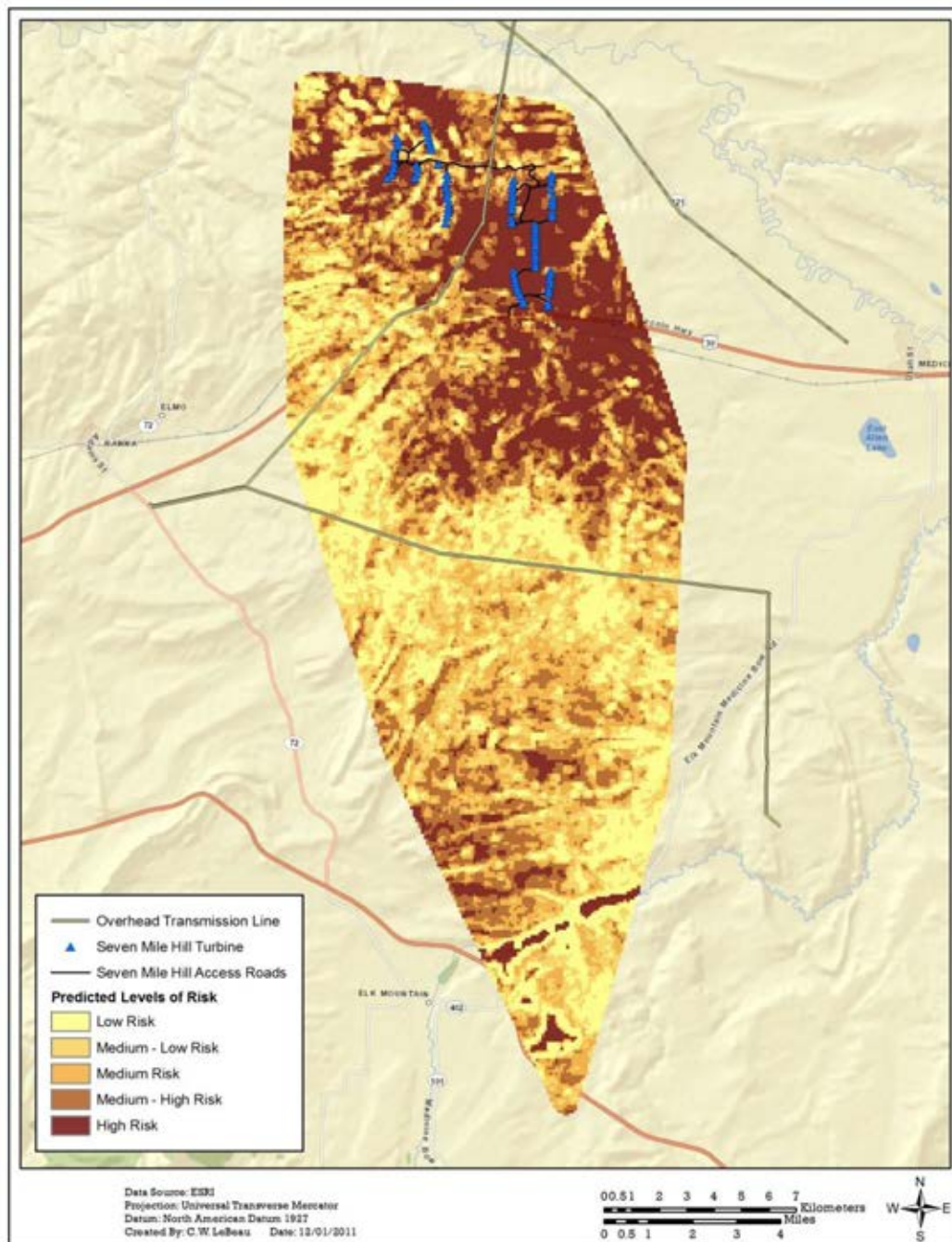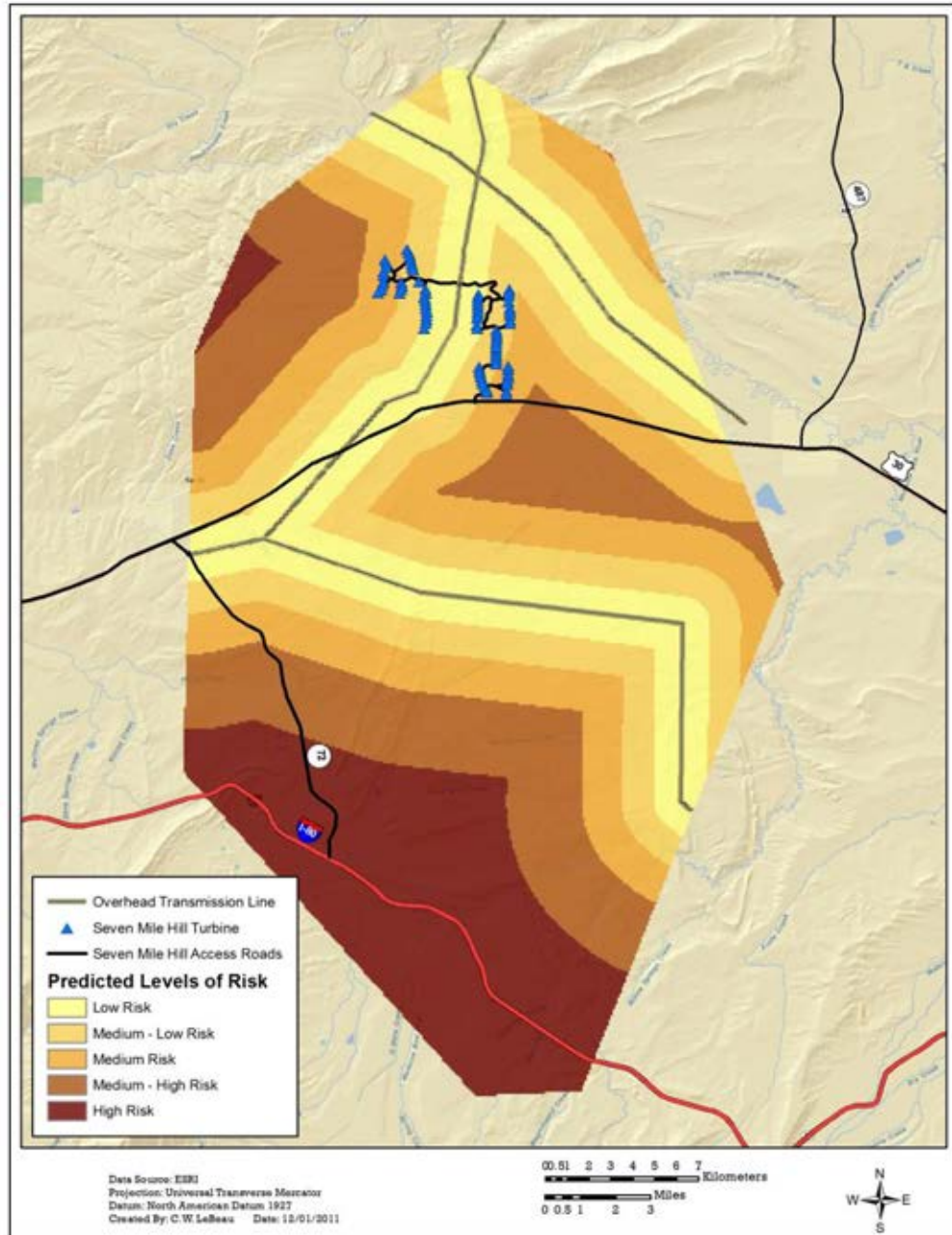
Figure 3-7. Spatial variation in the predicted relative risk of sage-grouse summer mortality (low – high) within the Seven Mile Hill and Simpson Ridge study areas, Carbon County, Wyoming, USA, 2009 and 2010.
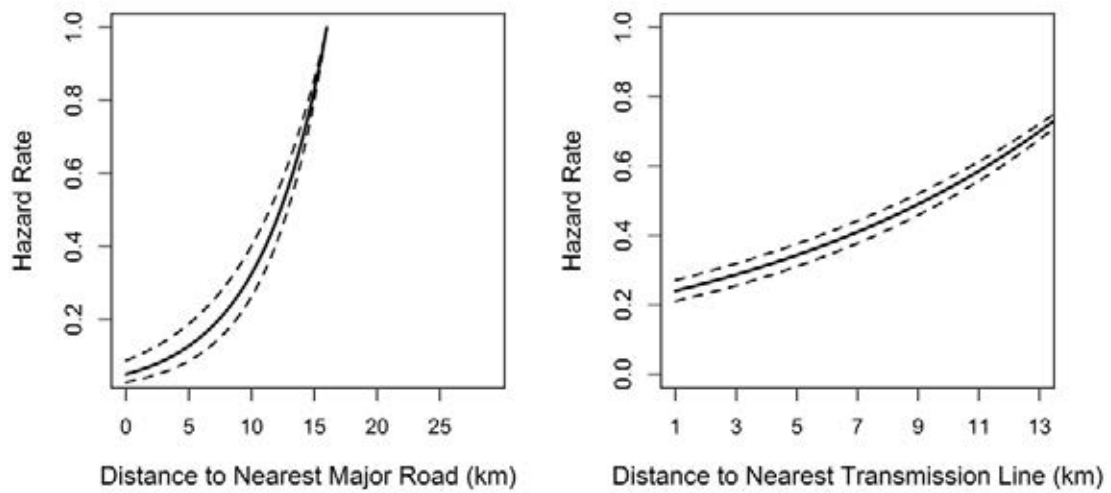
CHAPTER 4

Greater Sage-Grouse Male Lek Attendance Relative

to Wind Energy Development

In the format for manuscript submittal to the *Journal of Wildlife Management*

ABSTRACT

Trends in greater sage-grouse (*Centrocercus urophasianus*; hereafter, sage-grouse) population

abundance are typically indexed through lek counts documenting peak male attendance.

Monitoring male lek attendance can provide insight into the viability of sage-grouse populations.

Lek counts have been used to assess changes in male attendance rates and male recruitment at

leks impacted by anthropogenic features. Impacts to male lek attendance have been documented

at leks located in close proximity to oil and gas development. Furthermore, it has been

documented that there is a time lag of 2–10 years when measurable affects can be detected at

leks impacted by oil and gas development. It is unknown whether the same time lags or degree of

impact will occur at leks located in close proximity to wind energy development. My study

question focused on whether leks that were spatially proximate to wind energy infrastructure had

greater declines in male lek attendance from pre-development to 4 years post development of a

wind energy facility. I used a before-after-control-impact study design to assess male lek

attendance. Aerial surveys were flown to identify any unknown leks. In addition, 3 lek counts

were conducted at each occupied lek identified during the breeding season to determine the peak

number of males attending each lek. First, I used ratio of means of lek counts to investigate

differences among lek attendance pre and post development of the wind energy facility. Then, I

further investigated the changes in lek attendance pre and post development by calculating a

disturbance metric for each lek and regressing this metric with male lek attendance using linear

mixed effects models. Leks located within wind energy development experienced a significant decline in male lek attendance from pre development to 4 years post development. However, leks located outside of the wind energy development experienced similar significant declines. The top model derived from the mixed effects linear model included one fixed term (year) and one random component, the effect of individual leks. Leks that were influenced more by wind energy development experienced similar declines as leks with no influence from pre development to 4 years post development. The significant decline in male lek attendance from 1 year pre development to 4 years post development cannot solely be attributed to the presence of the wind energy facility. Impacts from the wind energy facility may not be initially realized due to the time lags associated with sage-grouse breeding populations. More than 4 years of post development monitoring and multiple sites may be necessary to adequately assess greater sage-grouse breeding response to wind energy development.

INTRODUCTION

Trends in sage-grouse population abundance are typically indexed through lek counts (Beck and Braun 1980, Connelly and Braun 1997, Walsh et al. 2004). While the use of telemetry is the best method to determine population demographic rates, lek counts provide a good index of breeding population levels and in many cases long-term data sets are available for trend analysis (Connelly and Braun 1997, Connelly et al. 2000*a*). Multiple studies have used lek counts to provide information on sage-grouse breeding populations in response to disturbances including prescribed burning (Connelly et al. 2000*b*) and oil and gas development (Holloran 2005, Walker et al. 2007, Harju et al. 2010, Holloran et al. 2010).

The purpose of my study was to investigate the effect of wind energy infrastructure on sage-grouse peak male lek attendance. Peak male lek attendance was defined as the highest

number of males attending each lek during any of the 3 counts initiated during the breeding season. I used a before-after-control-impact study design (BACI) to evaluate the impacts of wind turbines on male lek attendance (Green 1979, Morrison et al. 2008). BACI study designs consist of knowing what type of impact will occur, when and where it will occur, and having the ability to collect data prior to the impact (Green 1979) at the impacted site and a geographically similar site that remains unaffected (control). I employed this study design to evaluate whether the newly constructed wind turbines reduced male lek attendance at leks located near the facility within 4 years of development. The objectives of this chapter were to (1) estimate a trend in peak male attendance between leks with varying proximity to turbines pre and post-construction of the Seven Mile Hill wind energy facility, and (2) compare those trend(s) to peak male attendance at Simpson Ridge (control site).

STUDY AREA

The study area used in this chapter is consistent with the first 3 chapters of my thesis. Sage-grouse leks located south of U.S. Highway 30/287 were within the SR study area and leks located north of U.S. Highway 30/287 were within the SMH study area.

METHODS

Field Methods

To investigate the effect of wind energy infrastructure on the sage-grouse population, I determined the distribution and number of males at active leks throughout the SMH ($n = 5$) and SR ($n = 9$) study areas. I obtained the locations of known historic and existing sage-grouse leks within 6.4 km (twice the distance of non-disturbance around leks suggested by Connelly et al 2000*a*) of the proposed SRWRA located in the SR and the SMH project areas from the Wyoming Game and Fish Department (WGFD) lek database. Because it is important to detect all

leks when comparing lek counts to population trends (Walsh 2004), lek searches, following the methodology outlined by WGFD (Christiansen 2007), were conducted during the 2009 lekking period to detect any unknown leks within both study areas. Aerial surveys were conducted from fixed-wing aircraft flying parallel transects designed to provide full coverage of both project areas. These surveys were conducted during the peak of the lekking season from early April through early May. All mapped historic and existing leks were flown to check for occupancy in spring 2009. I conducted surveys from one-half hour before sunrise to one-half hour after sunrise (Patterson 1952) during optimal weather conditions. Aerial flight transects were oriented north-south and were separated by approximately 1.0 km. Transects were flown at a height of 91 to 137 m above ground level at an approximate speed of 161 kph. I recorded GPS coordinates and the approximate numbers of grouse observed at all located leks. In addition, I obtained lek locations and counts within 18 km (the furthest distance of a lek from the SMH turbines within SMH and SR study areas) of SR and SMH study area because SR may not be an adequate control for SMH because of its close proximity to SMH turbines. In addition, the area encompassing an 18-km radius was selected by Johnson et al. (2011) to evaluate the influence of environmental and anthropogenic features around sage-grouse leks because Connelly et al. (2000*a*) recommended this distance around leks to manage for migratory sage-grouse populations. These 22 leks were considered as the regional population (REG).

Ground surveys were conducted from 2008 to 2012 to count sage-grouse on identified leks within SMH and SR. Lek counts for the regional leks were obtained from WGFD and only included 2008 to 2011. Each active lek located during aerial surveys and known historic lek locations in the survey area were visited 3 times each spring to count the number of sage-grouse using the lek. Ground surveys were spaced a minimum of 7 days apart and occurred during the

lekking period (WGFD 2003). Counts were conducted for a 15–30 minute period in the early

morning when the lek was most active. I collected data on the maximum number of birds

counted by sex (males, females, unknown), date, time period of observation, and weather

information (temperature, wind speed and direction, cloud cover, precipitation; WGFD 2003).

    Analytical Methods.—Because data were collected at each lek each year, I first estimated

the difference in the ratio of means of the peak male lek attendance between 2008 to 2009, 2008

to 2010, 2008 to 2011, and 2008 to 2012 within both study areas using a 500 iteration

bootstrapping technique where I sampled counts with replacement from each lek during each

year and calculated the ratio of means between the study areas and years. I calculated SE and

90% CI from the SD of the 500 bootstrap iterations. A statistically significant difference (alpha =

0.10; 90% confidence interval [CI] not including 0.0) between pre-construction (2008) and any

of the 4 years post-construction of the SMH facility indicated a change in the mean lek

attendance and warranted further investigation.

    If there was statistically significant difference between any of the study areas then a more

complicated linear mixed-effects analysis (Henderson 1950, Goldberger 1962, McLean 1991,

Blickley et al. 2012) was used to investigate relationships between lek attendance and

disturbance metrics. Mixed models have both fixed and random effects. Fixed effects are

identical or constant for all groups (leks) in a population, and random effects are allowed to

differ from group to group (Gelman 2005). Random effects assume some type of relationship

within a group exists, and in this case we assumed a relationship within individual leks across

years. I used the following linear mixed model:

$$R_{ij} = \beta_0 + \beta_1 X_i + \beta_2 Year_j + \omega_i + \varepsilon_{ij} ,$$

where R_{ij} was the attendance count values for each lek i ($i=1,\ldots,14$) in year j (2008 = 1, 2009 = 2, 2010 = 3, 2011 = 4, and 2012 = 5), X_i was a disturbance covariate measured at lek i, $Year_j$ was the effect of year j, ω_i was a random lek effect, ε_{ij} were error terms for each lek and year assumed to be normally distributed, and β_0(intercept), β_1, and β_2 were fixed-effect coefficients to be estimated.

Fixed-effects (covariates) considered in my analysis included 5 disturbance metrics, which included distance to nearest turbine and the proportion of turbines that overlapped each lek. The distance to nearest turbine was the distance from the center of the lek to the nearest turbine (km). I also included 4 different decay functions (-*exp*[*distance*]/decay distance) representing various decay distances from turbines (i.e. 1.5, 5.0, 10, 15 km). The proportion of overlapping turbines was calculated by buffering each lek by 3.2 km, which is the suggested management area around each lek (Connelly et al. 2000*a*, Walker et al. 2007). I then buffered the individual turbines with their access roads by varying sizes to evaluate various disturbance proportions. These buffer sizes ranged from 0.60 km to 5.0 km and were determined from studies where sage-grouse leks have been impacted by energy development (Table 4-1). The resulting overlapping area(s) were used as covariates to estimate male lek attendance trends. I also included a categorical covariate identifying each study area (1 = SMH and 0 = SR).

In addition to fixed effects, I also included a random effect in the mixed model. Peak male lek attendance varied between leks located within both study areas. Subsequently, male lek attendance over the 4-year period was more likely to be related within individual leks than between leks. For example, lek attendance might consistently be 10–20 males at a lek for a span of 5 to 10 years and another lek might consistently have around 75–100 males attending that lek

over the same time frame. To account for this pseudo-replication (Zuur et al. 2009), I considered individual leks as a random effect in the mixed model.

To estimate the effects of turbines on male lek attendance, I followed a multiple step process that included simple linear regression, mixed modeling, model selection, and goodness-of-fit evaluations. I first used linear regression to investigate if there was an individual lek effect on lek attendance. My response variable was the natural log (*ln*) of peak number of males (hereafter count) and my explanatory variables was year interacting with the turbine disturbance metric. Some leks recorded 0 males, subsequently I added 1 to each count (i.e., *ln*(count+1)). I used residual plots to test for within lek-correlation and heterogeneity of the residuals (Zuur et al. 2009).

If within lek-correlation was present in the linear model further model development using a random intercept would be warranted (Zurr et al. 2009). Model development followed a top-down strategy (Diggle et al. 2002). I compared models using analysis of variance (ANOVA), likelihood ratio tests, and Akaike's information criterion corrected for small sample sizes (AIC*c*; Burham and Anderson 2002, Zuur et al. 2009). I first compared the linear model to a random intercept model using ANOVA and likelihood ratios to determine whether a random intercept for each lek was warranted and if further model development was needed (Zuur et al. 2009). If results of the linear and random intercept model comparison were significantly different I included lek as random effect in a mixed model (Zuur et al. 2009).

I used likelihood ratio tests and maximum likelihood estimation to compare the fixed effects for the nested models. I used ML estimation to determine the optimal fixed structure because models with different fixed effects fitted with REML cannot be compared on the basis of their restricted likelihoods (Pinheiro and Bates 2000, Zuur et al. 2009). The models that

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included the interaction of year and disturbance metric to models with no interactions were compared. Models with and without the fixed effects were also compared to estimate the final model. The final model parameters were estimated using REML (Zuur et al. 2009). Lastly, I validated the final model by inspecting the residuals for equal scatter and homogeneity to ensure a good model fit (Zuur et al. 2009). I also utilized a QQ-plot to assess the normality of the residuals and the normality of the random effects (Zuur et al. 2009). Because SR may not be an adequate control for SMH, I estimated mixed models with leks from all three study areas and with only leks from SMH and SR to see if SR was an adequate control. If it was I would see similar effects on lek attendance between the SR and REG leks.

RESULTS

Fourteen greater sage-grouse leks were observed during lek surveys in both study areas (5 within SMH and 9 within SR during 2008, 2010, 2011, and 2012 (Table 4-2; Fig. 4-1). Two leks located in SMH were not counted during 2009. During 2008 (pre-development of SMH wind energy facility) the maximum number of male birds present at the occupied leks within the SMH study area ranged from 18 males (Hanna Draw East 2) to 74 males (Missouri John), with a mean count of 36 males per lek. During 2009, 2010, 2011, and 2012 the mean lek counts decreased to 34, 22, 8, and 9 males per lek, respectively at SMH. Similarly to SMH, occupied leks located within SR had a mean count of 37 males/lek, ranging from 0 (Old Percy 2) to 111 males (Old Carbon 35-2) in 2008. The mean male count peaked in 2009 (40 males/lek) then decreased to 23, 20, and 14 males per lek in 2010, 2011, and 2012, respectively (Table 4-2). I included 22 regional leks in my analysis and the mean count ranged from 23 males/lek in 2008 to 7 males/lek in 2011.

Prior to construction in 2008, three leks were located within 1.6 km of the Seven Mile Hill turbines, including the Missouri John, Pine Draw, and Commo 1 leks (Fig. 4-1). In 2008,

130 males were observed on all of these leks combined. In 2009, 103 males were counted on these three leks (Table 4-2). There were 2 additional leks (Hanna Draw East 1 and 2) located >3.2 km; however these leks were not surveyed in 2009 (Table 4-2; Fig. 4-1). In 2010, 2011, and 2012, leks within 3.2 km of the Seven Mile Hill turbines were surveyed. Data collected from 2009 through 2012 represent the first, second, third, and fourth sage-grouse breeding seasons, respectively, after the wind-energy facility became operational. The three leks within 3.2 km were located 0.58, 1.6, and 1.5 km from the nearest wind turbine (Fig. 4-1). The total number of males counted on these three leks decreased from 130 the first year prior to construction (2008), to 33 in 2012 with one lek becoming inactive (i.e., no males observed at the Pine Draw lek in 2012; Table 4-2).

The results from the ratio of means test indicated there was no significant difference from 2008 to 2012 between the three study areas. Regressing the ratio of means for each study area against year indicated no significant difference between the slopes (SMH vs SR = 0.03; SE = 0.05; SMH vs REG = 0.04; SE = 0.07). I did however detect a significant difference in mean male lek attendance from 2008 to 2011 between SMH and SR (Fig. 4-2). I further investigated whether the addition of turbines to SMH had a greater impact on male lek attendance at leks with closer proximity to turbines than leks farther from turbines by using linear mixed effects models.

Model Development

The residual plot for the linear regression model indicated unequal scatter of the residuals, thus evidence of within-lek correlation in the data (Fig. 4-3). The likelihood ratio test indicated that the random intercept model including lek as the random term was considerably better than the linear model ($L = 42.56$, $df = 1$, $P < 0.001$). The optimal fixed structure included year interacting with distance to nearest turbine ($\Delta AIC = 0.402$); however, this interaction was insignificant ($\beta =$

0.013; 90% CI: -0.003 –0.03). The final resulting model only included year as the fixed term.

The final model showed a significant year effect on male lek attendance. Male lek attendance

decreased on average by 25.6% (90% CI: 17.5–32.9%) every year from 2008 to 2012 within leks

located at SMH and SR. I observed similar trends when I incorporated the data from the regional

leks ($n = 22$). The interaction between year and distance to turbine was not significant (β = -

0.003; 90% CI: -0.011–0.006). Male lek attendance at the regional leks decreased on average by

31.4% (90% CI: 24.6–37.7%) every year from 2008 to 2011. Similar to the ratio of means

analysis there appeared to be no significant difference in male lek attendance from 1-yr pre

construction to 4 years post construction between the three study areas.

DISCUSSION

Ratio of means and linear mixed models were used to investigate the trends in peak male

attendance at leks impacted by wind turbines. I utilized a BACI study design to detect changes in

peak male attendance at leks prior to the construction and operation of the SMH wind energy

facility to 4 years post-development. I hypothesized that leks closer to turbines, or leks that had a

greater proportion of overlapping wind energy infrastructure, experienced a significant decrease

in male lek attendance from pre-construction to 4 years post construction.

Male lek attendance significantly decreased from 2008 to 2012; however, this decrease

could not be attributed to the degree of influence by wind turbines or the study area in which

each lek resided. Leks located in both study areas and regionally, significantly decreased from

2008 to 2012. The SR study area, which was not influenced by turbines, experienced similar

trends from 2008 to 2012 as did the leks located within SMH, the area influenced by wind

turbines.

Holloran (2005) assessed peak male lek attendance at 21 leks in southwestern Wyoming over a time period that ranged from 1999 to 2004. Leks located within 5.0 km of oil and gas development had significantly greater annual rates of decline than control leks (Holloran 2005). Male lek attendance has also been shown to be negatively affected within 0.8, 3.2, and 4.8 km of active well surfaces (Walker et al. 2007, Harju et al. 2010). In addition, leks impacted by oil and gas development experience a time lag of when discernible affects on male lek attendance can be measured (Walker et al. 2007, Doherty 2008, Harju et al. 2010). These time lags range from 2–10 years (Harju et al. 2010) and 4 years (Doherty 2008) when effects of oil and gas development can be measured on male lek attendance.

Although the results of my study indicate there was no difference in male lek attendance between leks within and outside of wind energy development, the results from other studies where leks have been impacted by oil and gas development indicate there is a time lag and effects may not be realized until 2–10 years following development. There is only one grouse/wind energy published study I am aware of that assessed male grouse lek attendance relative to wind energy development. Black grouse (*Tetrao tetrix*) in Austria, were not impacted by the wind energy facility the immediate year following construction, but did show considerable declines 4 years after construction suggesting there may be a similar time lag to wind development as oil and gas development in grouse (Zeiler and Grünschachner-Berger 2009). In addition, a review of unpublished studies investigating the impacts to male lek attendance from wind energy development indicated that prairie grouse may continue to use habitats near wind energy developments and may experience similar time lags as oil and gas development (Johnson and Stephens 2011). Further monitoring and inventorying of these leks will be necessary to identify any long-term population trends (Fedy and Aldridge 2011).

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Table 4-1. Disturbance metrics included in the mixed modeling procedure to determine potential extents of impact from turbines to male lek attendance at leks located within the Seven Mile Hill and Simpson Ridge study areas in Carbon County Wyoming, USA, 2008–2012. Metrics were derived from male breeding use areas (0.60 km), identified management areas (3.2 km), or disturbance distances previously determined from oil and gas development.

Variable	Variable description
area_smh	Nominal variable indicating study area the lek was located in (1=SMH, 0=SR).
dist_turbine	The distance to nearest turbine from each active lek within both study areas (km).
sq_km600	The proportion of overlapping area within 0.60 km of turbines and a 3.2 km buffer of each lek (CGSSC 2008).
sq_km1600	The proportion of overlapping area within 1.6. km of turbines and a 3.2 km buffer of each lek (1.6 to 2 km, Harju et al. 2010)
sq_km3200	The proportion of overlapping area within 3.2 km of turbines and a 3.2 km buffer of each lek (Connelly et al. 2000*a*)
sq_km5000	The proportion of overlapping area within 5.0 km of turbines and a 3.2 km buffer of each lek (3-5 km Holloran 2005).

Table 4-2. Maximum counts, yearly averages, and totals of male sage-grouse on occupied leks located within the Seven Mile Hill and Simpson Ridge study areas, Carbon County, Wyoming, USA, 2008–2012. Entries of "NA" indicate no count was conducted.

Lek Name	2008	2009	2010	2011	2012
Seven Mile Hill					
Commo 1[a]	23	21	18	5	15
Hanna Draw East 1	32	NA	27	5	11
Hanna Draw East 2	18	NA	11	2	2
Missouri John[a]	74	62	38	20	18
Pine Draw[a]	33	20	14	6	0
Average	36	34	22	8	9
Total	180	103	108	38	46
Simpson Ridge					
Kyle 63	67	68	64	32	19
Kyle 65	5	8	4	0	2
Old Carbon 31	28	41	28	23	23
Old Carbon 32	9	33	4	20	12
Old Carbon 34	49	49	31	26	20
Old Carbon 35 2	111	88	41	55	22
Old Carbon 37	54	42	28	23	25
Old Carbon 38	10	1	0	0	0
Old Percy 2	NA	31	4	3	0
Average	37	40	23	20	14
Total	333	361	204	182	123

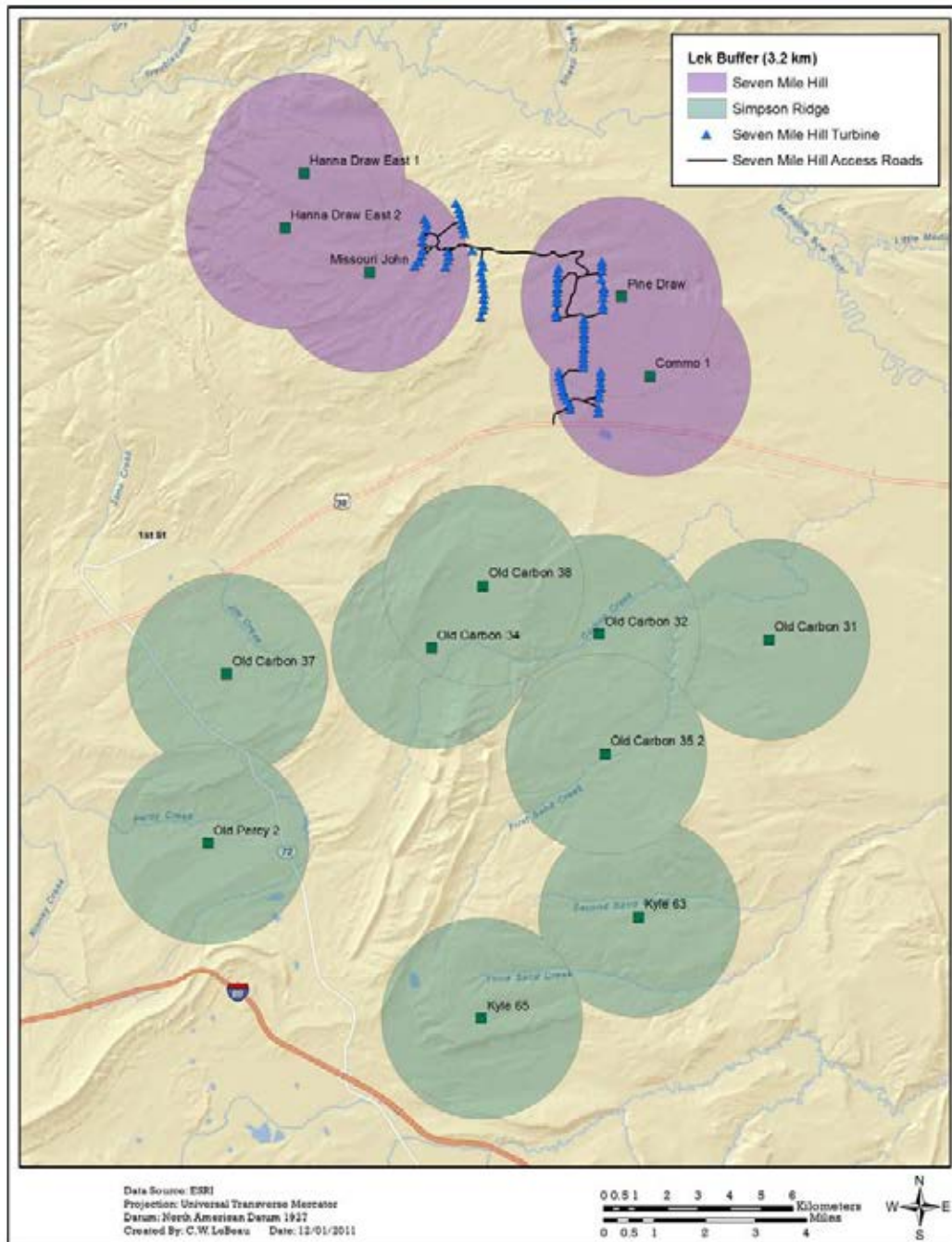[a]Leks located within 1.6 km of wind turbines at Seven Mile Hill

Figure 4-1. Lek locations within the Seven Mile Hill and Simpson Ridge study areas located in Carbon County, Wyoming, USA, 2008–2011.
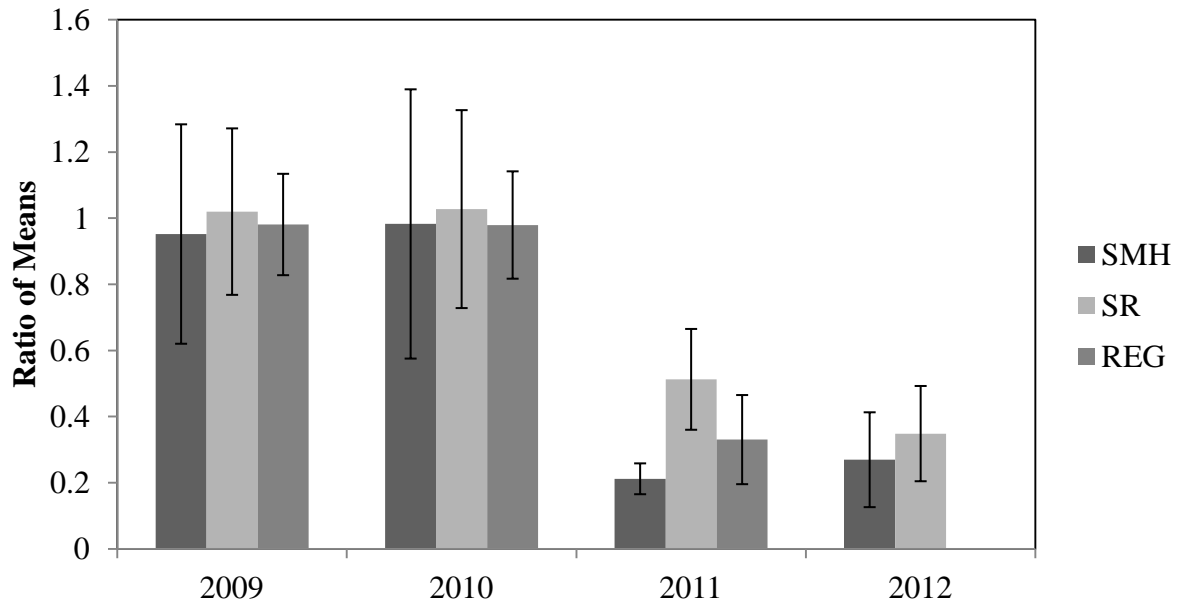
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Figure 4-2. Ratio of means (± 90% CI) of peak male lek attendance observed at Simpson Ridge (SR), Seven Mile Hill (SMH), and regional (REG) leks from 2008–2012, Carbon County Wyoming, USA. Pre-development (2008) counts were used as the baseline to detect changes in peak male lek attendance to 4 years post development. The 2012 lek data was not available for the regional lek population at time of publication.
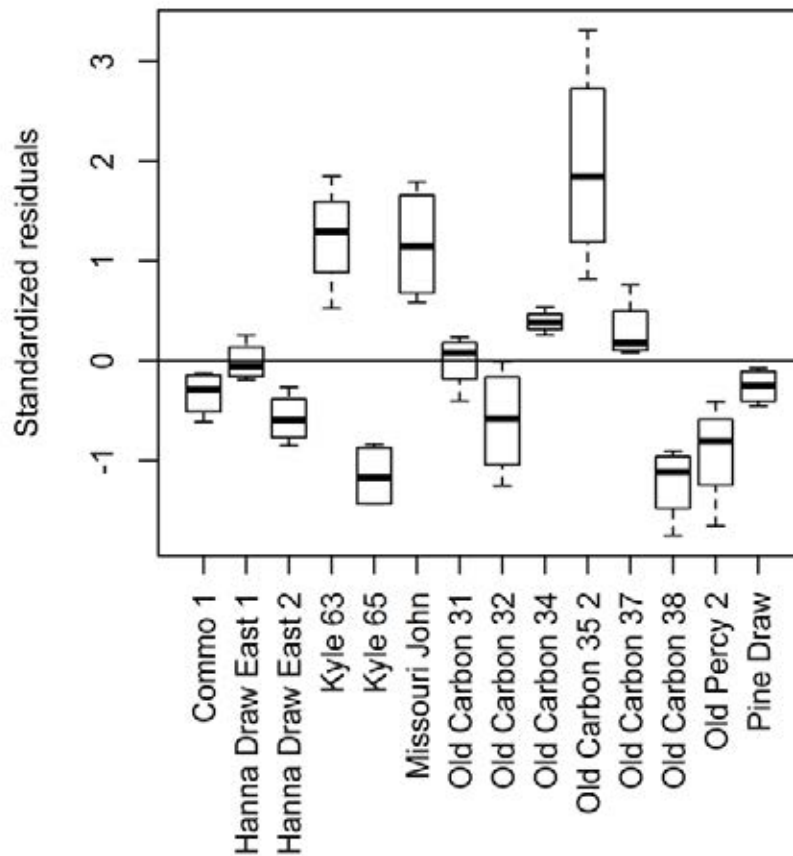
Figure 4-3. The distribution of standardized residuals from the linear regression model comparing male

lek attendance to year and study area in Carbon County, Wyoming, USA, 2008–2012. The standardized

residuals were plotted against individual leks within both study areas. Leks located above and below the

zero residual line indicate within lek correlation. Boxes include the interquartile range (25th–75$^{\text{th}}$

percentile) in standardized residuals; horizontal lines inside boxes are median standardized residuals;

lower and upper whiskers are standardized residuals extending to 1.5 times the interquartile range.