Effects of a Wind Energy Development on Greater Sage-Grouse Habitat Selection and Population Demographics in Southeastern Wyoming

Prepared for

National Wind Coordinating Collaborative

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EXECUTIVE SUMMARY

Western EcoSystems Technology, Inc. and Wyoming Wildlife Consultants, LLC initiated a greater sage-grouse radio-telemetry study at an existing wind energy development in southeastern Wyoming in 2009. The University of Wyoming joined this collaborative effort in January 2010, and the National Wind Coordinating Collaborative joined the effort in March 2011. The overall goal of the research was to establish the population-level effects of wind energy development on female sage-grouse seasonal habitat selection and demography. This study represents the only situation in the US where the responses of greater sage-grouse to the infrastructure associated with a wind energy development has been investigated. Our primary objective was to discern the relationship between sage-grouse nest, brood-rearing, and summer habitat selection patterns and survival parameters and the infrastructure of an existing wind energy facility.

The Seven Mile Hill (SMH) study area was located north of Interstate 80 and south of the Shirley Basin in Carbon County, Wyoming, US. A control and treatment area was included in the SMH study area, with boundaries of each of these areas determined from lek locations and radio-marked female sage-grouse distributions. The Seven Mile Hill Wind Energy Facility (SWEF; located in the treatment area) consisted of 79 General Electric 1.5-MW wind turbines and approximately 29 km of access roads. The facility became fully operational in December 2008. In addition to the SWEF, other anthropogenic features present in this portion of the study area included approximately eight km of paved roads and 26 km of overhead transmission lines. The control study area had no wind turbines and was adjacent to the SWEF and south of US Highway 30/287. There were approximately 50 km of paved roads and 17 km of overhead transmission lines in this area. The treatment area had four leks that had an average distance of 1.93 km from the nearest SWEF turbines (range = 0.53 to 4.15 km), while the control group consisted of 6 leks with an average distance of 10.99 km from the nearest SWEF turbine (range = 7.09 to 16.16 km).

We captured and radio-equipped 346 (160 treatment; 186 control) female sage-grouse within an area consisting of a wind energy development and a control area absent of wind energy development in southeastern Wyoming from 2009–2014. We relocated each radio-marked female approximately twice a week during the nesting, brood rearing, and summer periods. We developed a suite of anthropogenic, vegetation, and environmental covariates to estimate habitat selection and survival for all sage-grouse during the nesting, brood rearing, and summer periods. We used a discrete choice habitat selection model to estimate the relative probability of sage-grouse nest site, brood-rearing, and summer habitat selection within both the control and treatment areas during the post-development period. We did not detect a negative impact of the wind energy facility on nest site selection during the study period. Sage-grouse rearing broods generally avoided suitable brood-rearing habitat near anthropogenic infrastructure that includes wind energy development, major paved roads and transmission lines. Although avoidance was consistent across the years of our study, avoidance of wind turbines was more pronounced in 2012-2014 compared to 2009-2011, suggesting a lag period in the ultimate population-level response to the development of a wind energy facility. Although distance to turbine was not

strongly associated with summer habitat selection, the percentage of disturbance associated with wind energy infrastructure did appear to influence summer habitat selection.

In addition, we estimated survival during each seasonal period to estimate the effect of the SWEF on population fitness. The SWEF did not have a negative effect on sage-grouse nest survival within the study area over the six-year period, and nest survival did not differ between nests of females captured at treatment and control area leks over the study period. The SWEF did not have a negative effect on sage-grouse brood survival within the study area over the six-year period. Survival was related to habitat features and anthropogenic features that have existed on the landscape for >10 years. Lastly, the SWEF did not have a negative effect on female sage-grouse summer survival within the study area over the six-year period. After controlling for annual and natural variability, we observed a positive effect of the SWEF on female survival when the percentage of disturbance within 0.81 km of a sage-grouse location increased from 0% to 3%.

Our study is the first to estimate the impacts of wind energy development on sage-grouse habitat selection and fitness parameters. Female sage-grouse selection of seasonal habitats was variable relative to the infrastructure associated with wind energy facility, but fitness parameters did not appear to be influenced to a great degree by the infrastructure. This pattern of effect is similar to greater prairie-chicken response to a wind energy facility in Kansas but opposite of sage-grouse response to oil and gas development. Ideally, we would have preconstruction data to identify changes in the population and decipher mechanisms in sage-grouse response to infrastructure; however, we are confident that if such impacts to habitat selection and survival did occur then we would have been able to detect these changes over the 6-year study period.

The lack of other studies investigating impacts from wind energy development to sage-grouse habitat selection and survival limits our ability to make inferences about the cumulative impacts of wind energy development on sage-grouse, but we were able to describe some of the impacts that wind energy developments may have on sage-grouse populations. Although we attempted to account for possible confounding factors, there is the chance that we did not detect important interactions between environmental features and habitat selection and survival patterns.

Future wind energy developments should consider the potential impacts of wind energy development on sage-grouse habitat selection patterns and survival parameters. We recommend facilities similar in size that occupy similar habitats as our study be placed 1.20 km from any occupied sage-grouse nesting, brood-rearing, or summer habitats. We recommend that future research consider predator-prey mechanisms by estimating both avian and mammalian predator densities to better understand the impacts of wind energy development on sage-grouse fitness parameters and to develop appropriate mitigation measures.

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SUGGESTED CITATION

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Table of Contents

List of Tables

List of Figures

INTRODUCTION

Increasing concern for environmental sustainability, the demand for domestic energy, and an impetus on reducing dependence on fossil fuels have led to substantial investment in renewable energies over the last couple of decades. The U. S. Department of Energy (USDOE) adopted a nationwide energy policy establishing that 20% of all electricity will be provided by wind energy by 2030 (USDOE 2008). To accomplish this, the wind energy industry will need to increase production from 11.6 GW of power produced in 2006 to over 300 GW/year, which will require an estimated doubling of the number of transmission lines and a threefold increase in the number of annual wind turbine installations (USDOE 2008). The USDOE report (2008) further suggests that the United States has ample wind resources to reach the 20% by 2030 goal, but that one of the greatest hindrances to accomplishing this goal will be uncertainties regarding the potential impacts to wildlife of the infrastructure required.

Wind energy development is occurring across many landscapes, resulting in direct and indirect impacts to wildlife (Kuvlesky et al. 2007). Direct impacts are well documented and include bird and bat collisions with wind turbine blades or other infrastructure associated with wind energy development (e.g., guy wires, meteorological towers, power lines, turbine towers; e.g., Erickson et al. 2001, Johnson et al. 2003).

In addition to direct effects through collision mortality, wind energy development indirectly affects wildlife resources, causing a loss of habitat where infrastructure is placed and loss of habitat through behavioral avoidance and perhaps habitat fragmentation. Loss of habitat from installation of wind energy facility infrastructure (i.e., turbines, access roads, maintenance buildings, substations and overhead transmission lines) can be long-term or temporary; however, long-term infrastructure generally occupies only 5% to 10% of the entire development area (BLM 2005). Estimates of temporary construction impacts range from 0.2 to 1.0 hectares (0.5 to 2.5 acres) per turbine (Strickland and Johnson 2006, Denholm et al. 2009).

Behavioral displacement (avoidance) may lead to decreased habitat suitability for local populations. Birds displaced by wind energy development may move to lower quality habitat with fewer disturbances, with an overall effect of reducing breeding success. Behavioral avoidance may render much larger areas unsuitable or less suitable for some species of wildlife, depending on how far each species is displaced from wind energy facilities. Indirect effects also include habitat fragmentation (e.g., more habitat edges due to roads and smaller areas of contiguous habitat) which could provide more generalized habitats and resistance-free travel lanes for predators and competitors in, for example, large grasslands and forests. This may impact the survivorship and reproductive ability of birds in the vicinity of the wind energy facility. Some studies suggest displacement effects associated with wind energy may have a greater impact than collision mortality (Gill et al. 1996, Pearce-Higgins 2012). The greatest concern for indirect impact of wind energy facilities on wildlife resources is where these facilities have been constructed in native vegetation communities, such as grasslands or shrub steppe that provide comparatively rare, high-quality habitat for some bird species and species of concern (USFWS 2012).

Increases in wind energy development are especially noticeable in prairie habitats with high wind capacity. 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). The USFWS maintains that because prairie grouse evolved in habitats with little vertical structure, placement of tall man-made structures (e.g., wind turbines) in occupied prairie grouse habitat may result in a decrease in habitat suitability (USFWS 2004). However, most studies on breeding grouse have not isolated structure height from other potentially influencing factors, such as the occurrence of roads, other structures, and cultivation (Walters et al. 2014).

Direct impacts to prairie grouse are likely low (Winder et al. 2014a), but indirect impacts of wind turbines and associated power transmission lines likely affect movements and habitat selection of these species because of tendencies towards avoiding areas with high human activity (Pruett et al. 2009, Dzialak et al. 2012, Walters et al. 2014). In a meta-analysis investigating response of prairie grouse species to energy development in general, Hagen (2010) reported moderate to large displacement effects and small to moderate demographic effects of anthropogenic features on prairie grouse populations. The largest demographic effects of energy development were to annual survival and nesting propensity and success rates, but effects on nesting rates were relatively weak (Hagen 2010). Furthermore, authors of a meta-analysis of anthropogenic structures on grouse behavior and survival were unable to compute effect sizes for wind turbines due to lack of wind energy and grouse studies worldwide (Hovick et al. 2014). The majority of research specific to the response of prairie grouse to wind energy development has been conducted on greater prairie-chickens. Greater prairie-chicken nest site selection and survival of adult females and nests were not found to be influenced by a commercial wind energy facility in Kansas (McNew et al. 2014, Winder et al. 2014a). At this same facility, greater prairie-chicken lek abandonment was documented and was highest within eight kilometers [km] of turbines during a 3-year post-construction period. However, there was no evidence that rates of change in the maximum number of male prairie-chickens and lek persistence were influenced by proximity to wind turbines (Winder et al. 2015). In addition, female greater prairie-chickens avoided wind turbines during the breeding season (Winder et al. 2014b). It is important to note that both species of prairie chicken are apparently more tolerant of anthropogenic disturbance compared to other prairie grouse species (Hagen 2010).

The greater sage-grouse (hereafter sage-grouse) is an important species both politically and ecologically throughout the sagebrush-steppe habitats of North America. The USFWS determined in 2010 that listing the sage-grouse under the Endangered Species Act was warranted due to habitat loss and fragmentation and inadequacy of regulatory mechanisms that govern habitat loss and fragmentation (see Schroeder et al. 2004, Garton et al. 2011). Nevertheless, the USFWS determined that the listing was precluded because of higher-priority listing actions (USFWS 2010). On September 22, 2015, the USFWS determined that protection for the sage-grouse under the Endangered Species Act was no longer warranted due to their relative abundance and states' assurances to implement conservation practices that may significantly reduce threats throughout their range. Research suggests that anthropogenic features on the landscape influence sage-grouse populations, with general trends towards decreasing populations as infrastructure densities on the landscape increase. Substantial research has established that oil and gas developments negatively influence the ability of the landscape to support sage-grouse (see Naugle et al. 2011, Hess and Beck 2012, Taylor et al. 2013, Gregory and Beck 2014). Sage-grouse are also known to be negatively affected by roads, residential development, and transmission lines and other tall structures (Aldridge et al. 2008, Johnson et al. 2011, Copeland et al. 2013, Knick et al. 2013). Although definitive evidence linking sage-grouse population response to technologies such as wind energy is not extensive, LeBeau et al. (2014) found that nest and brood survival probabilities decreased 2 years following development of a wind energy facility as distance to wind turbine decreased, but no effect of distance to turbine on adult female survival was documented.

We studied the response of sage-grouse to wind energy development in southeastern Wyoming. Given that Wyoming received a qualitative rank of wind development prospects based on wind resources and existing transmission infrastructure of “good-superb” (US Department of Energy 2008), the potential for impacts to sage-grouse in Wyoming from wind energy development is thought to be high. It is imperative that the response of sage-grouse to wind energy development is further investigated so that the species can be effectively conserved. Our primary objective was to discern the relationship between sage-grouse nest, brood rearing, and summer habitat selection patterns and survival parameters and the infrastructure of an existing wind energy facility. This information is critical in planning future wind energy development facilities that occur within occupied or potential sage-grouse habitats.

STUDY AREA

The Seven Mile Hill (SMH) study area was located north of Interstate-80 and south of the Shirley Basin in Carbon County, Wyoming, USA between the towns of Hanna and Medicine Bow (Figure 1). Land ownership included Bureau of Land Management (22.5%), private (69.5%), and State of Wyoming lands (7.8%). The study area was classified as a semiarid, cold desert with a mean annual precipitation of 26.7 centimeters (cm) and average temperatures ranging from –2.33 degrees centigrade (°C) to 13.61°C (WRCC 2014). Shrub steppe, dominated primarily by Wyoming big sagebrush (*Artemisia tridentata wyomingensis*), was the most common cover type in the study area (USGS 2011). Dominant land uses included wind energy development, a surface coal mine near the southwestern edge of the study area (approximately 20 km from the nearest turbines), livestock grazing, and hunting. The Seven Mile Hill Wind Energy Facility (SWEF) was situated in the northern portion SMH study area.

A control and treatment area was included in the SMH study area. We defined boundaries for these study areas from radio-marked female distributions. The main sample unit for this study was occupied lek locations. From these sample units or lek locations, we captured female sage-grouse and monitored marked individuals through time. The leks targeted for captures were located throughout the SMH study area. We separated these lek locations into control and treatment groups. The treatment group consisted of four leks that had an average distance of 1.93 km from the nearest SWEF turbines (range = 0.53 to 4.15 km). The control group consisted of 6 leks that had an average distance of 10.99 km from the nearest SWEF turbine (range = 7.09 to 16.16 km). In addition, the average minimum distance between the treatment and control leks was 11.70 km. We considered females that were captured from treatment area leks to occupy habitats within the treatment study area and females that were captured from the control area leks to occupy habitats within the control study area.

The SWEF consisted of 79 General Electric 1.5-MW wind turbines and approximately 29 km of access roads (Figure 1). Construction of this facility began in late summer 2008 and the facility became fully operational in December 2008. The facility was situated north of US Highway 30/287 and south of the Medicine Bow River within the treatment study area (Figure 1). Elevations in the treatment study area ranged from 1,737 to 2,118 m above sea level. In addition to the wind energy facility, other anthropogenic features present in this portion of the study area included approximately eight km of paved roads (US Highway 30/287) and 26 km of overhead transmission lines.

The control study area had no wind turbines and it was adjacent to the SWEF and south of US Highway 30/287 (Figure 1). This portion of the study area contained numerous ridges interspersed with rolling to hilly plains. Elevations ranged from 2,040 to 2,390 m above sea level. There were approximately 50 km of paved roads (Interstate-80, US Highway 30/287, and Wyoming State Highway 72) and 17 km of overhead transmission lines that occurred in this area. The existing overhead transmission lines and paved roads have existed on the landscape for more than 10 years. The only anthropogenic features added to the SMH study area as a result of constructing the SWEF were wind turbines, associated access roads, and one operation and maintenance building (Figure 1). A portion of the control study area owned by Arch Coal located south of US Highway 30/287 was not accessible for monitoring (Figure 1). A portion of the control study area owned by Arch Coal located south of US Highway 30/287 was not accessible for monitoring (Figure 1), and this area was excluded from available habitat during habitat selection model development.

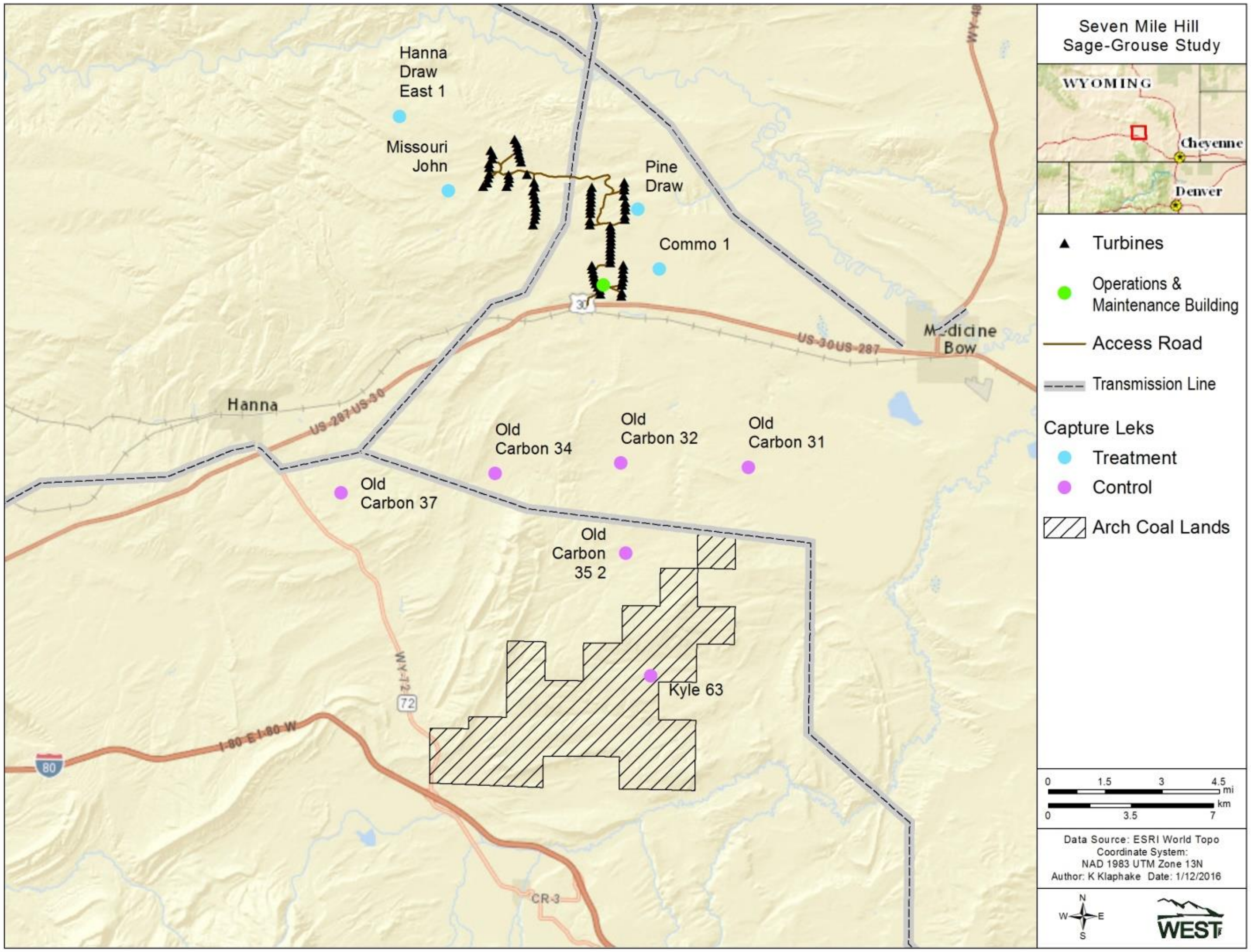


Figure 1. Seven Mile Hill study area and occupied leks targeted for capturing and monitoring female sage-grouse 2009–2014 in Carbon County, Wyoming, USA. The Seven Mile Hill Wind Energy facility consisted of 79, 1.5-MW wind turbines.

FIELD METHODS

We captured 346 (160 treatment; 186 control) female sage-grouse on roosts surrounding leks by night-time spotlighting and use of hoop nets (Giesen et al. 1982, Wakkinen et al. 1992) during the 2009 through 2013 breeding seasons. Our yearly-targeted sample size for monitoring was 100 distributed equally between treatment and control study areas, but the actual number of sage-grouse captured and monitored varied among years. We attempted to capture sage-grouse at all accessible, occupied, and active lek sites within 16 km of the SWEF wind turbines proportionately to the number of males attending those leks. We aged, weighed (0.1 gram [g] precision), acquired blood samples (year 2009), and fitted each captured grouse with a 22-g necklace-mounted Very High Frequency (VHF) radio transmitter with a battery life of 666 days (Advanced Telemetry Systems, Incorporated, model A4000, Isanti, MN). Radio transmitters were equipped with mortality censors set to trigger when transmitters were stationary for 8-hr. We classified each female as a yearling (first breeding season) or adult (≥second breeding season) based on the shape of the outermost wing primaries (Eng 1955). We released each radio-marked female at the point of capture and marked the location using a hand-held global positioning system (GPS) unit.

We relocated each radio-marked female three times each week during the pre-nesting and nesting period (April through June); and at least once each week for brooding and barren (i.e., females that were not currently nesting or raising young) females from hatch/nest loss through 31 October. Marked sage-grouse were monitored primarily from the ground using hand-held receivers and antennas. We determined sage-grouse locations by triangulation or homing until the grouse was visibly observed. Triangulation locations were estimated by recording two vectors in the direction of the signal from two locations. In addition, we estimated the triangulation error by placing 6 test transmitters for each technician throughout both project areas and estimated the mean telemetry error between the actual and estimated locations. The mean telemetry error rate was incorporated into our modeling effort. We used aerial telemetry to locate missing sage-grouse throughout the study period.

During the pre-nesting and nesting seasons (late April through 15 June) we monitored each radio-marked female sage-grouse from long range at least every third day. We assumed females were nesting when movements became small (approximately equal to telemetry error). Once movements were small, nests were located using a progressively smaller concentric circle approach by walking circles around the radio signal using the signal strength as an indication of proximity (Holloran and Anderson 2005). Once we visually confirmed the female was 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 meters [m]) using long distance triangulation to minimize potential disturbance.

Once a nest location was established, we conducted incubation monitoring on an alternate-day schedule to determine nesting fate. For each nest and second nesting attempt, we 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; Wallestad and Pyrah 1974) ≥1 egg was considered a successful nesting attempt (Rotella et al. 2004). Nests that failed to hatch successfully ≥1 egg were considered failed nesting attempts. Females that were unsuccessful in their first nesting attempt were monitored 3 times per week through 15 June to determine possible second nesting attempts.

To evaluate brood survival, we located radio-marked females that successfully hatched ≥1 egg each week through 35–37 days post-hatch (Walker 2008). We categorized the brood-rearing period as early (hatch through 14 days post-hatch; Thompson et al. 2006) or late (to 35–37 days post-hatch; Walker 2008). Females were considered successful through the early brood-rearing period if ≥1 chick survived to 14 days post-hatch. Chick presence during this period was established either through visual confirmation of a live chick or the brooding female's response to field observers (e.g., chick protective behavior exhibited). We determined fledging success (late brood success) for those females who were successful in early brood-rearing by assessing whether a female was brooding chicks through consecutive nighttime spotlight surveys conducted on days 35–37 post-hatch (Walker 2008). Successful females were those we confirmed brooding ≥1 chick.

COVARIATE DATA

We developed a suite of anthropogenic, vegetation, and environmental covariates to estimate habitat selection and survival for all sage-grouse locations, which included nest, brood-rearing, and summer locations (Table 1). We included the minimum distance from sage-grouse location to major roads (km), transmission lines (km), and wind turbines (km) as a metric for anthropogenic disturbances. In addition, we quantified the percentage of surface disturbance associated with the SWEF infrastructure (e.g., access roads and turbine pads) within multiple spatial scales. Distance to wind turbines and percentage of surface disturbance associated with the SWEF infrastructure was collectively referred to as SWEF covariates. We included US HWY 30/287, Wyoming State Highway 72, and Interstate 80 as major roads. Major roads, overhead transmission lines, and access roads were digitized using aerial satellite imagery and ArcMap 10 (ESRI 2011). Turbine locations were obtained from PacifiCorp Energy (Salt Lake City, Utah, USA), the operators of the SWEF.

Vegetation layers used in the analysis were remote sensed vegetation products developed from 1–m resolution National Agricultural Imagery Program (NAIP) image mosaics acquired in 2009 and 2012. In addition, we used vegetation products developed by Homer et al. (2012). We considered four primary continuous field components (percent bare ground, percent herbaceous cover, percent litter, and percent shrub cover) and four secondary components (percent sagebrush [*Artemisia* spp.], percent big sagebrush [*A. tridentata* spp.], percent Wyoming big sagebrush and shrub height) layers (Homer et al. 2009, 2012; Table 1). Percent big sagebrush, litter, and Wyoming big sagebrush cover and shrub height were obtained from Homer et al. (2012) and we developed percent bare ground, herbaceous cover, percentage of meadow, and shrub cover covariates for 2009 and 2012.

The 2009 1-m resolution imagery provided vegetation measures associated with 2009-2011 used and available sage-grouse locations, while 2012 imagery provided measures associated with 2012-2014 used and available sage-grouse locations. We employed a proprietary, semi-automated object oriented analysis procedure to generate herbaceous and shrub cover habitat maps in the ERDAS Imagine software (Figure 2 and 3). We processed vegetation variables on the landscape based on a focal neighborhood analysis of a Normalized Difference Vegetation Index (NDVI) and Brightness index (red, green, and blue channels) generated from the NAIP orthophotographs. NDVI and Brightness provide a measure of photosynthesizing vegetation and overall site albedo (also known as broad band reflectance). These two spectral variables were computed at 1-m pixel resolution and were used in a 10 pixel by 10-pixel orthogonal moving window analysis that computes the mean and standard deviation (SD) in a neighborhood surrounding each pixel. The resulting four products (mean and SD of NDVI and Brightness) are termed spectral-spatial metrics as they have both spectral and spatial neighborhood information (Roller et al. 2004).

Two sets of spectral-spatial metrics were generated, one for shrub cover analysis and one for herbaceous cover analysis. All four metrics were used for shrub cover mapping providing variables sensitive to shrub crown illumination and shading and as well as overall plant biomass. Mean NDVI and standard deviation of NDVI were two spectral-spatial metrics chosen for the herbaceous cover analysis because herbaceous cover produces minimal discernable crown shading that would be evident at the 1-m pixel resolution of the NAIP data. Once we calculated the spectral-spatial metrics, we stratified them across the landscape based on a cluster analysis of the numerical values in multi-dimensional space. We used the K-mean, a relative of the Iterative Self-Organizing Data Analysis Technique, unsupervised clustering algorithm in ERDAS Imagine’s software to define statistical clusters from the multi-dimensional spectral space. We chose 100 hundred clusters for shrub cover analysis and 80 clusters for herbaceous cover analysis. Statistical clusters were then plotted across the map space by sampling each spectral-spatial metric pixel and assigning the closest cluster number according to the K-mean rules. The plotted clusters could be then be geographically linked on computer display and compared to the original multispectral imagery. The shrub cover clusters were labeled to 5% cover increments and the herbaceous cover clusters were labeled to 2.5% cover increments. We used heads up, visual, analysis of the source imagery to determine what shrub cover or herbaceous cover class a cluster was following.

Shrub cover was mapped at 5% increments through 30% and above. Statistical clusters plotting with higher biomass in the shrub cover mapping did not easily differentiate between dense, mesic stands of shrubs (such as greasewood [*Sarcobatus vermiculatus*]) from wetland and riparian communities. Areas of higher biomass, as evident on the late summer and fall NAIP data setting, were found to be ones with perennial surface and subsurface water as compared to drier upland sites. These types were labeled maximum cover dry and maximum cover wet, and were used to calculate the percentage of meadow. Herbaceous cover was mapped at 2.5% increment through 35% and above. Once shrub and herbaceous cover were plotted across the study area bare ground percentage was computed pixel by pixel. Bare ground percentage was computed as the remainder of the combined shrub and herbaceous cover values subtracted from 100 percent.

We performed a standard accuracy assessment protocol for remote sensing based thematic mapping using field vegetation data that was collected in 2012 (Stehman and Czaplewski 1998). The accuracy procedure provides an overall accuracy, omission and commission accuracy for each map class. The accuracy for the 2012 classification was 89% for shrubs and 43% for the herbaceous layer.

We considered landscape features such as elevation, slope, compound topographic index (CTI), topographic positon index (TPI), and terrain ruggedness, all of which were calculated from a 10-m National Elevation Dataset (DEM; USGS 2015). Terrain ruggedness combined the variability in slope and aspect into a single measure ranging from 0 (no terrain variation) to 1 (complete terrain variation; Sappington et al. 2007; Table 1). CTI predicted surface water accumulation on the basis of landscape concavity and hydrology and TPI compared the elevation of each cell in a DEM to the mean elevation of a specified neighborhood around that cell. Positive TPI values represent locations that are higher than the average of their surroundings as defined by the neighborhood (ridges) and negative TPI values represent locations that are lower than their surroundings (valleys; Guisan et al. 1999).

Avian predators represent a significant source of mortality for all life stages of sage-grouse (Schroeder and Baydack 2001, Hagen 2011). By including avian predator density in our survival models, we attempted to isolate the effect of variability in raptor and common raven (hereafter, avian predators) densities on survival in our study area. We conducted avian predator use surveys from September 2011 to September 2013 using point count methodology (Reynolds 1980) at 41 locations established within sage-grouse high-use areas (20 within treatment and 21 within the control study areas). Avian predator survey plots consisted of 800-m radius circles centered on each point, and all avian predators observed during 20-minute (min) fixed-point surveys were recorded. Avian predators observed beyond 800-m were recorded but not included in the analysis. Landmarks were located within each plot to aid in identifying the 800-m boundary of each observation plot.

Avian predator point counts were conducted once every other week from 1 April–30 August and monthly from September 1 – March 30. The mean number of avian predators recorded within 800-m was used as the measure of avian predator use. Overall mean avian predator use was calculated by first averaging the total number of avian predators observed within each 800-m plot during a 20-min visit, then averaging across plots within each visit, followed by averaging across visits within the season.

Each observation point was buffered by 800 m to identify the extent of our avian predator covariate layer. We assigned the average mean use value to each observation point over the 3-year study period. We assumed mean use at each observation point had a local influence that diminished with distance and consequently used inversed distance weighted interpolation to predict mean use throughout the study areas. We calculated an inverse distance weighted layer in ArcMap 10.1 using a power of 2 (Figure 4).

Table 1. Explanatory anthropogenic and environmental covariates used in modeling sage-grouse nest, brood, and female habitat selection and survival at the Seven Mile Hill study area, Carbon County Wyoming, USA, 2009–2014. Percent cover was calculated at multiple scales specific to each analysis.

Covariates	Variable description
Anthropogenic infrastructure	
Distance to Major Roads	Distance from sage-grouse location to nearest major road [WYO HWY 72, US HWY 287/30, and I-80 (km)]
Distance to Transmission Line	Distance from sage-grouse location to nearest overhead transmission line (km)
Distance to Turbines	Distance from sage-grouse location to nearest turbine (km)
Proportion of Disturbance	Percentage of surface disturb by the SWEF (e.g., turbine pads and access roads) for each spatial scales.
Vegetation	
Bare ground	Percent bare ground (1-m resolution)
Big sagebrush[1]	Percent big sagebrush (*Artemisia tridentata* spp.; 30-m resolution)
Herbaceous	Percent herbaceous cover (1-m resolution)
Litter[1]	Percent Litter (30-m resolution)
Sagebrush[1]	Percent sagebrush (*Artemisia* spp.; 30-m resolution)
Shrub	Percent shrub cover (1-m resolution)
Shrub height[1]	Shrub height (0–253 cm; 30-m resolution)
Meadow	Percent meadow (1-m resolution)
Distance to Meadow	Distance from sage-grouse location to nearest meadow (km)
Slope	Degrees 0–90 (10-m resolution)
Wyoming big sagebrush[1]	Percent Wyoming big sagebrush (*Artemisia tridentata subsp. wyomingensis*; 30-m resolution)
Environmental	
Terrain ruggedness	Variability in slope and aspect (0–1; 1 = complete terrain variation; Sappington et al. 2007; (0-m resolution)
Distance to capture lek	Distance from sage-grouse location to respective lek of capture
Avian predator density	Predicted average mean avian predator use
Elevation	Altitude above sea level (ALS [m]; 10-m resolution)
Compound Topographic Index (CTI)	Water accumulation (large values = high water accumulation; 10-m resolution)
Topographic Position Index (TPI)	Variability in average elevation within a neighborhood (-1–1; Positive values = ridges; negative values = valleys; 10-m resolution)

[1] Vegetation covariates obtained from Homer et al. 2012.

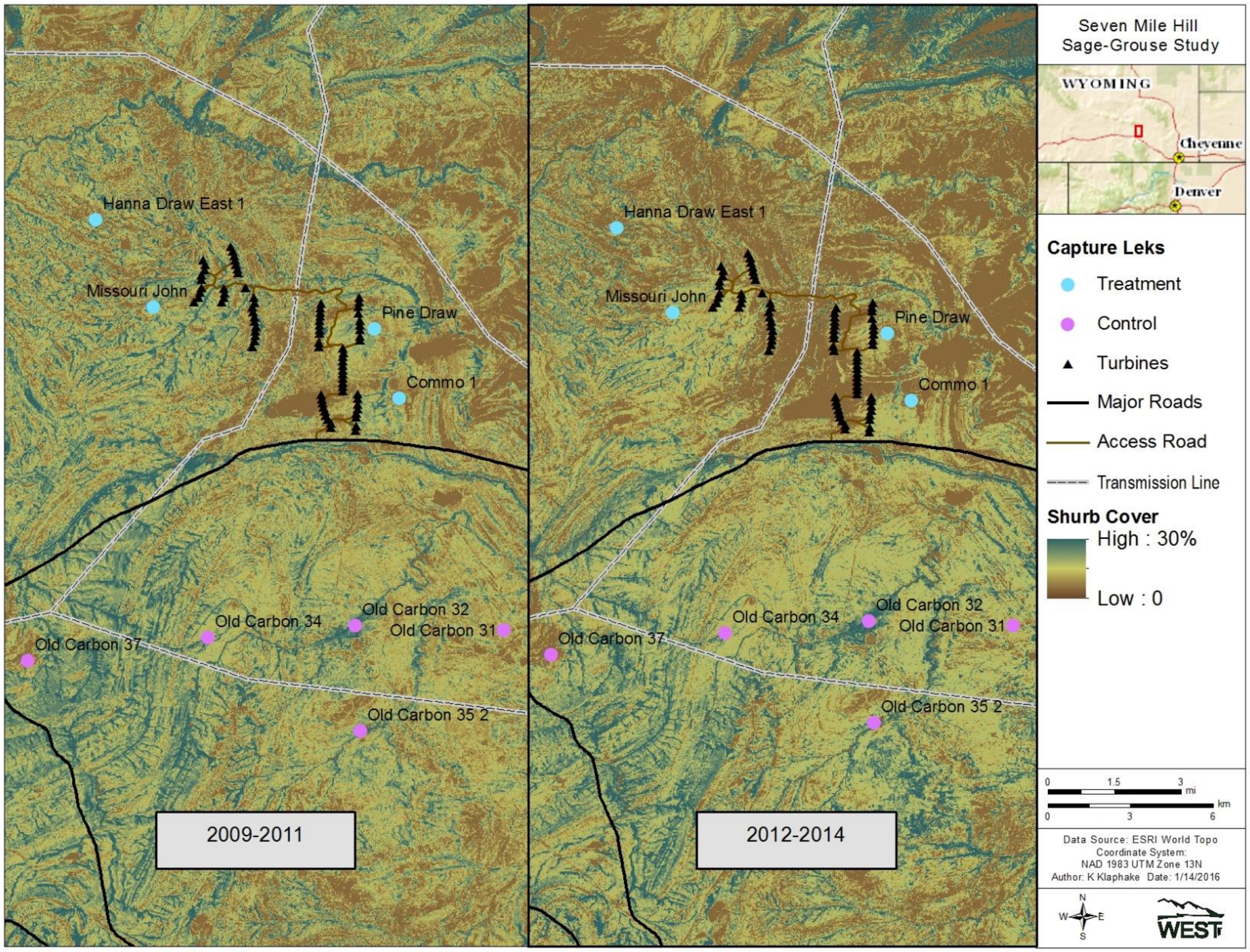


Figure 2. Shrub cover calculated from remote sensed vegetation products developed from 1-m resolution NAIP imagery (2009 and 2012) for the Seven Mile Hill study area, Carbon County, Wyoming, USA. The 2009 shrub cover was used for use and availability from 2009-2011 and the 2012 shrub cover was used for use and availability from 2012-2014.

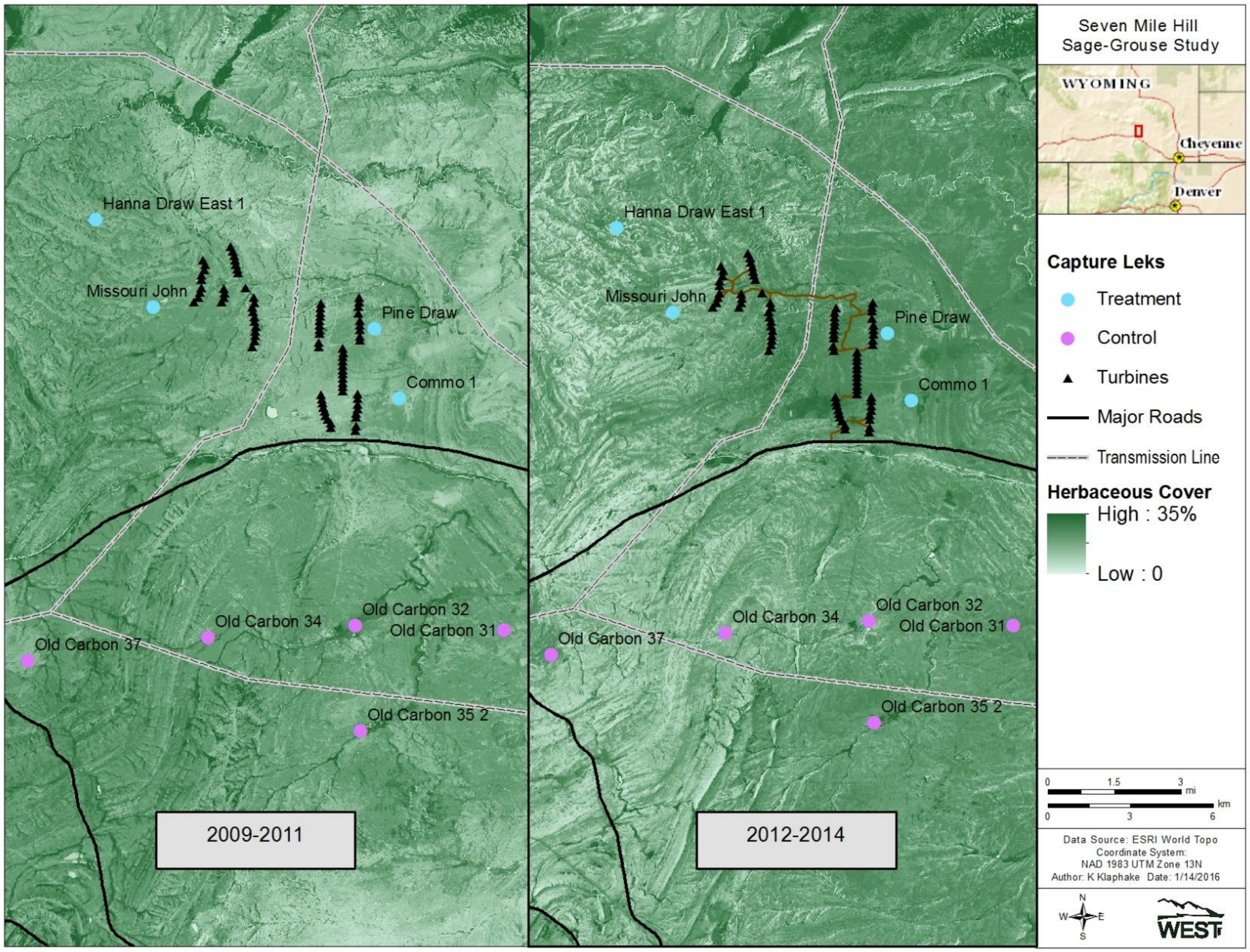
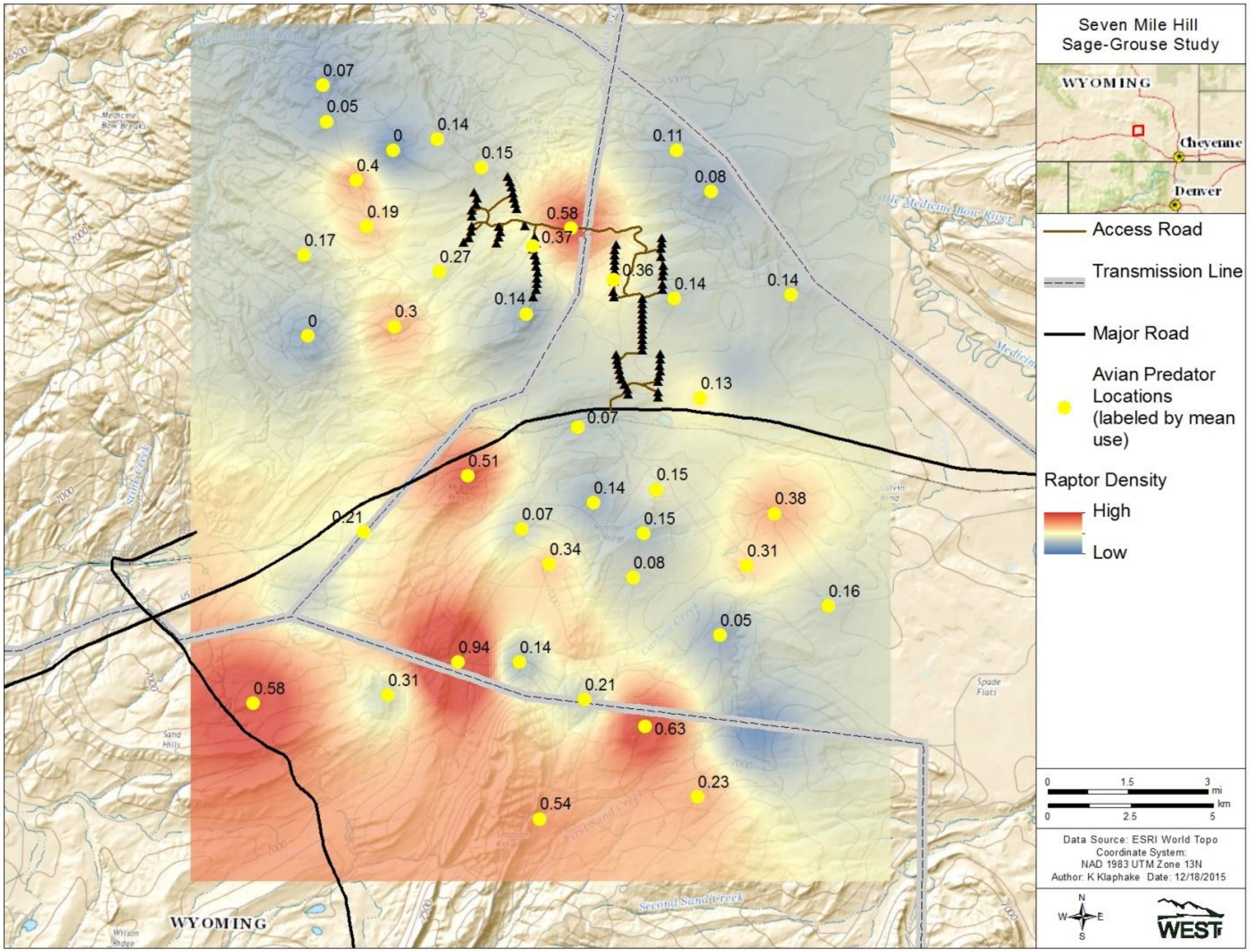


Figure 3. Herbaceous cover calculated from remote sensed vegetation products developed from 1-m resolution NAIP imagery (2009 and 2012) for the Seven Mile Hill study area, Carbon County, Wyoming, USA. The 2009 herbaceous cover was used for use and availability from 2009-2011 and the 2012 herbaceous cover was used for use and availability from 2012-2014.



Data Source: ESRI World Topo
Coordinate System:
NAD 1983 UTM Zone 13N
Author: K Klaphake Date: 12/18/2015

Figure 4. Greater sage-grouse avian predator density (average mean use from 2011 to 2013) within the Seven Mile Hill study area estimated from point count data from 2011–2013 in Carbon County, Wyoming, USA.

GREATER SAGE-GROUSE HABITAT SELECTION

Large home ranges and complex habitat selection patterns are characteristic of many sage-grouse populations (e.g., Doherty et al 2008, Atamian et al. 2010, Carpenter et al. 2010). The addition of wind energy 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 was 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 (see Naugle et al. 2011) is a growing concern for sage-grouse occupying habitats in close proximity to wind energy development. Some researchers have speculated 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 (Dzialak et al. 2011, Kirol et al. 2015). If sage-grouse are not displaced, it is unknown whether local populations may become acclimated to elevated structures. Although the potential exists for wind turbines to displace sage-grouse from occupied habitat, well-designed studies examining the potential impacts of wind turbines on sage-grouse are lacking (Johnson and Holloran 2010).

A purpose of this study was to investigate the effect of wind energy infrastructure on sage-grouse distribution and habitat selection patterns. Specifically, we investigated sage-grouse habitat selection during three biologically meaningful periods that included nesting, brood-rearing, and summer within the treatment and control study areas. This type of analysis is critical in planning future wind energy development facilities that occur within occupied sage-grouse habitats.

Methods

We used a discrete choice habitat selection model (Arthur et al. 1996, Manly et al. 2002, McDonald et al. 2006) to estimate the relative probability of sage-grouse nest site, brood-rearing, and summer habitat selection within both the control and treatment areas during the post-development period. We assumed individual sage-grouse selected habitats from a finite set of discrete habitat units known as choice sets. The discrete choice model was chosen over alternative analyses because it allows habitat covariates to vary over choice sets, and hence over time. In this case, percent shrub, herbaceous, meadow, and bare ground varied depending on year of the sage-grouse observation. The results of the discrete choice modeling is a resource selection function (RSF), which is defined as any function that provides predictions that are proportional to the probability of use (Manly et al. 1993, 2002). We employed a Type I study design where habitat selection and availability were estimated at the population level and over a 6-year time period (Thomas and Taylor 2006).

We developed RSFs during three biologically meaningful periods including the nesting, brood-rearing, and summer periods. All first and second nesting attempts were included in the nest site habitat selection analysis. All early and late brood locations associated with a female that successfully hatched at least one egg were included in the brood-rearing habitat selection analysis. Subsequent locations from females that were not successful during the early brood-rearing period were not included in the brood-rearing analysis because our goal was to model selection patterns of brooding females. Females that were not successful during the early brood-rearing period and all locations observed after the late brood-rearing period through October 31 of each year were included in the summer habitat selection analysis.

We defined available habitat by calculating kernel home ranges for all sage-grouse locations observed from 2009–2014 within each time period for both study areas. We selected a 99% kernel home range to capture the extent of all observed sage-grouse locations within the treatment area. Five percent of all sage-grouse captured at control area leks used habitats the treatment area during the study. We attempted to estimate habitat selection for sage-grouse within the control area that were uninhibited by the presence of the SWEF, thus we selected a 90% kernel home range to define available habitat within the control study area. Within each study area's available habitat polygon, we generated grid cells with 90 m x 90 m spacing to identify available habitat units. We extracted covariates associated with each available habitat unit to include in the RSF model development. A choice set included all available habitat units associated with a specific nest, brood-rearing, and summer location, as well as the used nest, brood, or summer habitat unit. Due to the large number of nest, brood, and summer locations, and the resulting large number of available habitat units, estimation of the RSF using the entire datasets was not feasible. Consequently, we randomly sampled 50, 25, and 10% of the nest brood rearing, and summer available habitat units, respectively.

Sage-grouse are a landscape level species that use multiple habitats throughout their annual cycles and likely select resources at varying scales depending on the seasonal period. We attempted to identify this variation in selection by extracting the average habitat covariate value for each used and available habitat unit at three biological meaningful scales. For the nest site selection analysis, we averaged covariates over percentiles (10th, 50th, and 90th) of the distance between annual nest locations among females who nested in consecutive years (0.13, 0.46, and 2.5 km, respectively). We also included the 0.09-km scale, which was the smallest scale possible. For the brood-rearing and summer analysis, we used percentiles (10th, 50th, and 90th) of distances between consecutive locations from individuals during each seasonal period to define the spatial scales over which we averaged covariate values.

Our model development process considered a large number of explanatory covariates measured at multiple scales. We first fit univariate models to identify the most appropriate spatial scale for each covariate. The univariate models and all subsequent models were evaluated by comparing the small sample version Akaike's Information Criterion (ΔAIC_c; Burnham and Anderson 2002). The spatial scale with the lowest ΔAIC_c was retained and considered further in the model building process.

The resulting suite of covariates was used to develop 10 environmental models to consider all natural processes prior to detecting potential SWEF influences on habitat selection. We included distance to capture lek into all *a priori* environmental models in an attempt to spatially control habitat selection patterns because the lek at which a female breeds likely influences selection patterns (Holloran and Anderson 2005). Many of the environmental covariates were highly correlated (Pearson's correlation analysis $|r| \geq 0.6$); however, we did not allow two highly correlated covariates in the same model. We added distance to existing anthropogenic features such as roads and transmission lines that have persisted on the landscape for over 10 years to the environmental model with the lowest AIC_c in an attempt to control for potential confounding factors associated with habitat selection patterns relative to the SWEF. We determined if the addition of these features considerably improved model fit (i.e., $\Delta AIC_c > 2$; Burnham and Anderson 2002). The resulting best approximating model for each study area explained the variation in habitat selection due to natural processes and existing infrastructure without the influence of the SWEF covariates.

Once the natural variation in habitat selection was controlled to the extent possible, we then added variables representing proximity to the SWEF to explain further the variation in selection patterns within the treatment study area. Covariates associated with the SWEF were not included in the model selection process for observations that were from females captured at the control area leks because we assumed the effect of the SWEF did not extend into the control area. If covariates associated with the SWEF were influencing habitat selection within the treatment area then we would expect a considerably improved model fit (i.e., $\Delta AIC_c > 2$) with the addition of the SWEF covariates.

We included a predictor to the top model for each habitat selection analysis to explain potential time lags associated with habitat selection. For example, female sage-grouse exhibit strong site fidelity and will select similar habitats in subsequent years (Berry and Eng 1985, Fischer et al. 1993, Holloran and Anderson 2005). Thus, selection patterns may be strongly influenced by fidelity rather than the presence of the SWEF 3 years following development compared to later years as new individuals were recruited into the population. The most explanatory SWEF covariate values identified during model selection associated with all sage-grouse observations from 2012 through 2014 (the last 3 years following development of the SWEF) was multiplied by 1 and all SWEF covariate values associated with sage-grouse observations from 2009 through 2011 (the first 3 years following development) were multiplied by 0. If this covariate estimate was statistically significant at the alpha level of 0.10 (i.e., 90% confidence intervals [CIs] did not include 0.0), then we considered selection patterns relative to the SWEF to be different between the last 3 years compared to the first 3 years following development.

We used 90% CIs to determine if coefficient estimates from the top approximating model were statistically significant (alpha level = 0.10). Estimates with CIs that did not contain 0.0 were considered statistically significant. We calculated CIs for each coefficient using a bootstrapping technique that treated the individual as the primary sampling unit. We randomly sampled with replacement used habitat units and their respective choice sets associated with each individual sage-grouse and refit the top approximating RSF (Manly et al. 2002). We used 200 bootstrap iterations and the percentile method to identify the lower and upper confidence limits for each coefficient. We calculated odds ratios [(exp(β)-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).

We evaluated the predictive ability of the best RSF for each time period using a k-fold cross-validation technique (Boyce et al. 2002). We randomly allocated the used habitat units and their respective choice sets into five equal-sized groups, maintaining the available habitat units within each choice set. We removed one group (testing data) and re-estimated the coefficients in the top RSF models using the used habitat units and their respective choice sets from the four groups remaining (training). The coefficients estimated from the training data were then used to make predictions to the testing used habitat units and their respective choice sets. We binned all predictions within each choice set into 20 classes of equal size using percentiles. The number of used habitat units from all the choice sets in each prediction class was compared to the class rank (1 = lowest, 20 = highest predicted odds of selection) using a Spearman's rank correlation coefficient. This process was repeated for each of K = 5 groups of used habitat units and their respective choice sets. The Spearman's rank correlation coefficients (r_s) were averaged to test how well the top model performed.

Following model validation, we made nest site, brood rearing, and summer habitat selection predictions for the average sage-grouse that breeds on leks within the treatment area. We placed a 90 m x 90 m grid within the 99% kernel home range on the landscape within the SWEF habitat to make predictive maps. There were three covariates with values that changed from 2009-2011 to 2012-2014; thus, we generated two predictive maps for each period. Distance to nearest occupied lek was used in place of distance to capture lek when we made predictions for the average individual sage-grouse. We calculated RSF values and placed them into 5 equal-area bins (low, medium-low, medium, medium-high, and high use) using percentiles to represent progressively selected habitats.

We evaluated the ability of the control and treatment RSFs to predict the relative probability of habitat selection within the treatment area by applying a goodness-of-fit test. We followed model evaluation methods outlined in Johnson et al. (2006) where we compared the expected proportion of use (median predicted RSF value) to the observed proportion of use within 20 equal-area prediction bins. We made predictions to the treatment area using RSFs that were developed at the control and treatment areas. Predictions were made for two time periods, 2009-2011 and 2012-2014, because habitat characteristics (e.g., shrub and herbaceous cover and bare ground) changed between those two periods. For each evaluation, we calculated Spearman's rank correlation between expected and observed use, which provided an assessment of the ability of the RSF to correctly rank the quality of the habitat, and then we fit a normal linear model regressing observed use to expected use for the 20 bins. If the 90% CI for the intercept of the linear model included 0.0, and the CI for the slope included 1.0 but excluded 0.0, then we determined that the RSF produced predictions of habitat use by sage grouse that were proportional to the observed use. In addition, we calculated the median distance to turbines for each of the 20 prediction bins to help interpret the relationship between expected use and distance to the SWEF turbines. We used these criteria to assess goodness-of-fit for the treatment RSF predicting habitat selection within the treatment area, and the control RSF predicting habitat selection to the treatment area.

Nest Site Habitat Selection

Results

A total of 154 nests from 104 female sage-grouse were used to estimate nest site selection within the treatment area from 2009-2014 (Figure 5). The average distance to nearest turbines during the study period for females with nests captured from leks within the treatment area were similar during the study period, ranging from 1.82 (2010) to 3.09 km (2014; Figure 6). The cumulative proportion of nests within multiple distance bands from turbines was consistent across study years, suggesting use of habitats relative to SWEF turbines did not differ over the study period (Figure 7). A total of 176 nests from 118 female sage-grouse were used to estimate nest site selection within the control area from 2009-2014.

The treatment area environmental model included distance to capture lek, bare ground, litter, and, Wyoming big sagebrush cover. This model improved with the addition of the quadratic effect of distance to transmission lines (ΔAIC_c = 24.4). The addition of the SWEF infrastructure metric that was the most informative (distance to turbines) did not improve model fit and was not significant (ΔAIC_c = 0.34; β = -0.07; 90% CI = -0.16 – 0.02). In addition, the covariate that estimated potential time lags associated with nest site selection relative to the turbines for females selecting nest sites between 2009-2011 and 2012-2014 was not significant suggesting selection patterns relative to turbines did not differ among these time periods (β = -0.07; 90% CI = -0.22 – 0.08). The relative probability of female sage-grouse nest site selection decreased by 45.5% with every 1 km increase from distance to capture lek (90% CI = 39.1 – 52.3%). Selection increased by 6.0 and 14.8% with every 1.0% increase in litter and Wyoming big sagebrush cover, respectively (Table 2). Selection decreased by 4.0% for every 1% increase in bare ground (90% CI = 3.0 – 4.9%). Selection increased as distance to transmission line increased up to 3.3 km, then declined.

The control area environmental model included distance to capture lek, percent Wyoming big sagebrush cover and bare ground, elevation, and SD percent shrub height. This model improved with the addition of distance to transmission lines and the quadratic effect of major roads (ΔAIC_c = 25.2). The relative probability of female sage-grouse nest site selection decreased by 4.2% with every 1 km increase from distance to capture lek (90% CI = 0.11 – 8.0%). Selection increased by 25.5% with every 1% increase in Wyoming big sagebrush cover (90% CI = 8.9 – 42.9%). Selection decreased by -0.68% with every 1 m increase in elevation (90% CI = -0.44 – 0.90%). Selection decreased by 1.8% with every 1% increase in percent bare ground and increased by 0.98% for every 1-unit increase in SD shrub height (Table 2). Selection decreased by 13.3% with every 1 km increase from distance to transmission line (90% CI = 6.6 – 19.0%). Selection increased as distance to major roads increased up to 7.3 km, and then declined.

The k-fold validation results indicated the RSF model developed at the treatment and control area had good overall predictability (average r_s = 0.67 and average r_s = 0.80, respectively). The

RSF developed at the treatment area using habitat data layers from 2009-2011 and 2012-2014 was good at predicting sage-grouse use based on the goodness-of-fit tests. The Spearman's rank correlation for the treatment RSF was slightly higher using the 2009-2011 datasets (r_s = 0.93) compared to the 2012-2014 datasets (r_s = 0.90). Both treatment tests had a slope that was significantly different from 0; however, the test using the 2009-2011 data produced an intercept that included 0 and a slope that included 1, suggesting a 1:1 relationship between expected and observed use when predictions were made to the 2009-2011 habitat data layers. The RSF correctly ranked predictions with the 2012-2014 habitat data layers but did not accurately predict the relative probability of nest site selection.

The RSF developed at the control area using habitat data layers from 2009-2011 and 2012-2014 was also good at predicting sage-grouse use within the treatment area. The Spearman's rank correlation for the control RSF was 0.93 when predictions were made to the 2009-2011 and 2012-2014 habitat data layers. The goodness-of-fit tests produced an intercept that included 0 and a slope that included 1 and excluded 0, suggesting a 1:1 relationship between expected and observed use. Spatially, we estimated a higher proportion of expected use from the control and treatment RSFs and observed a higher proportion of use closer to SWEF turbines (Figure 8 and 9).

Discussion

Nest site selection was not influenced by the SWEF 6 years following development, but was influenced by proximity to lek of capture, vegetation variables including a positive effect of Wyoming big sagebrush cover, negative effect of bare ground and anthropogenic effects of distance to transmission lines and major roads. At the treatment study area, proportion of nest locations across the eight, 1-km distance bands was consistent from 2009 through 2014, suggesting little change in nest locations in response to wind turbines. In addition, the time lag covariate we considered at the treatment study area, that compared short-term (2009–2011) and long-term (2012–2014) nesting site selection relative to distance to turbines was not significant, providing further evidence that sage-grouse were not avoiding wind turbines at our treatment study area.

Our nest site selection analyses benefitted from short (2009–2011) and longer-term (2012–2014) comparisons of nest site selection. We found good predictability for our RSF models at treatment and control sites during both time periods, indicating our models adequately predicted sage-grouse nesting habitat selection in both study areas. Furthermore, changes in the average difference in prediction bins was centralized around 0 suggesting little changes among treatment and control RSF model predictions. The small differences in these models indicate that a RSF model developed from females at the control area was good at predicting nest site selection for females within the treatment area, which provides further evidence that the SWEF did not influence nest site selection patterns within the treatment study area.

Models of nesting habitat selection for both study areas indicated a strong, positive effect of nest placement in proximity to lek of capture. This finding is corroborated by sage-grouse research from Wyoming that indicates 64% of sage-grouse nests occurred within 5 km of leks (Holloran and Anderson 2005). Our results also suggest that female sage-grouse selected nest sites regardless of distance to wind energy infrastructure, which differs from nest site selection in oil and gas fields. For instance, Lyon and Anderson (2003) reported 91% of female sage-grouse from undisturbed leks nested within 3 km of lek of capture compared to only 26% females captured on leks disturbed by oil and gas development in southwestern Wyoming. Many studies conducted in Wyoming support our finding that nesting habitat selection in both study areas increased with increasing cover of Wyoming big sagebrush (e.g., Holloran and Anderson 2005, Dinkins et al. 2014, Kirol et al. 2015). The stronger selection for valley-type habitats in the control study area as modeled through elevation was likely associated with greater access to Wyoming big sagebrush, which tends to grow taller and denser in valley bottoms where moisture availability is higher compared to ridgetops (Knight et al. 2014). In addition, we detected an effect of variability of shrub height on nesting habitat selection, which has also been documented elsewhere in southern Wyoming (Kirol et al. 2015). The effect of increasing nest selection on areas of lower bare ground was reciprocal with increasing selection in areas of greater litter and sagebrush cover. We found some avoidance of the transmission line up to 3.3 km by nesting sage-grouse in our control area as well as variability in individuals selecting nests near roads.

If nesting females had responded to the SWEF, we would have expected increasing numbers of female sage-grouse from the treatment study area to nest south of Highway 30/287 over time. However, there was little of that response suggesting nesting females responded to habitat conditions nearest to leks instead of avoiding wind energy infrastructure. Instead, females continued to select nest sites in similar habitats relative to turbines during the nesting period up to 6 years post construction. This was further supported by our time lag analysis, which showed no time lag effect. Our study would have been more optimal had it included pre-development data; however, because we did not detect large avoidance of wind turbines over our six-year study, we conclude that female sage-grouse in our study were selecting nesting habitats in response to vegetation, environmental, and non-wind energy anthropogenic factors. Although we controlled for confounding factors during the model-building process by identifying the best environmental model first before considering wind and anthropogenic model variables, there was a chance we did not consider a particular covariate that would have better elucidated nesting habitat selection. However, we feel confident in our modeling approach and in the set of variables we considered, which are well supported in the literature.

Table 2. Odds ratios, slope coefficients, and 90% confidence intervals (CI) for covariates in the sage-grouse nest site selection models for a treatment and control study area within the Seven Mile Hill study area in Carbon County, Wyoming, USA, 2009–2014. Odds ratios measure the multiplicative change in relative probability of selection when a covariate changes by one unit, assuming values for all other covariates remain constant. Odds ratios were not calculated for insignificant (alpha level = 0.10) covariates and covariates involved with a quadratic effect because they were dependent on values of other covariates.

Description	Scale (km)	Coefficient	90% CI		Odds Ratio (%)	90% CI (%)	
			Lower	Upper		Lower	Upper
Treatment							
Distance to lek of capture	NA	-0.607	-0.740	-0.496	-45.52	-52.31	-39.10
Bare ground	0.13	-0.041	-0.050	-0.030	-4.04	-4.87	-2.95
Litter	0.46	0.058	0.019	0.106	5.97	1.88	11.16
Wyoming big sagebrush	0.13	0.138	0.017	0.256	14.76	1.76	29.20
Distance to Transmission Line	NA	0.853	0.439	1.316	NA	NA	NA
(Distance to Transmission Line)^2	NA	-0.128	-0.184	-0.079	NA	NA	NA
Control							
Distance to lek of capture	NA	-0.043	-0.084	-0.001	-4.21	-8.01	-0.11
Wyoming big sagebrush	0.46	0.227	0.085	0.357	25.51	8.87	42.87
Elevation	0.09	-0.007	-0.009	-0.004	-0.68	-0.90	-0.44
Bare ground	0.09	-0.018	-0.028	-0.011	-1.81	-2.75	-1.10
SD shrub height	0.13	0.010	0.005	0.014	0.98	0.52	1.45
Distance to Transmission Line	NA	-0.142	-0.211	-0.068	-13.27	-19.04	-6.57
Distance to Major Roads	NA	0.381	0.243	0.566	NA	NA	NA
(Distance to Major Roads)^2	NA	-0.026	-0.044	-0.014	NA	NA	NA

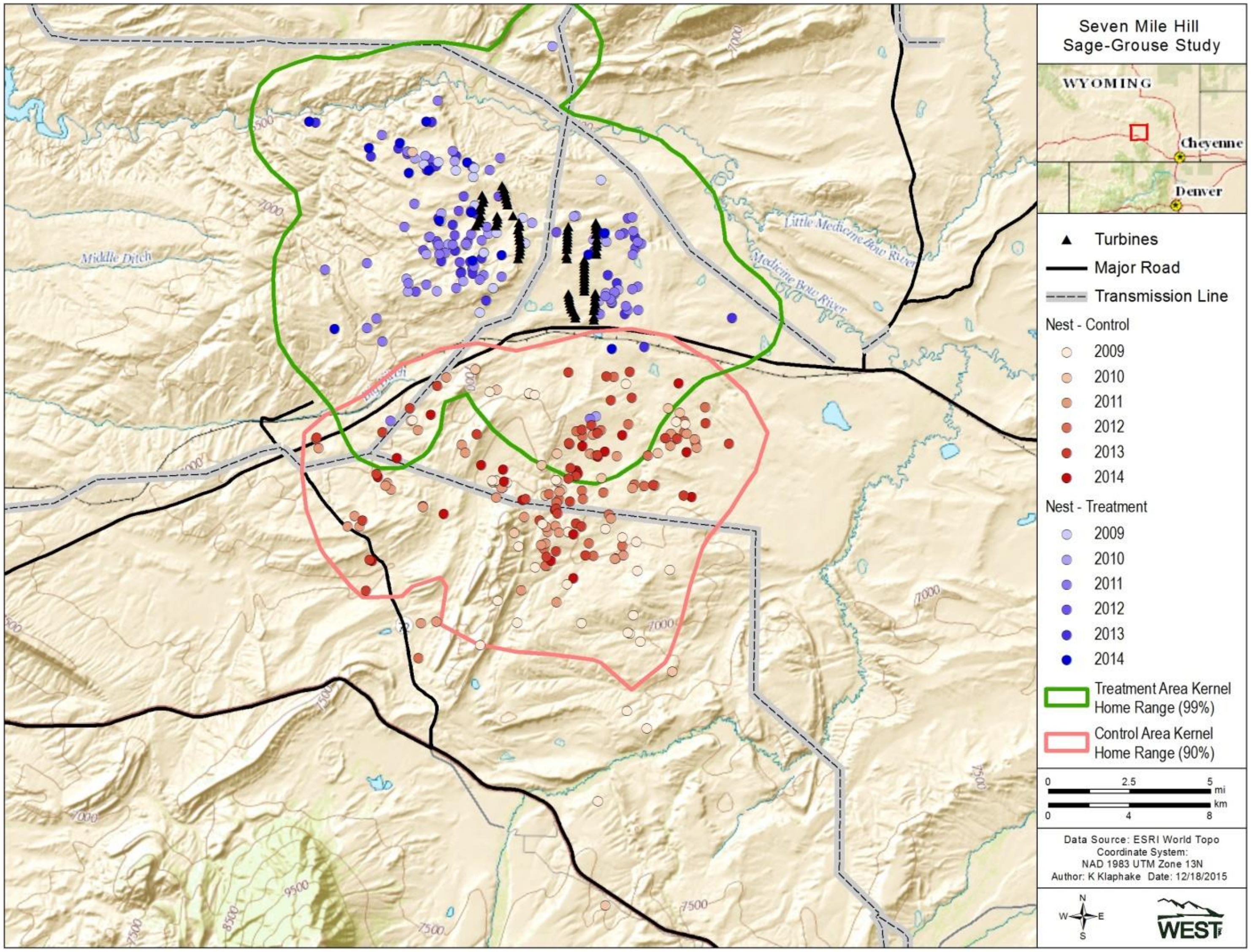


Figure 5. Sage-grouse nest locations observed at the control and treatment areas from 2009–2014 within the Seven Mile Hill study area, Carbon County, Wyoming, USA.

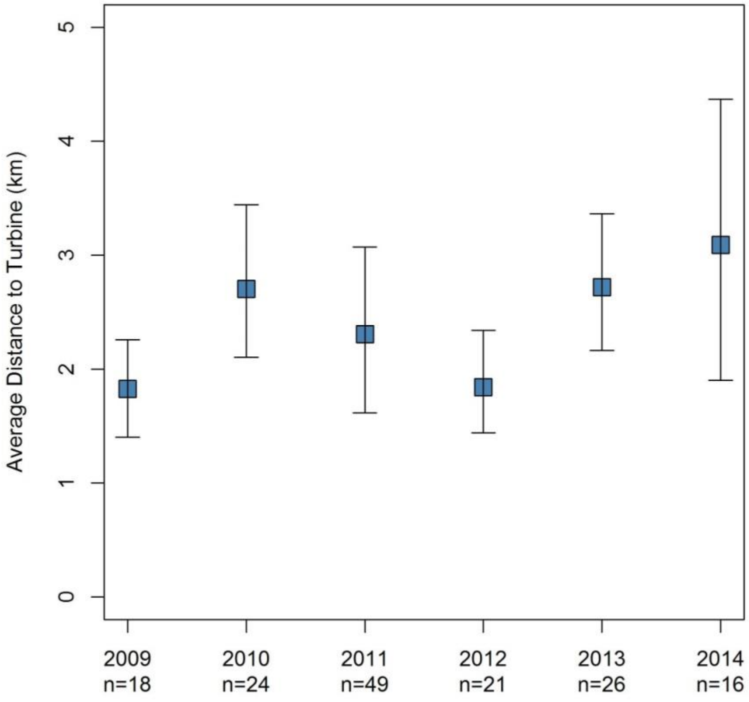


Figure 6. The average distance to turbines for greater sage-grouse nests observed within the treatment area at the Seven Mile Hill study area from 2009 – 2014, Carbon County, Wyoming, USA. Confidence levels (alpha = 0.90) were estimated using a bootstrapping technique that treated the individual as the sampling unit.

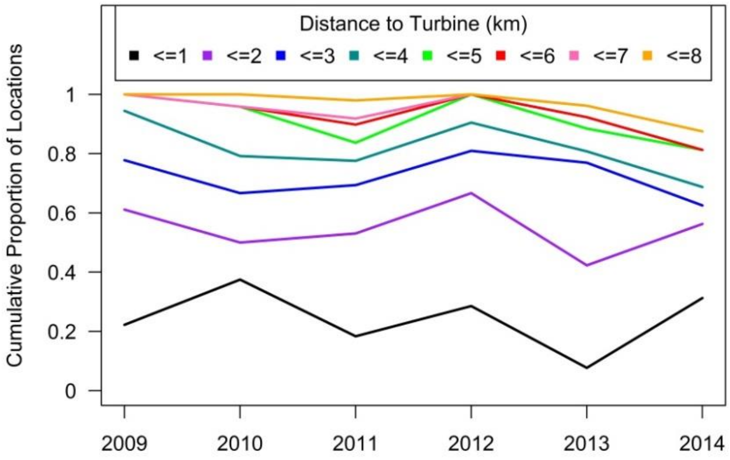


Figure 7. Cumulative proportion of greater sage-grouse nest locations relative to the Seven Mile Hill Wind Energy Facility turbines observed at the treatment study area within the Seven Mile Hill study area from 2009–2014, Carbon County, Wyoming, USA.

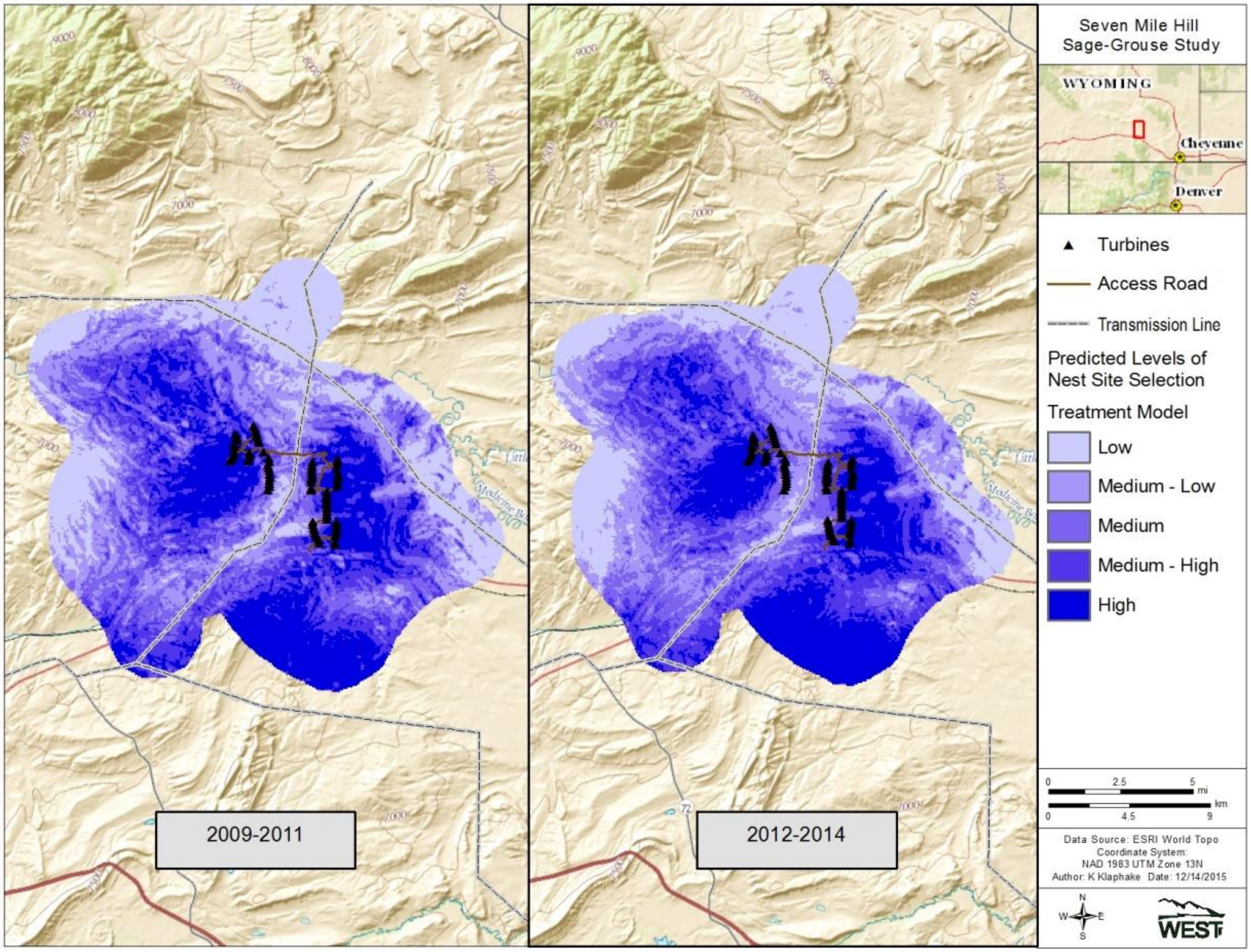


Figure 8. Predicted levels of sage-grouse nest site selection within the treatment area at the Seven Mile Hill study area, Carbon County, Wyoming, USA. Predictions were made for study years 2009–2011 and 2012–2014 using a RSF model developed at the treatment study area.

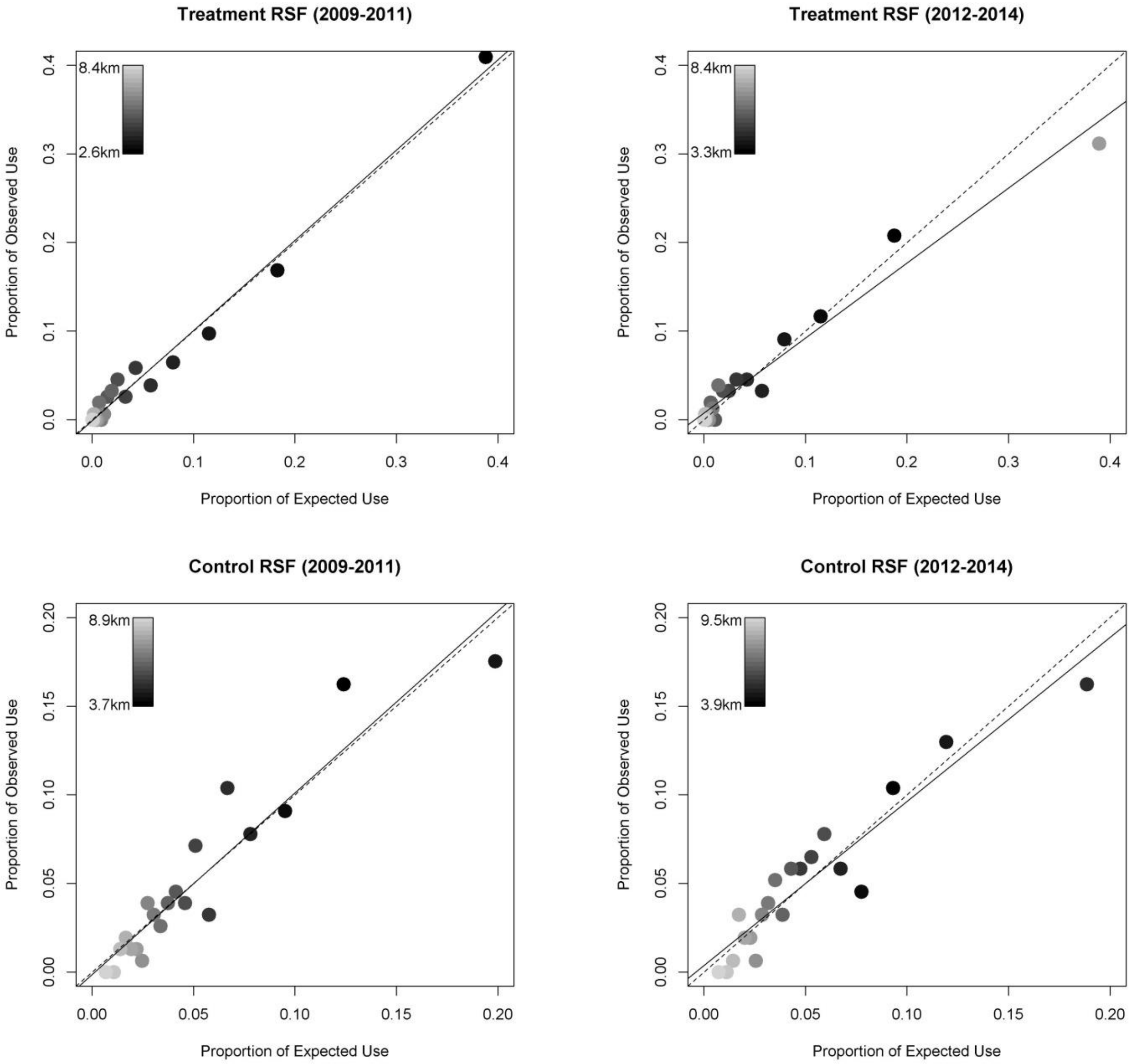


Figure 9. Proportion of expected use compared to the proportion of observed use for sage-grouse nest locations within the treatment area. Expected use was calculated using RSFs developed at the control and treatment area for covariate values observed during 2009–2011 and 2012–2014. The dashed line represents observed equals expected and the dark line represents the fitted regression line. Darker points represent smaller median distances to SWEF turbines for each bin value.

Brood-Rearing Habitat Selection

Results

A total of 438 brood-rearing locations from 42 female sage-grouse were used to estimate brood-rearing habitat selection within the treatment area from 2009-2014 (Figure 10). The average distance to nearest turbines during the study period for females with broods captured from leks within the treatment area ranged from 2.37 (2010) to 4.82 km (2014; Figure 11). The cumulative proportion of broods within multiple distance bands from turbines was variable across study years. However, the proportion of broods increased from 2009 to 2010 within 1.0 km of the turbines before decreasing from 2011-2014 compared to proportion of broods at distances greater than 1 km (Figure 12). A total of 543 brood-rearing locations from 46 female sage-grouse were used to estimate brood-rearing habitat selection within the control area from 2009-2014.

The treatment area environmental model included distance to capture lek, Wyoming big sagebrush, bare ground, elevation, and SD of shrub height. The environmental model improved with the addition of the quadratic effect of distance to major roads and transmission line (ΔAIC_c = 86.52). The addition of the SWEF infrastructure metric that was the most informative (percentage of disturbance within 1.2 km) improved model fit and was significant (ΔAIC_c = 24.31; β = -0.90; 90% CI = -2.18 – -0.25; Figure 13). The next best fitting model was percentage of disturbance within 0.80 km (ΔAIC_c = 2.32). The covariate that estimated the potential time lags associated with brood-rearing selection relative to the percentage of disturbance for females with broods between 2009-2011 and 2012-2014 was significant, suggesting selection patterns relative to percentage of disturbance differed among these time periods (β = -1.49; 90% CI = -2.27 – -0.70).

The relative probability of brood-rearing habitat selection decreased by 42.1% with every 1 km increase from distance to capture lek (90% CI = 37.0 – 50.6%). Selection increased by 20.7% with every 1% increase in Wyoming big sagebrush cover (90% CI = 11.0 – 33.3%). Selection increased by 1.2% for every 1 m increase in elevation and decreased by 5.6% for every 1.0% decrease in bare ground (Table 3). Selection increased as distance to major roads and transmission lines increased up to 11.4 and 2.9 km, then declined, respectively. Selection decreased by 59.2% with every 1% increase in the percentage of disturbance (90% CI = 22.2 – 88.7%). The SD of shrub height was included in the top model; however, it was not significant suggesting some variability in selection patterns among individuals relative to the SD of shrub height.

The control area environmental model included distance to capture lek, herbaceous, sagebrush, TPI, and distance to meadow. The environmental model improved with the addition of distance to major road and transmission line (ΔAIC_c = 10.5). The relative probability of female sage-grouse nest site selection decreased by 25.0 and 59.1% with every 1.0 km increase from distance to capture lek and distance to meadow (Table 3). Herbaceous and sagebrush cover and TPI, distance to transmission line and major road were included in the top model; however, these estimates were not significant, suggesting some variability in selection patterns among individuals relative to these features (Table 3).

The k-fold validation results indicated the RSF developed at the treatment and control area had good overall predictability (average r_s = 0.86 and average r_s = 0.82, respectively). The RSF developed at the treatment area using habitat data layers from 2009-2011 and 2012-2014 was good at predicting sage-grouse brood-rearing selection based on the goodness-of-fit tests. The Spearman's rank correlation for the treatment RSF was slightly higher using the 2009-2011 datasets (r_s = 0.89) compared to the 2012-2014 datasets (r_s = 0.84). Both treatment tests had a slope that was significantly different from 0.0; however, the test using the 2012-2014 data produced an intercept that included 0.0. The slope did not include one for any of these tests, suggesting the RSF correctly ranked predictions but some RSF bins were different than expected.

The RSF developed at the control area using habitat data layers from 2009-2011 and 2012-2014 was also good at predicting sage-grouse use within the treatment area. The Spearman's rank correlation for the control RSF was r_s = 0.90 when predictions were made to the 2009-2011 and 2012-2014 habitat data layers and r_s = 0.85 when predictions were made to the 2012-2014 habitat data layers. The goodness-of-fit tests produced an intercept that included 0.0 and a slope that included 1.0 and excluded 0.0, suggesting a 1:1 relationship between expected and observed use when predictions were made to the 2009-2011 habitat data layers. Similarly, the goodness-of-fit test using the 2012-2014 habitat data layers produced an intercept that included 0.0 and the slope excluded 0.0 but did not include 1.0, suggesting the RSF correctly ranked predictions but some RSF bins were different than expected. Spatially, we estimated a higher proportion of expected use from the control and treatment RSFs and observed a higher proportion of use closer to SWEF turbines (Figure 14 and 15), although we did detect high correlations for some RSF bins further from turbines (Figure 15).

Discussion

Sage-grouse rearing broods generally avoided suitable brood-rearing habitat near anthropogenic infrastructure including wind energy development, major paved road and transmission lines. Avoidance of the infrastructure associated with natural gas development by sage-grouse during the brood-rearing period has been well documented (Aldridge and Boyce 2007, Dzialak et al. 2011, Kirol et al. 2015, Dinkins et al. 2014, Fedy et al. 2014). Although avoidance was consistent across the years of our study, avoidance of wind turbines was more pronounced in 2012-2014 compared to 2009-2011, suggesting a lag period in the ultimate population-level response to the development of a wind energy facility. The lag in the reaction to infrastructure is similar to reactions documented for nesting females in a natural gas development (Holloran et al. 2010), and may be related to adult philopatry of seasonal habitats dictating that eventual reactions to infrastructure are determined by individuals born after the infrastructure has been constructed. The scale of the relationship between the locations of infrastructure in a wind energy development – as estimated as the disturbance footprint within 1.2 km – and brood-rearing habitat selection was similar to studies investigating brood response to the infrastructure of a natural gas development. Aldridge and Boyce (2007) found a negative association between visible well densities within 0.5 km and brood occurrence, Kirol et al. (2015) reported a negative relationship with the number of visible wells within 1.26 km and brood occurrence, and Dinkins et al. (2014) reported a negative relationship between brood occurrence and well densities within 3 km. The distribution of brood locations (see Figure 12) corroborated that the scale of avoidance of wind energy development infrastructure during the brood-rearing season was relatively small.

The habitat selection models developed from data in the control area predicted sage-grouse brood occurrence in the treatment area relatively well. Although the environmental covariates included in each model were not identical between the control and treatment models, the same general patterns emerged across study areas with selection of habitats based on sagebrush cover, topography, and distance to leks. However, our results could have been strengthened with pre-construction data allowing for a before-after control-impact (BACI) analytical approach, and the results should be interpreted given the limitations in the design of the study. Additionally, although our modeling approach controlled for confounding effects by investigating anthropogenic covariates given relationships between selection and environmental conditions, as with any study relying on remote-sensed covariates, the results could be biased depending upon the explanatory data used.

Sage-grouse broods selected sites close to leks, further from major roads, and with higher sagebrush cover across the study areas. These selected sites also had higher herbaceous cover or greater diversity in shrub height, and were located in areas that were characteristic of drainage features. This selection pattern is consistent with past research suggesting sage-grouse during the brood-rearing season are seeking food resources consisting of forbs and insects in close association with sagebrush that is used for escape and thermal protection (Johnson and Boyce 1990, Drut et al. 1994, Thompson et al. 2006).

Our results suggest that sage-grouse during the brood-rearing period are responding to the infrastructure associated with a wind energy development similarly to that found in a natural gas field. Results from studies of sage-grouse response to natural gas development suggest that avoidance is of human activity rather than the infrastructure itself (Dzialak et al. 2012, Holloran et al. 2015). Although vehicle activity levels at a wind turbine are markedly less than a natural gas well (LeBeau et al. 2014), responses suggest similar mechanisms. The movement of turbines themselves may be adding to the perception by sage-grouse of high levels of human activity. Conversely, the threshold of human activity levels at which sage-grouse respond by avoiding sites may be below the levels found in a wind energy development (Lyon and Anderson 2003, Holloran et al. 2015). Regardless, our results suggest that management approaches established for gas and oil development may be pertinent to managing sage-grouse during the brood-rearing period and wind energy developments (see Doherty et al. 2011, Naugle et al. 2011).

Table 3. Odds ratios, slope coefficients, and 90% confidence intervals (CI) for covariates in the sage-grouse brood-rearing habitat selection models for a treatment and control study area within the Seven Mile Hill study area in Carbon County, Wyoming, USA, 2009– 2014. Odds ratios measure the multiplicative change in odds of selection when a covariate changes by one unit, assuming all other covariates remain constant. Odds ratios were not calculated for insignificant (alpha level = 0.10) covariates and covariates involved with a quadratic effect because they were dependent on values of other covariates.

Description	Scale (km)	Coefficient	90% CI		Odds Ratio (%)	90% CI (%)	
			Lower	Upper		Lower	Upper
Impact							
Distance to lek of capture	NA	-0.547	-0.705	-0.463	-42.11	-50.57	-37.04
Wyoming big sagebrush	0.18	0.188	0.104	0.288	20.66	10.98	33.33
Elevation	0.89	0.012	0.004	0.018	1.17	0.36	1.86
Bare ground	0.18	-0.058	-0.079	-0.033	-5.64	-7.57	-3.27
SD shrub height	0.18	-0.003	-0.018	0.010	-0.29	-1.76	0.97
Distance to transmission line	NA	0.368	-0.030	0.915	NA	NA	NA
(Distance to transmission line)^2	NA	-0.064	-0.150	-0.007	NA	NA	NA
Distance to major roads	NA	0.454	0.198	0.788	NA	NA	NA
(Distance to major roads)^2	NA	-0.020	-0.045	-0.005	NA	NA	NA
Percent of SWEF surface disturbance	1.20	-0.898	-2.184	-0.251	-59.25	-88.75	-22.16
Control							
Distance to lek of capture	NA	-0.288	-0.375	-0.211	-24.99	-31.30	-19.06
Herbaceous	0.89	0.151	-0.051	0.336	16.34	-4.98	39.93
Sagebrush	0.18	0.030	-0.004	0.067	3.00	-0.40	6.91
TPI	0.89	-0.006	-0.014	0.002	-0.65	-1.42	0.17
Distance to meadows	NA	-0.893	-1.255	-0.543	-59.05	-71.48	-41.88
Distance to transmission lines	NA	0.105	-0.022	0.230	11.08	-2.19	25.799
Distance to major roads	NA	0.037	-0.061	0.128	3.77	-5.912	13.68

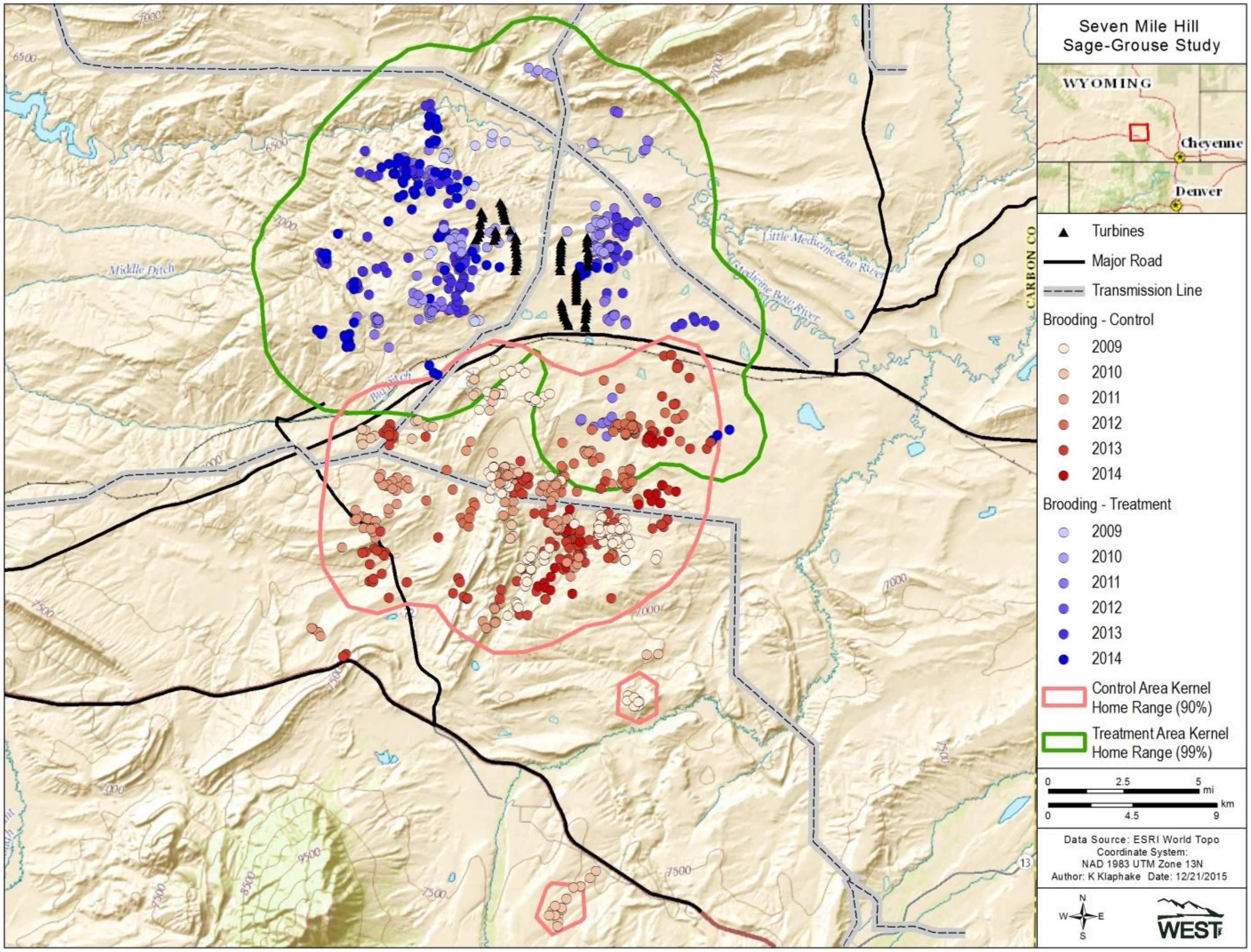


Figure 10. Sage-grouse brood-rearing locations observed at the control and treatment areas from 2009–2014 within the Seven Mile Hill study area, Carbon County, Wyoming, USA.

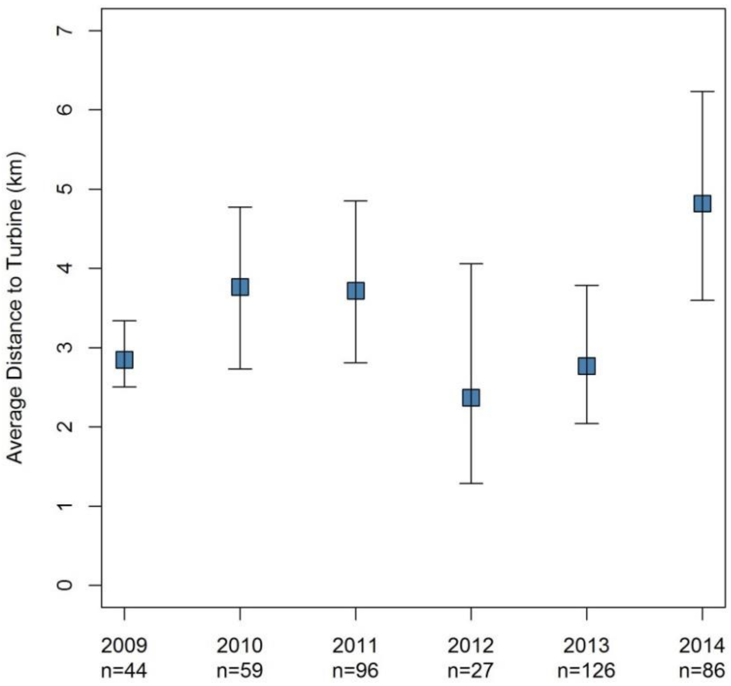


Figure 11. The average distance to turbines for greater sage-grouse brood-rearing locations observed within the treatment study area at the Seven Mile Hill study area from 2009–2014, Carbon County, Wyoming, USA. Confidence levels (alpha = 0.90) were estimated using a bootstrapping technique that treated the individual as the sampling unit.

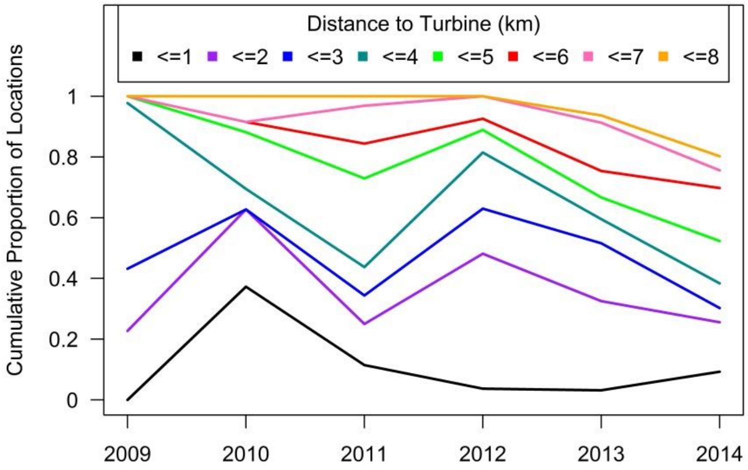


Figure 12. Cumulative proportion of greater sage-grouse brood-rearing locations relative to the Seven Mile Hill Wind Energy Facility turbines observed at the treatment study area within the Seven Mile Hill study area from 2009–2014, Carbon County, Wyoming, USA.

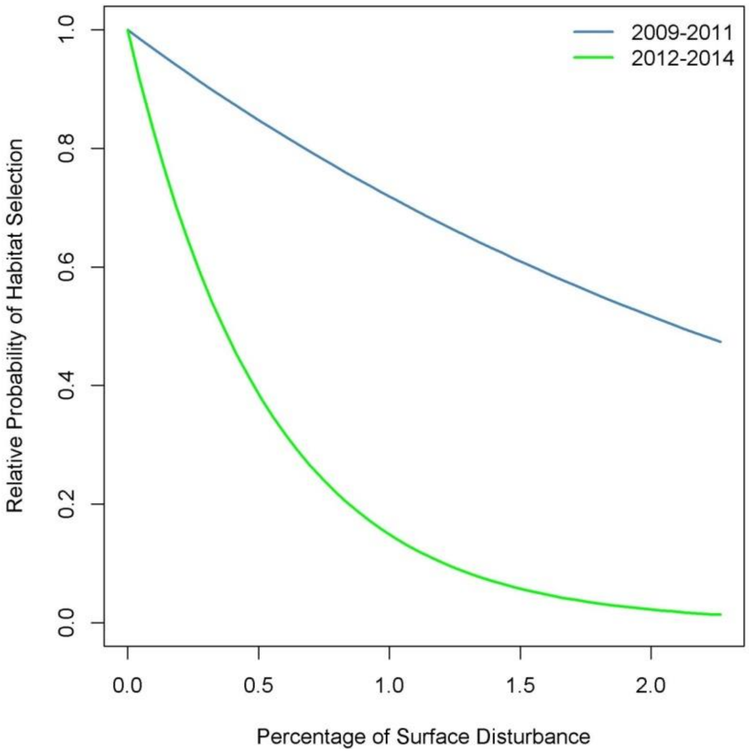


Figure 13. Marginal effects plot for percentage of SWEF surface disturbance within 1.2 km included in the top treatment brood-rearing RSF model at the Seven Mile Hill study area, Carbon County, Wyoming, USA. All other RSF model covariates were held at their median values.

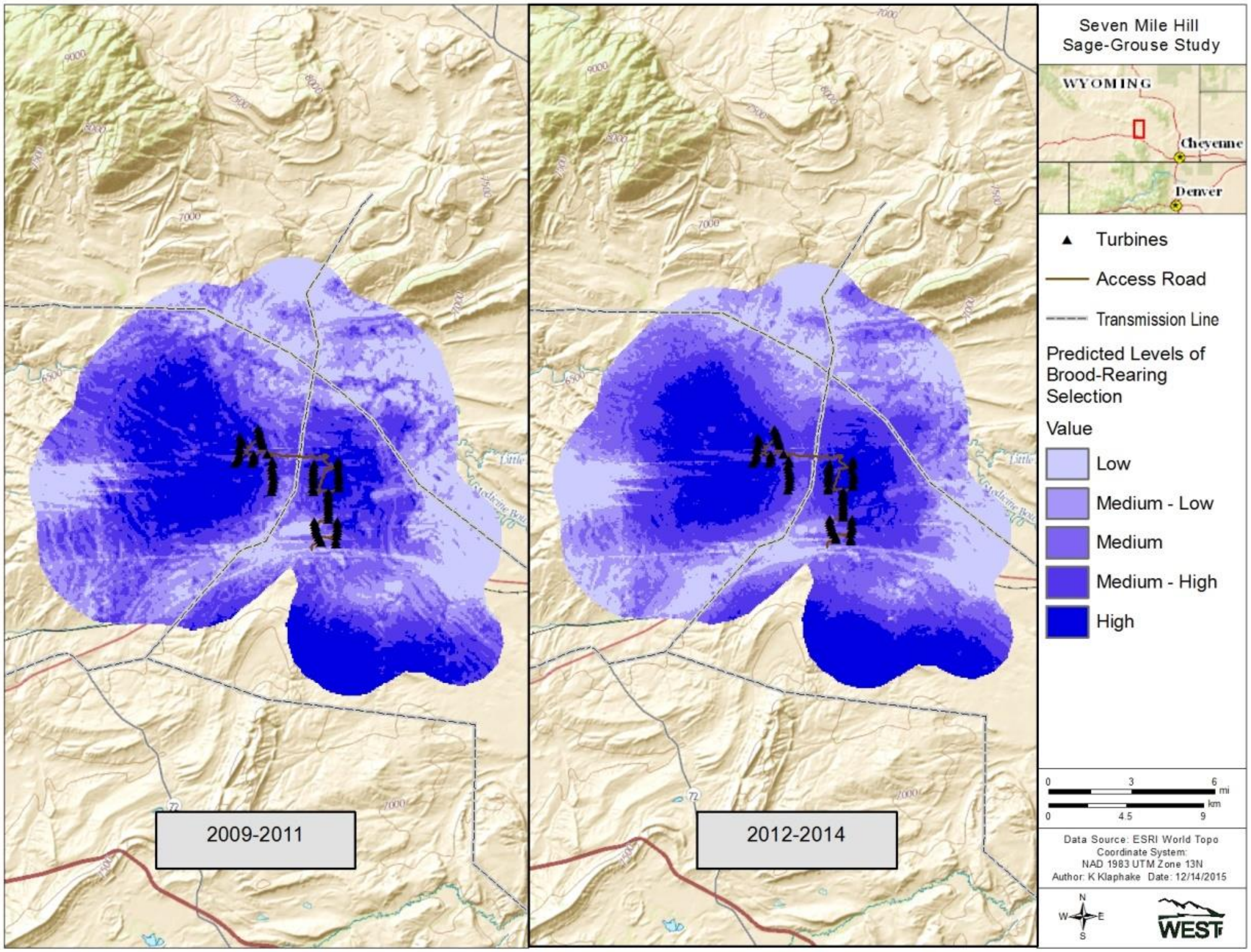


Figure 14. Predicted levels of sage-grouse brood-rearing habitat selection within the treatment area at the Seven Mile Hill study area, Carbon County, Wyoming, USA, 2009–2014. Predictions were made for study years 2009–2011 and 2012–2014 using a RSF model developed at the treatment study area.

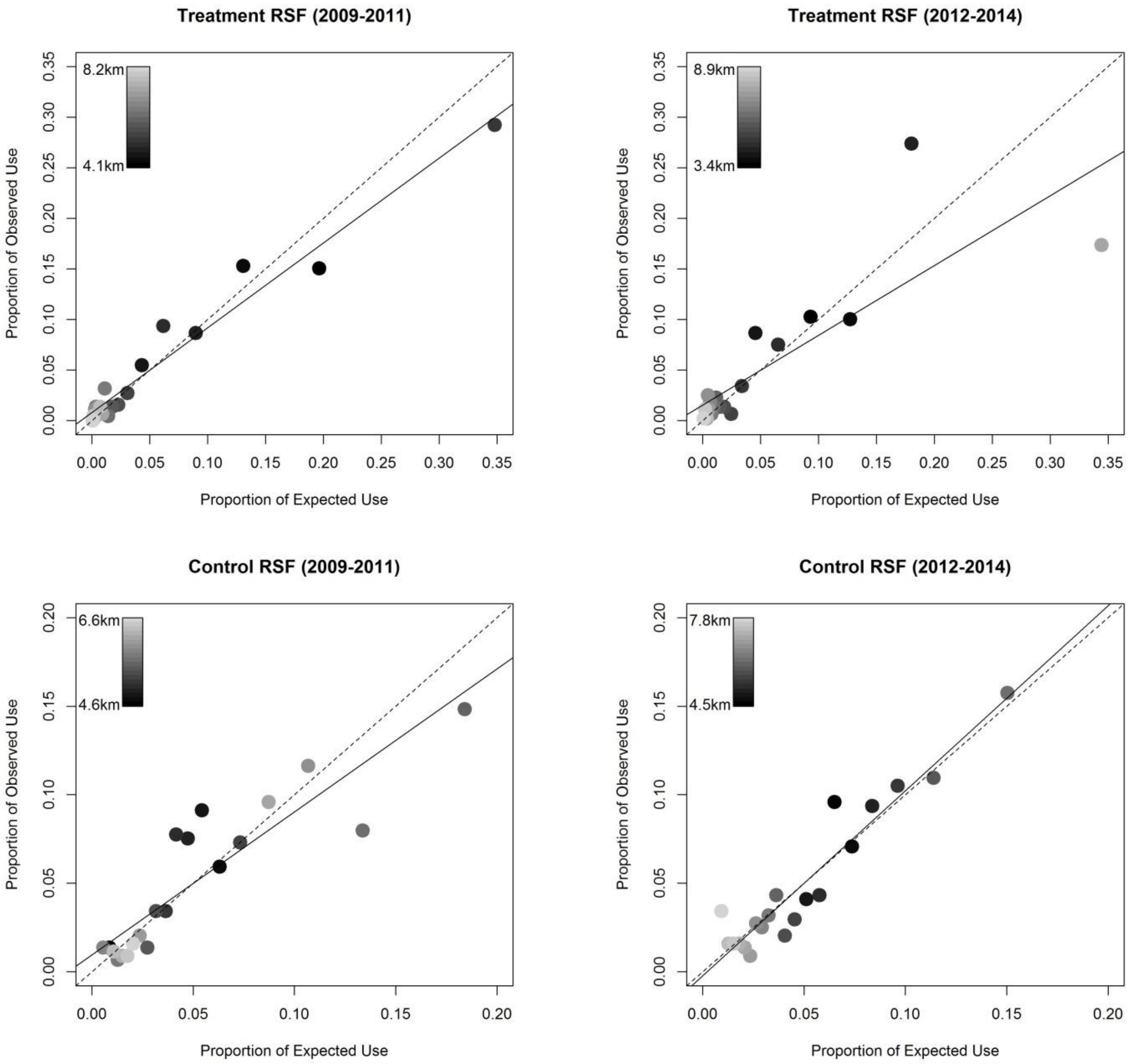


Figure 15. Proportion of expected use compared to the proportion of observed use for sage-grouse brood-rearing locations within the treatment study area. Expected use was calculated using RSFs developed at the control and treatment study area for covariate values observed during 2009–2011 and 2012–2014. The dashed line represents observed equals expected and the dark line represents the fitted regression line. Darker points represent smaller median distances to SWEF turbines for each bin value.

Summary Habitat Selection

Results

A total of 2,314 summer locations from 125 female sage-grouse were used to estimate summer habitat selection within the treatment study area from 2009–2014 (Figure 16). The average distance to nearest turbines during the study period for females captured from leks within the treatment area ranged from 2.35 (2009) to 5.38 km (2014; Figure 17). The cumulative proportion of summer locations within multiple distance bands from turbines was variable across study years and appeared to decrease from 2009 to 2014 (Figure 18). However, the proportion of female locations appeared to be consistent for each study year at distances > 4 km (Figure 18). A total of 2,537 summer locations from 153 female sage-grouse were used to estimate summer site selection within the control area from 2009-2014.

The treatment area environmental model included distance to capture lek, herbaceous, SD of shrub, TPI, and slope. This model improved with the addition of distance to major roads ($\Delta AIC_c = 59.7$). The addition of the SWEF infrastructure metric that was the most informative (percentage of SWEF disturbance within 1.2 km) improved model fit and was significant ($\Delta AIC_c = 5.24$; $\beta = -0.24$; 90% CI = -0.46 – -0.04; Table 4; Figure 19). In addition, the covariate that estimated the potential time lags associated with summer site selection relative to the percentage of disturbance for female summer habitat selection between 2009–2011 and 2012–2014 was not significant suggesting selection patterns relative to the percentage of SWEF disturbance did not differ among these time periods ($\beta = 0.07$; 90% CI = -0.20 – 0.33).

The relative probability of female sage-grouse summer habitat selection within the treatment area decreased by 0.45 and 5.25% with every 1-unit increase in TPI and 1 degree increase in slope, respectively (Table 5). Habitat selection decreased by 16.6% with every 1.0 km increase from distance to capture lek (90% CI = 15.0 – 18.9%). Selection increased by 14.6% with every 1-unit increase in the SD of shrub cover (90% CI = 8.4 – 21.9%). Selection increased by 2.8% for every 1 km increase in distance to major roads (90% CI = 2.6 – 7.6%). Selection decreased by 21.0% for every 1% increase in the percentage of disturbance (Table 5). The relative probability of selection related herbaceous cover was variable among individuals and these estimates were not significant (Table 5).

The control area environmental model included distance to capture lek, meadow, TPI, SD of shrub, and slope. This model improved with the addition of distance to major road and transmission line ($\Delta AIC_c = 108.75$). The relative probability of female summer selection decreased by 1.8% for every 1 km increase in distance to capture lek (90% CI = 0.64 – 3.1%). Selection increased by 39.8% for every 1% increase in percentage of meadow (90% CI = 31.8 – 49.1%). Selection decreased by 1.2 and 11.0% for every 1-unit increase in TPI and 1 degree increase in slope, respectively (Table 5). Selection increased by 16.6% for every 1-unit increased in shrub cover (90% CI = 8.4 – 21.9%). Selection increased by 4.6 and 9.5% for every 1 km increase in distance to transmission line and major road (Table 5).

The k-fold validation results indicated the RSF model developed at the treatment and control study area had good overall predictability (average $r_s = 0.95$ and average $r_s = 0.94$, respectively). The RSF developed at the treatment area using habitat data layers from 2009-2011 and 2012-2014 was good at predicting sage-grouse summer use determined by the goodness-of-fit tests. The Spearman's rank correlation for the treatment RSF was slightly higher using the 2009-2011 datasets (r_s = 0.97) compared to the 2012-2014 datasets (r_s = 0.96). Both treatment tests had a slope that was significantly different from 0.0; however, the test using the 2012-2014 data produced an intercept that included 0.0 and a slope that included 1.0, suggesting a 1:1 relationship between expected and observed use when predictions were made to the 2012-2014 habitat data layers. The slope did not include 1 and the intercept did not include 0.0 for the 2009-2011 test, suggesting the RSF correctly ranked predictions but some RSF bins were different than expected.

The RSF developed at the control study area using habitat data layers from 2009-2011 and 2012-2014 was not adequate at predicting sage-grouse use within the treatment study area. The Spearman rank correlation for the control RSF was 0.65 when predictions were made to the 2009-2011 and 2012-2014 habitat data layers. The goodness-of-fit tests produced an intercept that did not include 0.0 and a slope that included 0.0, suggesting model fit was lower than expected and the majority of RSF bins were different than expected. Spatially, we estimated a higher proportion of expected use from the treatment RSFs and observed a higher proportion of use closer to SWEF turbines (Figure 20 and 21), although we did detect high correlations for some RSF bins further from turbines (Figure 21). Due to the inability of the control RSF to predict accurate use within the treatment study area, we were unable to identify any correlation trends relative to turbines. The control RSF expected high use approximately 9.65 km from turbines but expected use was not proportionate to observed use, suggesting selection patterns differed between study areas possibly due to differences in available summer habitats.

Discussion

The average distance from summer locations to nearest turbine increased from 2.21 km to 5.26 km between 2009 and 2014, indicating a possible lag effect of turbines on summer habitat selection and the full impact of the SWEF facility on summer habitat selection may not be fully realized 6 years following development. However, the proportion of female locations at distances > 4 km from turbines was similar through all six-study years, indicating no strong avoidance of turbines over time. Although distance to turbine was not strongly associated with summer habitat selection, the percentage of disturbance associated with wind energy infrastructure did appear to influence summer habitat selection. The addition of proportion of disturbance within 1.2 km of summer locations improved model fit and was significant. Summer habitat selection was found to decrease by 21% for every 1% increase in the percentage of disturbance within 1.2 km. Avoidance of disturbed areas during summer during the first three years (2009–2011) was not significantly different from years (2012-2014) suggesting this avoidance effect did not become stronger over time. The maximum amount of disturbance in the study area was 1.55%, and summer selection was lowest in habitats with this level of disturbance. In western portions of the species' range a higher probability of sage-grouse lek persistence was reported in landscapes <3% developed within 5 km (Knick et al. 2013), but it is worth noting that the "developed" covariate examined included urban and suburban areas, and interstate and state highways in addition to energy infrastructure. Substantial amounts of research on a metric similar to proportion of surface area disturbed suggest that infrastructure densities (i.e., number per unit area) negatively influence sage-grouse population persistence and seasonal habitat selection (Hagen 2010, Naugle et al. 2011, Taylor et al. 2013, Gregory and Beck 2014). These results are similar to that documented for greater prairie-chickens at a wind energy facility in Kansas where habitat selection during the 6-month breeding period (March 1 – August 31) increased with increasing distance to turbine, suggesting behavioral avoidance of turbines (Winder et al. 2014b).

Within the treatment study area female sage-grouse during the summer season selected for areas with lower TPIs and less slope. These areas are generally associated with valleys where both forbs and wetter areas are more abundant (Knight et al. 2014). Females also selected for areas with higher SD in sagebrush cover, suggesting selection for areas with high variability in sagebrush cover classes. Female sage-grouse during this period also appeared to avoid paved roads. In the control area, female sage-grouse during summer selected for areas closer to leks, higher percentage of meadows, higher shrub cover, and areas with lower TPIs and slopes characteristic of valleys in the project area. Adding distance to major road and transmission line improved model fit, and summer habitat selection in the control area was higher in areas further from major roads and transmission lines, indicating sage-grouse were avoiding these features.

The habitat selection models developed from data in the control area did not adequately predict the relative probability of sage-grouse summer habitat selection in the treatment area. Although the environmental covariates included in each model were similar, the magnitude and effect of each covariate included in respective models varied. For example, the magnitude associated with distance to capture lek for the treatment RSF was approximately 16 times greater than the magnitude within the control RSF suggesting selection patterns within the control area were not dependent on habitats located in close proximity to lek of capture. In addition, sage-grouse within the treatment area selected for habitats with less herbaceous cover, which is similar to control females selecting for greater percentage of meadow. The treatment area had a larger amount of percentage of meadow compared to the control area so the predictions were magnified when we applied the control RSF to the treatment area. Even though sage-grouse from both study areas use habitats that are in relative close proximity to each other we did detect substantial differences between habitat selection patterns of the two groups. The different selection patterns between the two groups could be influenced by the facility; however, we do not suspect this to be the case as the treatment model indicated a small avoidance of the facility and estimated areas of low predicted levels of use far from the SWEF. Our results could have been strengthened with pre-construction data allowing for a BACI analytical approach, and the results should be interpreted given the limitations in the design of the study. Additionally, although our modeling approach controlled for confounding effects by investigating anthropogenic covariates given relationships between selection and environmental conditions, as with any study relying on remote-sensed covariates the results could be biased depending upon the explanatory data used. Nonetheless, we are confident that we would have detected a large magnitude of avoidance of the SWEF within the treatment study over the 6-year study if such magnitude existed.

Table 4. Odds ratios, slope coefficients, and 90% confidence intervals (CI) for covariates in the sage-grouse summer habitat selection models for a treatment and control study area within the Seven Mile Hill study area in Carbon County, Wyoming, USA, 2009–2014. Odds ratios measure the multiplicative change in odds of selection when a covariate changes by one unit, assuming all other covariates remain constant. Odds ratios were not calculated for insignificant (alpha level = 0.10) covariates and covariates involved with a quadratic effect because they were dependent on values of other covariates.

Description	Scale (km)	Coefficient	90% CI		Odds Ratio (%)	90% CI (%)	
			Lower	Upper		Lower	Upper
Impact							
Distance to lek of capture	NA	-0.181	-0.210	-0.163	-16.55	-18.92	-15.04
Herbaceous	1.80	-0.059	-0.112	0.013	-5.76	-10.59	1.32
TPI	0.81	-0.005	-0.008	-0.001	-0.45	-0.82	-0.12
Shrub SD	0.37	0.136	0.080	0.198	14.56	8.36	21.91
Slope	0.37	-0.054	-0.079	-0.026	-5.25	-7.60	-2.60
Distance to major roads	NA	0.027	0.006	0.054	2.79	0.59	5.52
Percentage of SWEF Disturbance	1.20	-0.236	-0.459	-0.039	-21.00	-36.81	-3.83
Control							
Distance to lek of capture	NA	-0.019	-0.032	-0.006	-1.84	-3.11	-0.64
Meadow	1.80	0.335	0.276	0.399	39.80	31.82	49.08
TPI	0.81	-0.012	-0.016	-0.008	-1.19	-1.61	-0.75
Shrub SD	0.37	0.153	0.107	0.202	16.57	11.25	22.38
Slope	1.80	-0.116	-0.139	-0.091	-10.99	-12.97	-8.70
Distance to transmission line	NA	0.045	0.021	0.074	4.64	2.16	7.73
Distance to major roads	NA	0.090	0.074	0.107	9.45	7.65	11.32

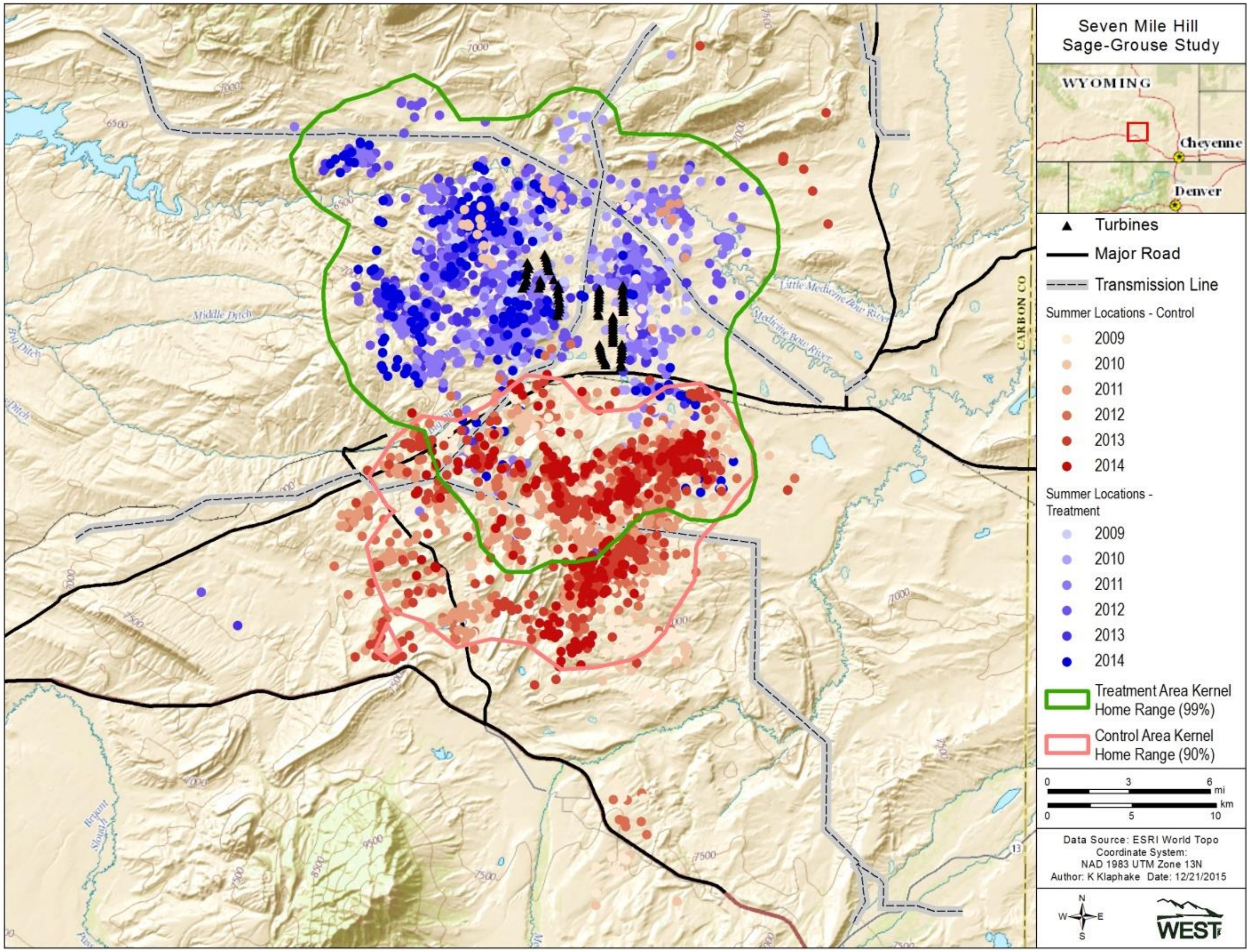


Figure 16. Sage-grouse summer locations observed at the control and treatment areas from 2009–2014 within the Seven Mile Hill study area, Carbon County, Wyoming, USA.

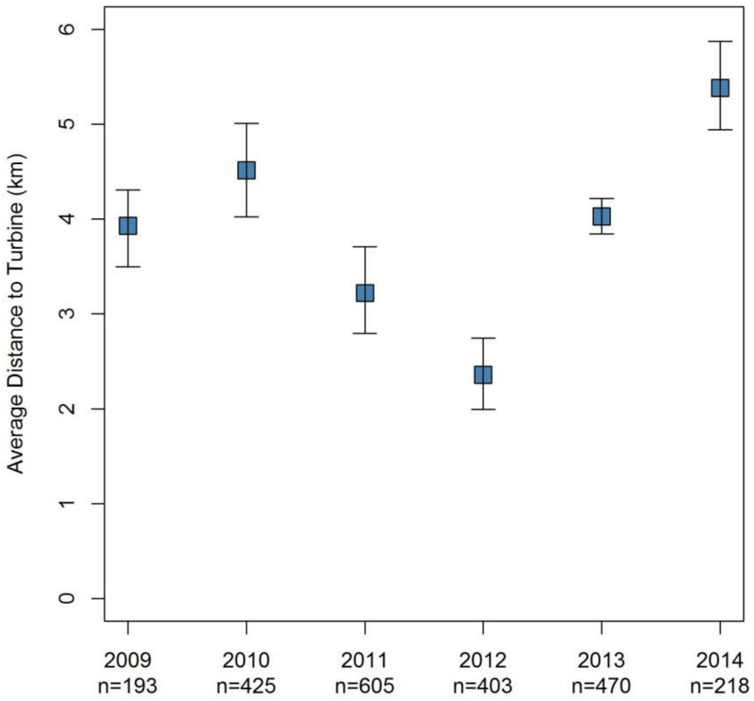


Figure 17. The average distance to turbines for greater sage-grouse summer locations observed within the treatment area at the Seven Mile Hill study area from 2009–2014, Carbon County, Wyoming, USA. Confidence levels (alpha = 0.90) were estimated using a bootstrapping technique that treated the individual as the sampling unit.

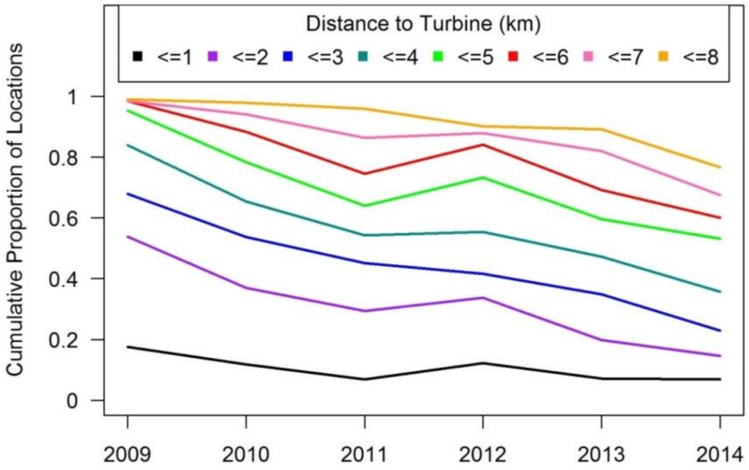


Figure 18. Cumulative proportion of sage-grouse summer locations relative to the Seven Mile Hill Wind Energy Facility turbines observed at the treatment study area within the Seven Mile Hill study area from 2009–2014, Carbon County, Wyoming, USA.

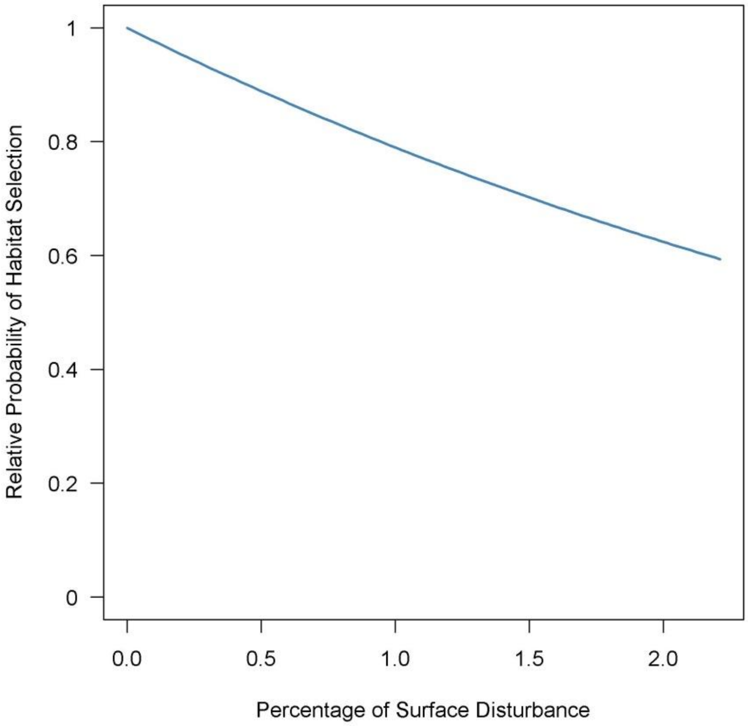


Figure 19. Marginal effects plot for percentage of SWEF surface disturbance within 1.2 km included in the top treatment summer RSF model at the Seven Mile Hill study area, Carbon County, Wyoming, USA. All other RSF model covariates were held at their median values.

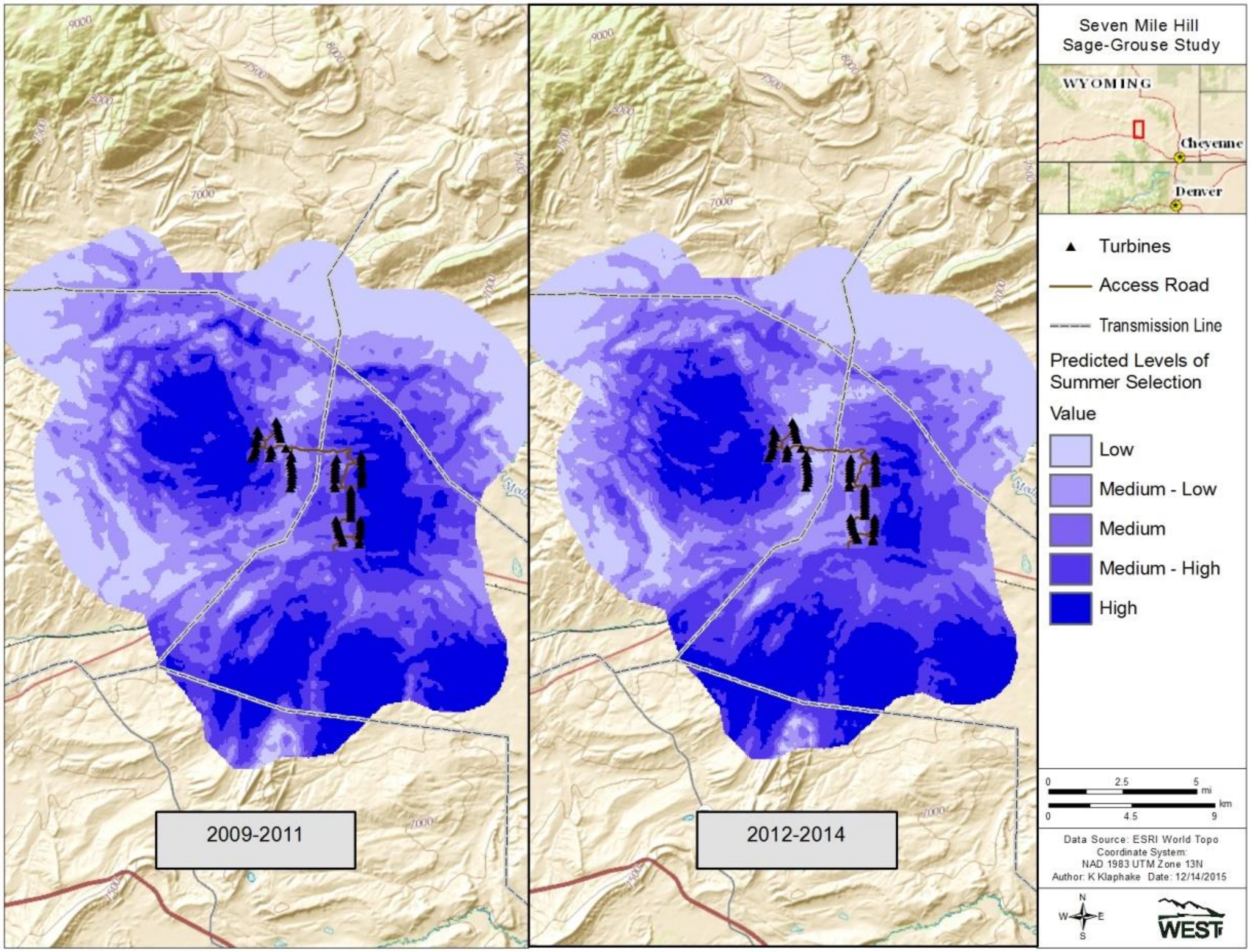
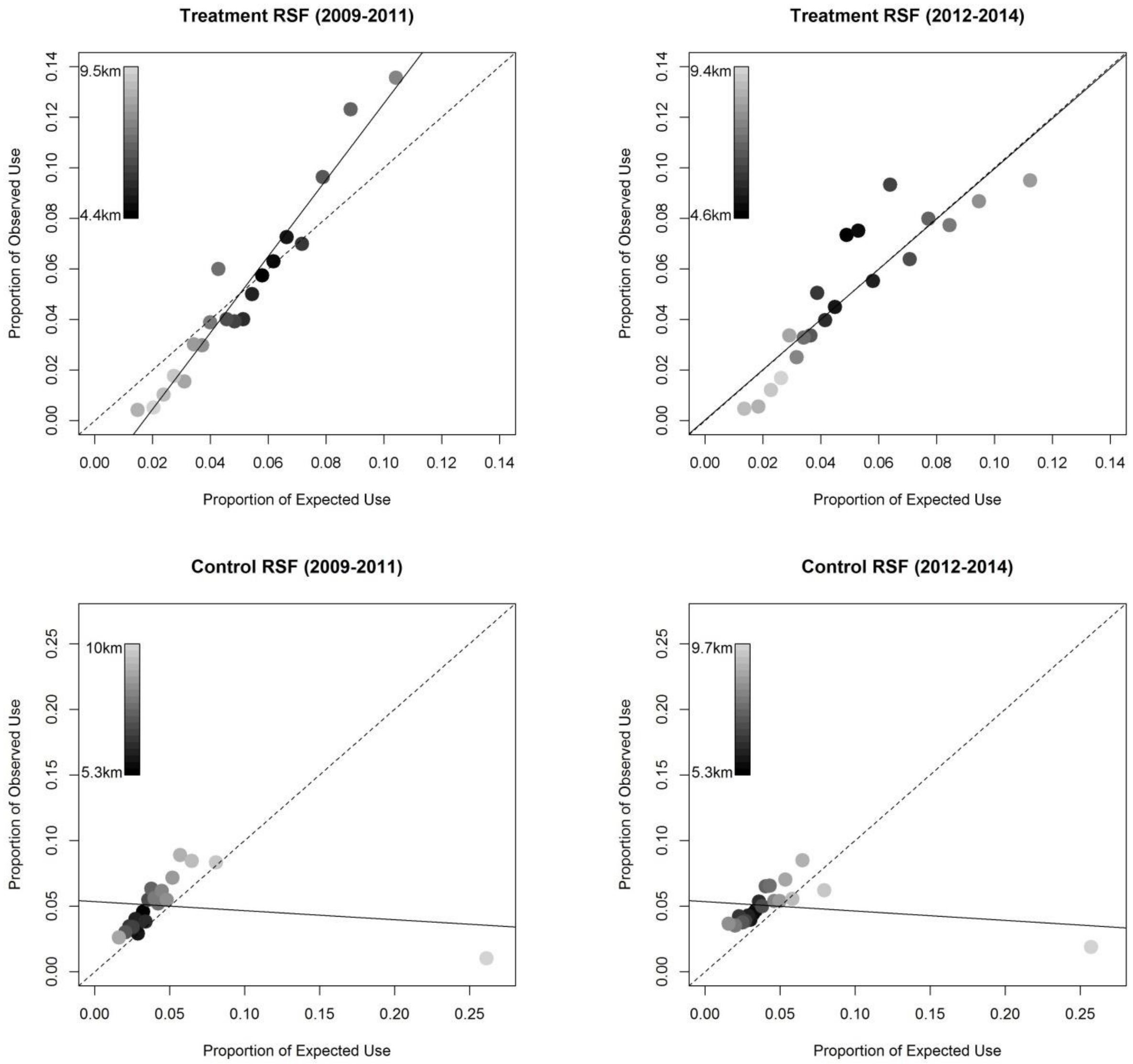


Figure 20. Predicted levels of sage-grouse summer habitat selection within the treatment study area at the Seven Mile Hill study area, Carbon County, Wyoming, USA. Predictions were made for study years 2009–2011 and 2012–2014 using a RSF model developed at the treatment study area.



Treatment RSF (2009-2011)

Treatment RSF (2012-2014)

Control RSF (2009-2011)

Control RSF (2012-2014)

Figure 21. Proportion of expected use compared to the proportion of observed use for sage-grouse brood-rearing locations within the treatment study area. Expected use was calculated using RSFs developed at the control and treatment area for covariate values observed during 2009–2011 and 2012–2014. The dashed line represents observed equals expected and the dark line represents the fitted regression line. Darker points represent smaller median distances to SWEF turbines for each bin value.

GREATER SAGE-GROUSE SURVIVAL

Sage-grouse declines are at least partially explained by lower annual survival of adult female sage-grouse (Taylor et al. 2012) and, in the case of oil and gas development, the impacts to female survival contribute to population-level declines (Holloran 2005). Another contributing factor to population level declines is the effect of oil and gas development on nest initiation and success (Lyon and Anderson 2003, Holloran 2005, Dzialak et al. 2011). Holloran (2005) found that sage-grouse nests were more successful in areas of lower natural gas well densities. Nests initiated in close proximity to a natural gas well that existed or was installed the previous year were at greater risk of failing than nests initiated farther from natural gas wells (Dzialak et al. 2011). In addition, nest initiation rates were reduced in areas of greater vehicle traffic associated with gas development (Lyon and Anderson 2003). Similar to nesting parameters, the impacts of 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 within 1 km of brood-rearing sites in southern Alberta, Canada. Brood survival began to decrease when 4% of the area within 1 km of brood locations was disturbed by natural gas development (Kirol et al. 2015). In addition, Holloran et al. (2010) found that chicks reared in natural gas fields had lower yearling survival rates compared to those reared outside of gas fields. These examples describe at least some degree of anthropogenic influence on sage-grouse fitness parameters, and suggest it is important to consider similar impacts to sage-grouse populations from wind energy development.

A purpose of our study was to investigate the effect of wind energy infrastructure on sage-grouse fitness parameters. Specifically, we investigated sage-grouse nest, brood, and female survival in relation to wind energy infrastructure and environmental features. Based on sage-grouse response to other anthropogenic features and one study relative to wind turbines (LeBeau et al. 2014), we hypothesized that sage-grouse nest, brood, and female survival decreased as proximity to infrastructure, specifically turbines, increased because these relationship have been documented for sage-grouse inhabiting areas with oil and gas development (Holloran 2005, Aldridge and Boyce 2007, Holloran et al. 2010, Doherty et al. 2011, Dzialak et al. 2011, and Kirol et al. 2015). Modeling the influence of wind energy infrastructure on sage-grouse population fitness parameters is critical to provide information for planning future wind energy developments in occupied sage-grouse habitats. Because the presence of the wind energy facility may act as an ecological trap to sage-grouse (Aldridge and Boyce 2007, Kirol et al. 2015), we incorporated the results of the habitat selection analyses into our survival analysis to identify potential impacts (e.g., ecological traps) on survival. The model development process for all survival analyses answered two basic questions: 1) How much of the variation in survival is due to natural process? and (2) After accounting for natural variability, does a variable representing proximity to SWEF explain a substantial portion of the remaining variation in survival?

Methods

We estimated Cox models to relate hazard of death to study covariates which in turn estimated survival within the control and treatment study areas. Cox models (Cox 1972) estimate the relationship between multiple explanatory variables and the instantaneous probability of death (called ‘hazard’; Therneau and Grambsch 2000). Cox models provide risk ratios or hazard ratios that can be used to compare the effects of different levels of a particular covariate of interest (e.g., distance to nearest turbine) on the risk of failure (e.g., nest, brood, or female death). In addition, survival can be estimated from Cox models by summing estimated hazard over a time period.

We used the Andersen-Gill (A-G) formulation of the Cox model to estimate brood and female survival (Anderson and Gill 1982). Under the A-G formulation, hazards are assumed proportional within time intervals where covariates are constant, rather than over the entire study period, as assumed by the non-AG formulation. The A-G formulation of the Cox model thus accommodates time-varying covariates by breaking the study period into multiple monitoring intervals (Therneau and Grambsch 2000, Johnson et al. 2004). The ability to utilize time-varying covariates was important because important habitat characteristics changed during the brood-rearing and female survival period.

Survival Parameters

We assessed nest survival for a 28-day incubation period during the 2009 through 2014 nesting seasons (incubation period lasts 25-29 days; Schroeder et al. 1999). We estimated nesting propensity as the number of females observed initiating a nesting attempt. We estimated apparent nest success for all first nest attempts. We use proportion tests to calculate 90% confidence intervals for nesting propensity and apparent nest success estimates. Nests observed within the SMH study area (treatment and control) were combined into one sample to model survival relative to the SWEF. Nests from second attempts following failed nest (so called re-nests) might not be independent of first nests, and were excluded from analyses. Assumed first nesting attempts that hatched in early July were considered re-nests because they were within the hatch date range of other re-nests and we assumed the first nesting attempt was likely missed by the observer. Failures occurred when a female abandoned its nest or its nest was destroyed by a predator. Abandoned nests thought to be caused by field observers were not included in the survival analysis because they were potentially caused by an anthropogenic source other than SWEF. We estimated the nest’s date of failure half way from the last known monitoring interval. The condition of the nest and eggs were evaluated to determine type of predator responsible (mammalian or avian). Nests that contained at least one egg at the end of the 28-day incubation period were considered successful and were censored (Nur et al. 2004).

We combined early and late brood-rearing locations from both years for survival modeling (Aldridge and Boyce 2007). Female sage-grouse successfully hatching at least one egg during the nesting season were monitored by triangulation or visually observing the female at least once each week from time of hatch to 35–37 days post hatch. We used five weekly monitoring intervals during the brooding period to assess brood survival. We assessed the presence of chicks with hens at least two times during the first 14 days of the brood-rearing period and one final time at the end of the brood-rearing period. The first monitoring interval began directly after a successful hatched nest and monitoring ended on the fifth interval 35–37 days post hatch. Events or failures occurred when no chicks were observed or the female did not elicit behaviors indicating she had chicks during any one of the checks. The observer performed an additional check in event chick status could not be determined during the previous check. We defined the interval containing the event to be the interval between the last monitoring visit where chick presence was confirmed and the first visit where chicks were absent. Due to our revisit schedule, events could have occurred during weeks 1, 2, and 5 when survival was assessed. The exact week of the event could not be determined if chicks were absent during week 5 (i.e., brood could have failed during weeks three or four). By assigning the event to week 5, we are slightly overestimating the overall magnitude of survival, but the relative difference in survival associated with different covariate values is unbiased because all broods were treated this way. Broods that were successful and survived the entire monitoring period to week 5 were censored (Nur et al. 2004). When a female was located twice in a single interval, the covariates value associated with interval was the average covariate value at the two locations.

Lastly, we modeled female sage-grouse survival from time of capture to 31 October during all study years. Female sage-grouse were monitored at least once each week during this period. Events or mortalities occurred only when we confirmed mortality via telemetry. We estimated the date of mortality by the condition of the carcass and last known monitoring interval. We attempted to categorize causes of mortality into avian or mammalian predators based on conditions of the carcass or location where radio transmitter was collected. We grouped weeks where multiple observations were recorded and corresponding covariates were averaged.

Model Development

We estimated daily and weekly Kaplan-Meier survival curves for each year to inspect raw survival during the study period (Kaplan and Meier 1958). If annual variation appeared to exist in the brood and female survival curves we added year as a strata to account for underlying factors that may affect brood and female survival that we could not measure (e.g., cyclical predator-prey interactions, weather).

We included random effects associated with all individuals captured at specific leks to the best approximating model to allow for random fluctuations in the baseline hazard for each individual (Liebezeit et al. 2009). Variation in survival could be related to the habitat associated with the lek at which a female bred (Connelly et al. 2000), and the application of the random effects attempted to capture this variability. Inclusion of the random effects mitigates natural spatial dependencies for individuals breeding on a particular lek if such dependencies exist (Liebezeit et al. 2009). Cox models containing random effects were calculated using R statistical coxme package (Therneau 2015). The utility of including random effects was assessed by an analysis of variance (ANOVA) and a Wald chi-squared test (Therneau 2015). We excluded the random effects term from the best approximating survival model if the ANOVA test indicated no significant differences between the random effects model and the proportional hazards model with only fixed effects. Random effects or frailties estimates associated with each lek of capture from the best approximating survival model were used to describe the unobserved random proportionality factor that modified the hazard function.

Model development was similar to the habitat selection analysis in that it involved a tiered approach. During the first tier, we identified the best measurement scale (buffer size) for each covariate by estimating univariate models and selecting the scale, which produced the lowest AIC_c (Table 1). Many of the covariates used to estimate the variability in survival were correlated with one another (Pearson's correlation coefficient $| r | \geq 0.6$), thus we constructed sets of uncorrelated environmental variables and considered all possible models within each set. We ranked all possible models from each set of uncorrelated environmental variables by AIC_c. We considered the highest-ranking environmental model to have explained the maximum amount of variation in survival due to natural processes within the SMH study area.

Once the best model containing natural covariates was constructed, we added covariates representing the SWEF to evaluate the effect of the SWEF on survival. We considered all possible interactions between covariates included in the environmental model and SWEF covariates. If covariates associated with the SWEF were influencing survival then we would expect model fit to improved considerably (i.e., $\Delta AIC_c > 2$) with the addition SWEF covariates. After identification of the best model, we added age of female (adult = 1, yearling = 0), the relative probability of habitat selection measured at a nest or observed location, and avian predator density to help explain any additional variability in survival within the study area.

We removed year as a strata and estimated survival relative to the most explanatory SWEF covariate to consider the potential differences among years and any potential time lags associated with survival. We added an indicator term for observations within years 2012-2014 and interacted the indicator term with the most explanatory SWEF covariate. If this interaction was significant at the 90% CI level, then the relationship between survival and the SWEF was different among the last 3 years compared to the first 3 years following development.

We calculated hazard ratios and 90% CIs for the hazard ratios to interpret the magnitude and influence of habitat variables on survival. Hazard ratios that included 1 within their 90% CI were considered statistically insignificant (alpha level = 0.10). We estimated CIs for each coefficient in the nest, brood, and female survival models using a bootstrapping technique that treated individuals as the sampling unit because some individuals had more than one nest or brood in multiple years or a female survived multiple summers during the study period. We randomly sampled with replacement individuals and estimated the top approximating survival model from the new sample of nests, broods, and summer locations (Manly et al. 2002, Manly 2007). We used 500 bootstrap iterations to identify the lower and upper confidence limits for each coefficient estimate. The value at the 5th percentile of the 500 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"; Manly 2006).

Nest Survival

Results

Nesting propensity, or the number of females observed initiating a nesting attempt, ranged from 46% (90% CI: 38–54%) in 2013 to 64% (90% CI: 54–73%) in 2009. Overall nesting propensity was 54% (90% CI: 50–57%) during the study period. Nest hatch dates ranged from 28 April (2014) to 28 June (2010) (mean = 25 May) for all assumed first nesting attempts. We observed 35 re-nest attempts within the study area during the study period ranging from one in 2012 to 15 in 2011. Eighteen of the 35 (51%) observed re-nests were successful. In addition, we removed two nests from the analysis after the female died early on in the nest initiation phase. No abandoned nests there thought to be caused by the observer. Overall apparent nest success for all first nest attempts was 62% (90% CI: 55–67%, *n* = 302) and ranged from 45% (90% CI: 34–56%, *n* = 58) in 2013 to 77% (90% CI: 69–85%, *n* = 75) in 2011. We observed 187 failed nesting attempts and we were able to attribute 105 (56%) and 29 (16%) of those failures to predation by mammals and avian predators, respectively. The median distance to turbines from all successful nests (5.84 km) was similar to all failed nesting attempts (6.29 km).

A total of 302 first nesting attempts were used in the Cox proportional hazard modeling (Figure 22). Nest survival did not fluctuate considerably among study areas and years (Figure 23). To explore yearly variations between study years, we included year and study area in the Cox model and nest survival ranged from 0.23 (2011) to 0.68 (2014) for nest from females captured at treatment area leks and from 0.21 (2014) to 0.54 (2013) for nests from females captured at control area leks (Figure 23). The overall, daily nest survival rate estimated from a Cox model that only included year for all sage-grouse nests ranged from 0.23 in 2011 to 0.56 in 2013.

The model that explained the natural variation in daily nest survival included SD of shrub, TPI, and distance to major roads and transmission lines (Figure 24). None of the SWEF infrastructure covariates improved the environmental model. The addition of female age, habitat selection values, or avian predation covariates did not improve the environmental model (age ΔAIC_c = 0.37; RSF values ΔAIC_c = 0.68; avian predation ΔAIC_c = 1.43). The addition of percentage of disturbance within 0.40 km was the most informative SWEF covariate when added to the environmental model; however, this additional covariate did not improve model fit and was not significant (ΔAIC_c = 1.31; β = 0.15; 90% CI: -0.12–0.43). The environmental model with lek of capture included as a random intercept term was not significantly different (*P* = 0.21) from the top environmental model that did not included the random term. In addition, the model that estimated the potential differences between study periods associated with nest survival relative to the turbines for nests between 2009-2011 and 2012-2014 was not significant, suggesting survival relative to percentage of disturbance within 0.40 km did not differ among these time periods (β = -0.003; 90% CI = -0.009 – 0.002). There was a transmission line that intersected the SWEF, and although these covariates were not correlated with each other, the effect of the SWEF may have been masked by the presence of the transmission line. However, after removing the transmission line from the environmental model and including the percentage of disturbance within 0.40 km, the model did not improve model fit and the SWEF infrastructure covariate was not significant (ΔAIC_c = 2.06; β = 0.19; 90% CI: -0.08 – 0.46).

The risk or the odds of a nest failing decreased in habitats located farther from transmission lines. For example, the risk of a nest failing decreased by 7.2% (90% CI: 0.6 – 14.1%) for every 1 km increase from transmission lines (Table 1). The risk of a nest failing decreased by 12.5% and 76.9% for every 1-unit increase in TPI and variation of shrub cover within 0.90 km of a nest location, respectively. In addition, the risk of a nest failing increased as distance to major roads increased up to 4.5 km before decreasing.

Discussion

The SWEF did not have a negative effect on sage-grouse nest survival within the study area over the six-year period. Nest survival did not differ between nests of females captured at treatment and control area leks over the study period. There was some evidence that survival was lower for nests from females captured at the treatment area in 2010, but survival of nests was generally higher in the treatment area than nests from females captured at control area leks from 2011 to 2014 (three to six years following development). As with most studies of nest success (Connelly et al. 2011), we did not detect any influence of the age of a female on nest survival. The presence of the SWEF could act as an ecological trap to nesting female sage-grouse where habitats in close proximity to the facility appear to be of high quality but in fact fitness associated with these habitats are low. We attempted to identify these source-sink habitats by including the relative probability of habitat selection associated with each nest, but we were unable to identify such habitats.

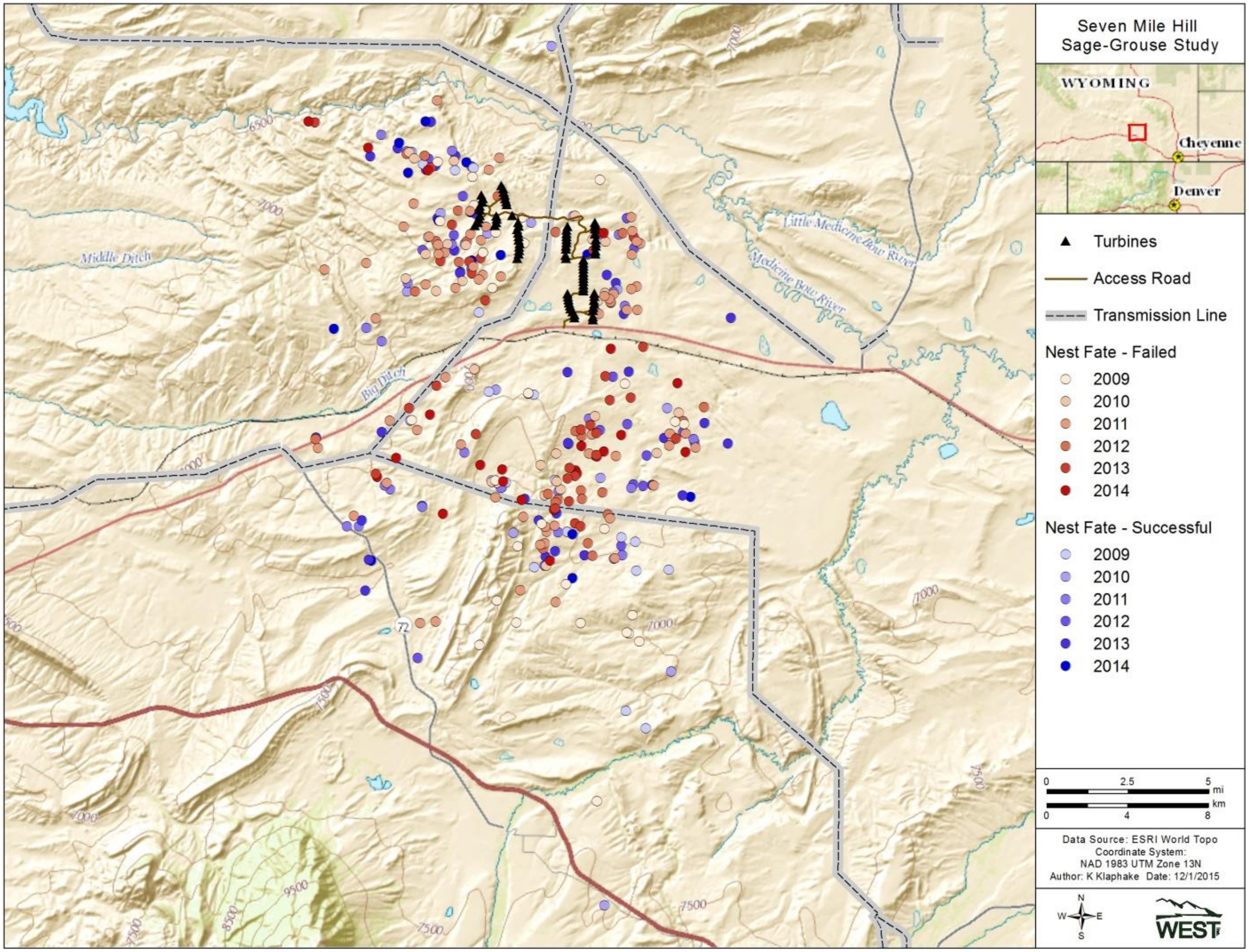
We investigated whether pooling all nests from females captured at treatment and control area leks may have obscured the influence of the SWEF on nest survival from females captured at treatment area leks. At this finer scale, the effects of the SWEF were restricted to females with nests that were captured at treatment area leks. We did not detect a significant turbine effect analyzing the restricted data set. In addition, variation in survival could be related to the habitat associated with the lek at which a female breeds (Connelly et al. 2000); however, inclusion of this random effect term did not improve model fit, suggesting the lek at which each individual sage-grouse bred did not influence nest survival within our study area.

Our results indicated there was substantial temporal variability in nest survival suggesting risk of failing was not proportionate during the study period. We corrected for non-proportional hazards by adding year as a stratum and subsequently included a separate baseline hazard for each year. Blomberg et al. (2012) concluded that sage-grouse abundance as determined by demography (i.e., survival and productivity) is influenced in large part by annual variation in resource availability, suggesting that covariates that were not considered could influence nest survival and there are variables that are difficult to control for when estimating the variability in survival. We attempted to control for this natural variability by developing a rigorous environmental model that would explain survival relative to environmental features. The effect of the SWEF on nest survival, if present, may be small relative to the natural variability within the study area making it difficult to detect any impact if present. Transmission lines are tall structures that are similar to wind turbines, and nest survival relative to each feature could be confounded, especially for nests located in close proximity to both features. We removed transmission lines from the model and added turbines to identify any potential confounding issues, but this post hoc analysis suggested that our results were not influenced by confounding effects between turbines and transmission lines.

Survival was related to habitat features and anthropogenic features that have existed on the landscape for > 10 years. Nest survival was highest for nests that were located farther from transmission lines and major roads and in habitats with higher variation in shrub cover and characteristic of ridges. Predation is the primary cause of nest failure (Hagen 2011) and the majority of nests appeared to have been destroyed by mammalian predators within our study area. Nests located in drainage features had lower survival rates than nests located on ridges. Drainage features may be used as travel corridors by mammalian predators resulting in a higher probability of detection for nests located within these features (Kuipers 2004). In addition, reduced survival in habitats characteristic of higher variation in shrub cover could be the result of an edge effect where nests become more susceptible to predation based on proximity to edge (Batary and Baldi 2004). Nest survival was lower in habitats closer to transmission lines and major roads; however, these estimates were only slightly significant, suggesting survival relative to these features may be variable among individual sage-grouse. The average distance to transmission line and major roads for all failed nests (2.90 km and 5.47 km) was lower than all successful nests (3.28 km and 6.02 km), respectively. We observed 35 and 12% of all nest failures within 2 km of a transmission line or a major road, respectively. The lack of pre-development data and concurrent mammalian predator surveys limit our ability to speculate as to the mechanism (e.g., edge effects) driving predator-prey interactions in the study area. Although the information relating sage-grouse to transmission lines is not conclusive (see Walters et al. 2014), Beck et al. (2006) reported that power line collisions accounted for 33% of juvenile (1st winter) mortality in low-elevation areas in Idaho. Walker et al. (2007) found negative effects on lek persistence of proximity to power lines and of proportion power line development within 6.4 km of leks in Wyoming; Gillan et al. (2013) estimated that sage-grouse constantly avoided habitats within 300 m of transmission lines in Idaho.

Table 5. Relative risks of sage-grouse nests for each covariate or risk factor included in the top model for the treatment and control study areas in Carbon County, Wyoming, USA, 2009–2014.

Covariate	Scale (km)	Estimate	Hazard Ratio [*exp*(Estimate)]	Hazard Ratio 90% CI	
				Lower	Upper
Shrub SD	90	-1.466	0.231	0.072	0.712
TPI	90	-0.133	0.875	0.784	0.985
Distance to major roads	NA	0.145	1.156	0.997	1.385
(Distance to major roads)^2	NA	-0.016	0.984	0.969	0.997
Distance to transmission line	NA	-0.074	0.928	0.859	0.994



Data Source: ESRI World Topo
Coordinate System:
NAD 1983 UTM Zone 13N
Author: K Klaphake Date: 12/1/2015

Figure 22. Sage-grouse nest fate from monitored individuals within the Seven Mile Hill Wind Energy Facility from 2009–2014, Carbon County, Wyoming, 2009–2014.

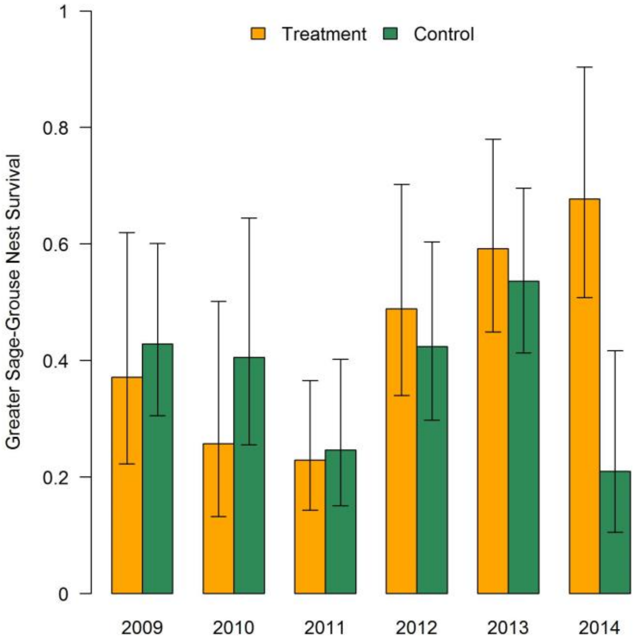


Figure 23. Mean sage-grouse nest survivorship and 90% confidence levels at each study area and year, calculated from the terminus of respective Kaplan- Meier curves within the Seven Mile Hill study area, Carbon County, Wyoming, 2009–2014.

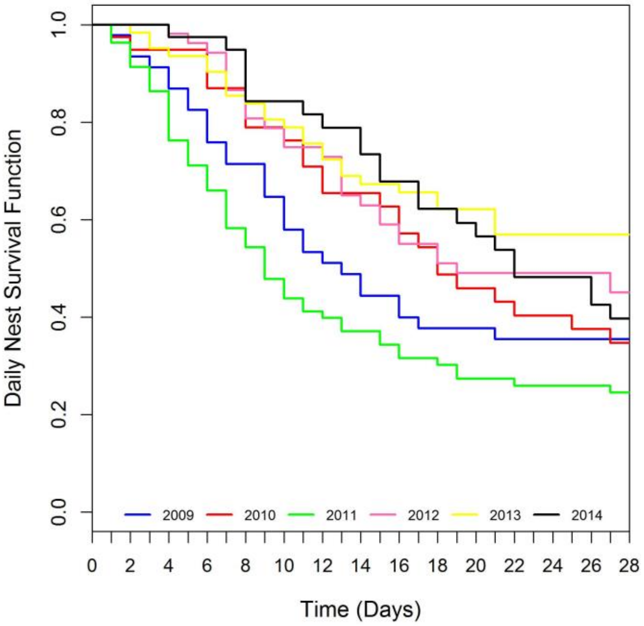


Figure 24. Sage-grouse nest survival predicted from the top proportional hazards model containing, TPI, SD shrub cover, and distance to transmission line and major road from 2009–2014 within the Seven Mile Hill Wind study area, Carbon County, Wyoming, USA.

Brood Survival

Results

A total of 123 females with broods were monitored during the brood-rearing period from 2009-2014 (treatment n = 59; control n = 64; Figure 25). We used 502 locations, 5 monitoring intervals, and 123 females with broods to model brood survival relative to the SWEF. Brood survival fluctuated among study areas and years (Figure 26). To explore yearly variations between study years, we included year and study area in the A-G mode. Brood survival was relatively high at both study areas, ranging from 0.46 (2009) to 0.68 (2015) for broods from females captured at treatment study area leks and from 0.54 (2010) to 1.00 (2014) for broods from females captured at control study area leks (Figure 26). The overall, weekly brood survival rate estimated from an A-G model that only included year for all sage-grouse broods ranged from 0.48 in 2010 to 0.75 in 2015.

The model that explained the natural variation in weekly brood survival included terrain ruggedness, TPI, distance to capture lek, major roads, and a quadratic effect of transmission line. The addition of female age, habitat selection values, or avian predation covariates did not improve the environmental model (age ΔAIC_c = 1.26; RSF values ΔAIC_c = 1.66; avian predation ΔAIC_c = 0.23). Distance to turbines was the most informative SWEF covariate when added to the environmental model; however, this additional covariate did not improve model fit nor was it significant (ΔAIC_c = 0.234; β = -0.069; 90% CI: -0.107 – 0.048). In addition, the model that estimated the potential differences between study periods in brood survival relative to the turbines for broods between 2009-2011 and 2012-2014 was not significant, suggesting survival relative to distance to turbines did not differ among these time periods (β = -0.92; 90% CI = -0.23 – 0.07). There was a transmission line that intersected the SWEF and although these covariates were not correlated with each other, the effect of the SWEF may be masked by the presence of the transmission line. The environmental model did not improve model fit after removing transmission line and including distance to turbine (ΔAIC_c = 2.29).

The model with lek of capture included as a random intercept term improved model fit (P = 0.039); however, the addition of turbines to the random lek intercept model did not improve model fit (P = 0.12). Five of the 10 leks targeted for capture had frailty effect estimates > 1 indicating broods from females captured at these leks had a higher risk of failure compared to leks with frailty effect estimates < 1 (Table 6). Of these 5 leks with greater frailty effects, one was located within the treatment study area. Two leks had significant frailty effects estimates, Old Carbon 31 (β = 0.893; 90% CI: 0.231 – 2.681) and Old Carbon 35 2 (β = -0.972; 90% CI: -2.621 – -0.448) located within the control study area. Females with broods captured at the Old Carbon 31 lek had 2 times the risk of failing compared to females with broods captured at other leks. The risk of failing decreased by 62.2% for females with broods captured at Old Carbon 35 2 (Table 6).

The risk or the odds of a brood failing decreased by 74.1% for every 100-unit increase in terrain ruggedness (90% CI: 31.5 – 96.2%; Table 7). The risk of a brood failing decreased by 43.7% for every 1-unit increase in TPI; however, this estimate was not significant suggesting some variability among individual broods. The risk of failing increased by 12.9% for every 1 km increase in distance to lek of capture (90% CI: 0.6 – 31.6%). In addition, the risk of failing increased by 21.0% for every 1 km increase in distance to major road (90% CI: 9.6 – 51.0%; Table 7). The risk of brood failure increased up to 4 km from a transmission line then declined.

Discussion

The SWEF did not have a negative effect on sage-grouse brood survival within the study area over the six-year period. Brood survival did not differ between females captured at treatment and control area leks over the study period. There is some evidence that survival was lower for broods from females captured at the treatment area in 2009 and 2012 but small sample sizes within both study areas make it difficult to detect any significant differences. We did not detect any influence of the age of a female on brood survival. The presence of the SWEF could act as an ecological trap to brood-rearing female sage-grouse where habitats in close proximity to the facility appear to be of high quality but in fact their fitness associated with these habitats are low. We attempted to identify these source-sink habitats by including the relative probability of habitat selection associated with each brood-rearing location in the survival models, but we were unable to identify such habitats.

We investigated whether pooling all broods from females captured at treatment and control area leks may have obscured the influence of the SWEF on brood survival from females captured at treatment area leks. At this finer scale, the effects of the SWEF were restricted to females with broods that were captured at treatment area leks and we did not detect a significant SWEF effect. In addition, we did not observe any brood failures during the 2014 brood-rearing period, likely due to small sample sizes at the control area.

Variation in brood survival could be related to the habitat associated with the lek at which a female breeds (Connelly et al. 2000). Adding capture lek as a random effect improved the environmental model, suggesting that the lek at which an individual breeds affects brood survival. None of the leks within the treatment area had significant frailty effects; however, two leks within the control area did have significant effects. Broods from females captured at the Old Carbon 35 2 lek had approximately half the risk of failing compared to broods from females captured at other leks. Conversely, the risk of failing for broods from females captured at the Old Carbon 31 lek had twice the risk of failing compared to broods from females captured at other leks. We attempted to account for the unobserved frailty and not underestimate the true hazard function associated with broods from females captured at different leks within the study area. There was a possibility that we did not include all possible covariates to explain the variability in brood survival and the effect of turbines on survival could be confounded by an unknown covariate. The lek at which a female breeds is highly influential as to which habitats they will likely use to nest and raise their broods (Holloran and Anderson 2005). Our brood survival model indicated that survival was higher closer to the lek of capture and there may be some features associated with these leks that we were unable to detect or include in our analysis. By including the frailty effects, we were able to determine if leks located within the treatment area had a higher frailty effect; however, we did not detect such an effect. Identifying the reasons why Old Carbon 35 2 had lower frailty effects and Old Carbon 31 had higher frailty effects compared to other leks is difficult because we are capturing the additional risk that cannot be identified by the model covariates. The percentage of broods failing over the study period was higher for females captured at Old Carbon 31 (62.5%; n = 8) compared to Old Carbon 35 2 (10.3%; n = 29).

Our results indicated there was substantial temporal variability in brood survival for all broods throughout the study period. In an attempt to control for this variability, we included year as a stratum and subsequently included a separate baseline hazard for each year. Blomberg et al. (2012) concluded that sage-grouse abundance as determined by demography (i.e., survival and productivity) is influenced in large part by annual variation in resource availability, suggesting that environmental covariates that were not considered could influence brood survival and are variables that are difficult to control for when estimating the variability in survival. In addition, the number of broods we could monitor was dependent on a female successfully hatching at least one egg during the nesting period. Low nest success years resulted in fewer broods to monitor indicating the importance of a separate baseline hazard for each year. We attempted to control for this natural variability by developing a rigorous environmental model that would explain survival relative to environmental features. The effect of the SWEF on brood survival, if present, may be small relative to the natural variability within the study area (e.g., lek of capture, weather patterns) which makes it difficult to detect any impact. Transmission lines are tall structures similar to wind turbines and brood survival relative to each of these features may have been confounded by each other, especially when they were located in close proximity. Distance to transmission line and turbines were not correlated covariates in our modeling procedure; however, we removed transmission lines from the model and added turbines to identify any potential confounding issues. We did not discover any confounding issues with turbines and transmission lines as they relate to brood survival.

Survival was related to habitat features and anthropogenic features that have existed on the landscape for > 10 years. Brood survival was highest for broods that were located in rugged habitats, closer to their lek of capture, closer to major roads, and farther from transmission lines. The quadratic effect on distance to transmission lines indicated lower survival within four km but beyond 4 km risk of failing decreased. It is supposed that predation is the primary cause of brood failure (Hagen 2011) but we were unable to determine the primary cause of death because individual broods were not marked. Broods that used habitats with flat topography appear to be at higher risk than broods that use more rugged habitats. In addition, broods that used habitats in close proximity to major roads had higher survival than broods located further from roads. Numerous predators prey on broods but there may be reduced predation by mammalian predators closer to roads due to the increased presence of human activity. Brood survival was lower in habitats within four km of transmission lines. The reason why survival is lower closer to transmission lines is unknown; however, avian predator density was higher closer to transmission lines and increased predator densities could influence brood survival (β= -0.010; 90% CI: -0.014 – -0.006; Dinkins et al. 2014).

Table 6. Frailty estimates associated with each lek of capture included in the best approximating brood survival model. Frailty estimates confidence intervals not containing 1 were considered statically significant (alpha = 0.10).

Lek Of Capture	Frailty Estimate (exp(β))	90% Lower	90% Upper
Treatment			
Commo 1	0.639	0.194	1.308
Hanna Draw East 1	0.862	0.302	1.573
Missouri John	1.143	0.552	2.211
Pine Draw	0.755	0.174	2.243
Control			
Kyle 63	1.675	0.814	9.506
*Old Carbon 31**	*2.442*	*1.26*	*14.606*
Old Carbon 32	0.922	0.389	1.721
Old Carbon 34	1.113	0.422	2.709
*Old Carbon 35 2**	*0.378*	*0.073*	*0.639*
Old Carbon 37	1.324	0.527	6.51

*Indicates a significant frailty effect at an alpha level 0.10.

Table 7. Relative risks of sage-grouse broods for each covariate or risk factor included in the top model for the treatment and control study areas in Carbon County, Wyoming, USA, 2009 - 2014.

Covariate	Scale (km)	Estimate	Hazard Ratio [*exp*(Estimate)]	Hazard Ratio 90% CI	
				Lower	Upper
Terrain Ruggedness	130	-1.350	0.259	0.038	0.685
TPI	90	-0.575	0.563	0.28	1.043
Distance to Capture Lek	NA	0.121	1.129	1.006	1.316
Distance to Major Roads	NA	0.191	1.21	1.096	1.51
Distance to Transmission line	NA	0.766	NA	NA	NA
Distance to Transmission line^2	NA	-0.105	NA	NA	NA

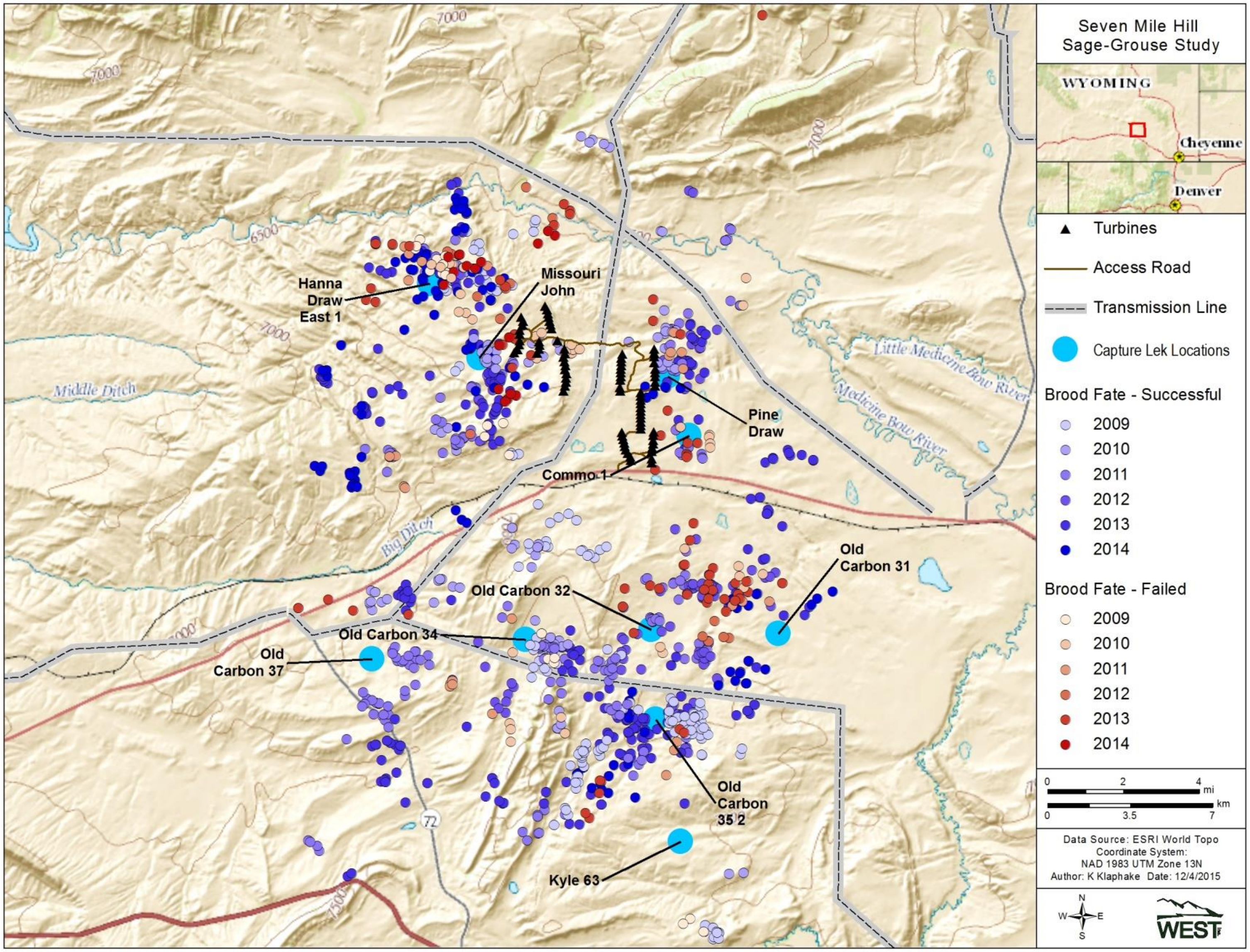


Figure 25. Greater sage-grouse brood fates from monitored individuals within the Seven Mile Hill Wind Energy Facility from 2009-2014, Wyoming.

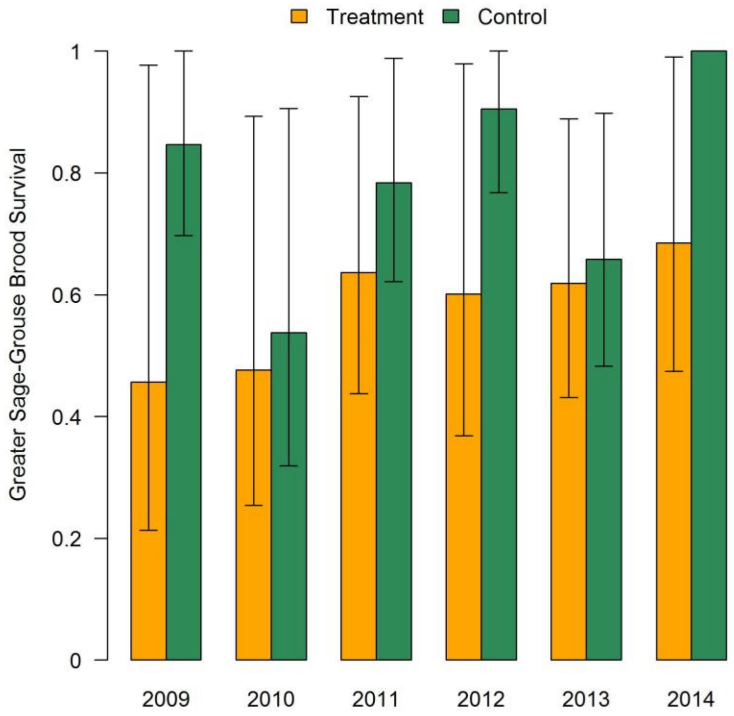


Figure 26. Mean sage-grouse brood-rearing survivorship and 90% confidence levels at each study area and year, calculated from the terminus of respective Kaplan-Meier curves within the Seven Mile Hill study area, Carbon County, Wyoming, USA, 2009–2014.

Summer Survival

Results

A total of 340 females were monitored during the summer period from 2009-2014 (treatment *n* = 156; control *n* = 184). We observed 189 mortalities during the study period (treatment mortalities = 85; control mortalities = 99; Figure 27). There were 14 instances where the radio transmitter possibly fell off the female and those individuals were censored at the time and location of their last known location. In addition, we removed five mortalities from the analysis that could be related to the stress of capture and handling because these mortalities were recorded within 10 days of capture. The majority of mortalities (56.1%) were recorded during the first 10 weeks of summer (April 1 through June 10). The cause of mortality for the majority of females was unknown (n=101; 55%). We attributed 24 (13%) and 57 (31%) mortalities to avian and mammalian predators, respectively. The control study area appeared to incur more avian predator mortalities than the treatment study area (treatment = 7; control = 17). Carcasses from two mortalities tested positive for West Nile virus. To explore yearly variations between study years, we included year and study area in the A-G mode and female summer survival fluctuated at both study areas during the study period ranging from 0.16 (2011) to 0.64 (2010) for females captured at treatment area leks and from 0.28 (2010) to 0.63 (2012) for females captured at control area leks (Figure 28). Overall, weekly summer survival rate estimated from an A-G model that only included year for all female sage-grouse during the summer ranged from 0.34 in 2009 to 0.52 in 2012.

We used 6,378 locations, 31 monitoring intervals, and 511 females to model female summer survival relative to the SWEF. Consequently, we included year as a strata in the A-G model to allow different baseline hazards each year. The model that explained the highest amount of natural variation in weekly female survival included bare ground, herbaceous cover, CTI, terrain ruggedness, TPI, and distance to capture lek. The addition of female age, habitat selection values, or avian predation covariates did not improve the natural variation model (age ΔAIC_c = 1.20; RSF values ΔAIC_c = 1.84; avian predation ΔAIC_c = 1.74). The addition of percentage of SWEF disturbance within 0.81 km to the environmental model improved model fit (ΔAIC_c = 1.57) and was significant (β = -0.71; 90% CI: -1.63 – -0.14; Table 8, Figure 28) implying higher survival in areas with higher disturbance, at least up to the maximum observed in this study. The addition of lek of capture included as a random intercept term in the top model was not significantly different from the model that excluded the random intercept term (P = 0.94). In addition, the covariate that estimated the potential differences between study periods associated with female survival relative to the percentage of disturbance for females between 2009-2011 and 2012-2014 was not significant, suggesting survival relative to percentage of disturbance did not differ among these time periods (β = -0.09; 90% CI = -1.47 – 1.30).

The risk or the odds of a female mortality increased by 1.6% for every 1% increase in bare ground (90% CI: 0.40 – 3.3%; Table 1). The risk of female mortality decreased by 14.5% and 3.9% for every 1-unit increase in CTI and TPI, respectively (Table 8). The risk of female mortality increased by 26.5% for every 100-unit increase in terrain ruggedness (90% CI: 6.9 – 60%). The risk of mortality increased by 8.4% for every 1-km increase in distance to lek of capture (90% CI: 4.4 – 12.4%; Table 8). In addition, the risk of mortality decreased by 50.8% for every 1% increase in percentage of SWEF infrastructure within 810 m of a location (90% CI: 13.0 – 80.5%: Table 8, Figure 29). The risk of female mortality increased as herbaceous cover increased; however, this relationship was variable among individuals.

Discussion

The SWEF did not have a negative effect on female sage-grouse summer survival within the study area over the six-year period. Survival did not differ between females captured at treatment and control area leks over the study period based on a univariate study area A-G model. There is some evidence that survival was lower for females captured at the treatment area in 2011 and 2012 compared to females captured at the control area. We did not detect any influence of the age of a female on survival. The presence of the SWEF could act as an ecological trap to female sage-grouse where habitats appear to be of high quality but in fact their fitness associated with these habitats are low. We attempted to identify these source-sink habitats by including the relative probability of habitat selection for each location, but we were unable to identify such habitats using the A-G model.

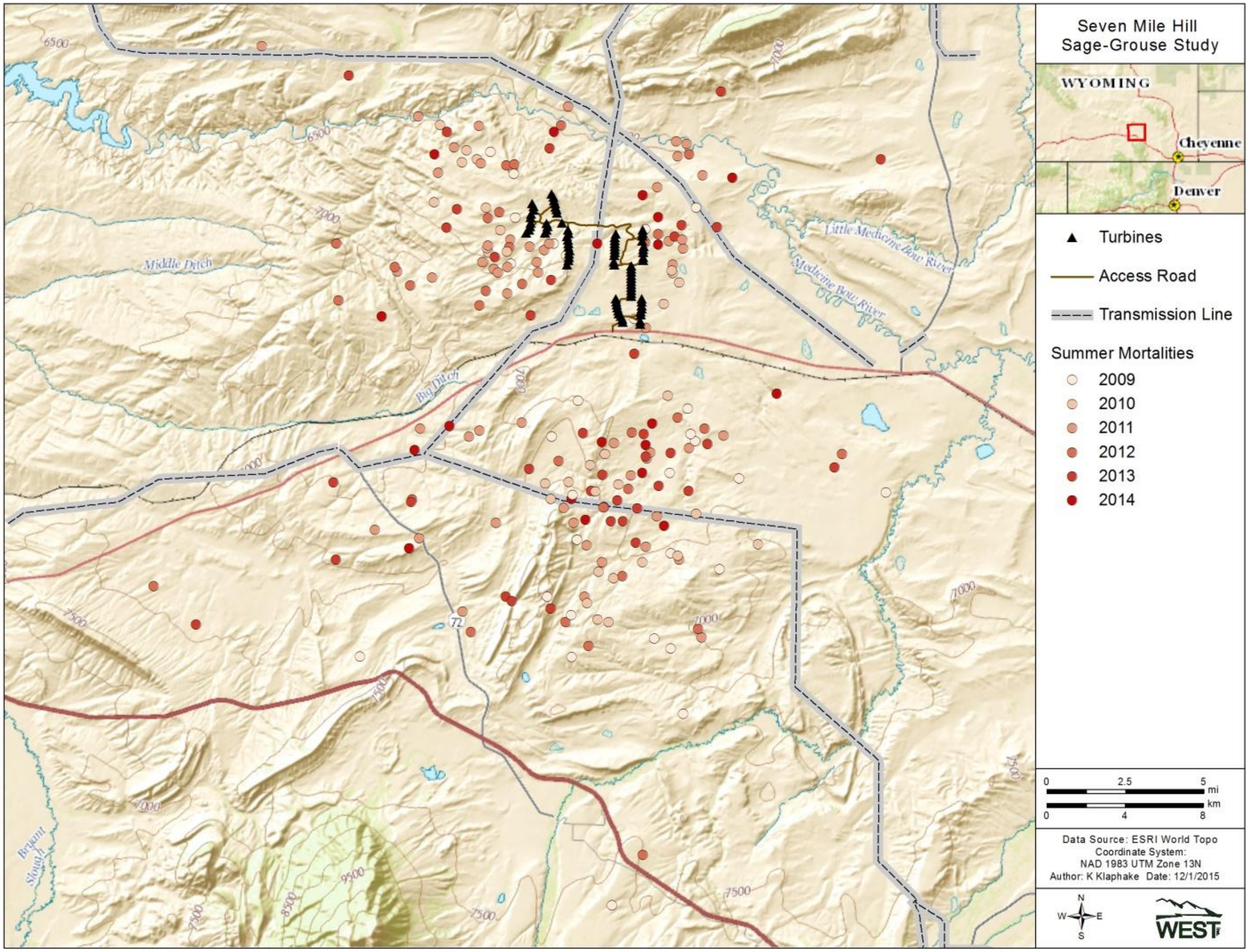
We investigated whether pooling all mortalities from females captured at treatment and control area leks may have obscured the influence of the SWEF on survival. We did this by eliminating females captured at the control area and re-estimating the A-G model. In this data set, the effects of the SWEF were similar to those observed in the larger dataset. In addition, variation in survival could be related to the habitat associated with the lek at which a female breeds (Connelly et al. 2000); however, inclusion of this random effect term did not improve model fit, suggesting the selection of habitat relative to lek location did not influence female survival within our study area.

Our results indicated there was substantial temporal variability in sage-grouse survival. Annual variability in summer survival was relatively high throughout the study period. In an attempt to control this variability, we included year as a stratum and subsequently estimated separate baseline hazards for each year. The unexplained annual variation in survival allowed in our model could be a product of a number of factors, Blomberg et al. (2012) concluded that sage-grouse abundance as determined by demography (i.e., survival and productivity) is influenced in large part by annual variation in resource availability, suggesting that environmental covariates that were not considered. In addition to unexplained annual variability, we controlled for as much natural variability as possible by developing a rigorous “natural” model containing only non-anthropogenic factors.

Survival was related to habitat features and the percentage of disturbance within the SWEF. Female survival was highest for females that used habitats characteristic of lower bare ground, ridges, wet areas, closer to their lek of capture, and more percentage of disturbance. Avian predation is the primary cause of female mortality (Hagen 2011) and, similar to brood survival, females that used habitats with flat topography appeared to be at higher risk of predation than females that used more rugged habitats. In addition, females that use habitats with more bare ground may be more susceptible to avian predators due to reduced cover in these areas. After controlling for annual and natural variability, we observed a large positive effect of the SWEF on female survival when the percentage of disturbance within 0.81 km of the bird increased from 0% to 3%. A similar relationship was observed in a study of greater prairie-chickens in Kansas (Winder et al. 2014a). In that study, females had higher survival near the wind energy facility post development compared to pre development (Winder et al. 2014a). The effect of the SWEF is large relative to the natural variability within the SMH study area but this effect does not exist beyond 0.81 km of the SWEF suggesting the effect is small relative to the larger SMH study area. Regardless, we did not detect a negative effect of the SWEF on female survival. We can only speculate as to why adult survival was higher closer to the facility but it is likely related to lower densities of avian predators. Avian predator density was lower closer to turbines within the SMH study area (β= 0.014; 90% CI: 0.014 – 0.015).

Table 8. Relative risk of female sage-grouse summer mortality for each covariate or risk factor included in the top model for the treatment and control study areas in Carbon County, Wyoming, USA, 2009–2014.

Covariate	Scale (km)	Estimate	Hazard Ratio [*exp*(Estimate)]	Hazard Ratio 90% CI Lower	Hazard Ratio 90% CI Upper
Bare ground	0.81	0.016	1.016	1.004	1.033
CTI	0.37	-0.157	0.855	0.731	1.000
Herbaceous	0.37	0.104	1.110	0.999	1.261
Terrain Ruggedness	0.13	0.235	1.265	1.069	1.600
TPI	0.37	-0.040	0.961	0.932	0.985
Distance to Capture Lek	NA	0.081	1.084	1.044	1.124
Percentage of Disturbance	0.81	-0.709	0.492	0.195	0.870



Data Source: ESRI World Topo
Coordinate System:
NAD 1983 UTM Zone 13N
Author: K Klaphake Date: 12/1/2015

Figure 27. Sage-grouse summer mortalities from monitored individuals within the Seven Mile Hill Wind study area from 2009–2014, Carbon County, Wyoming, USA.

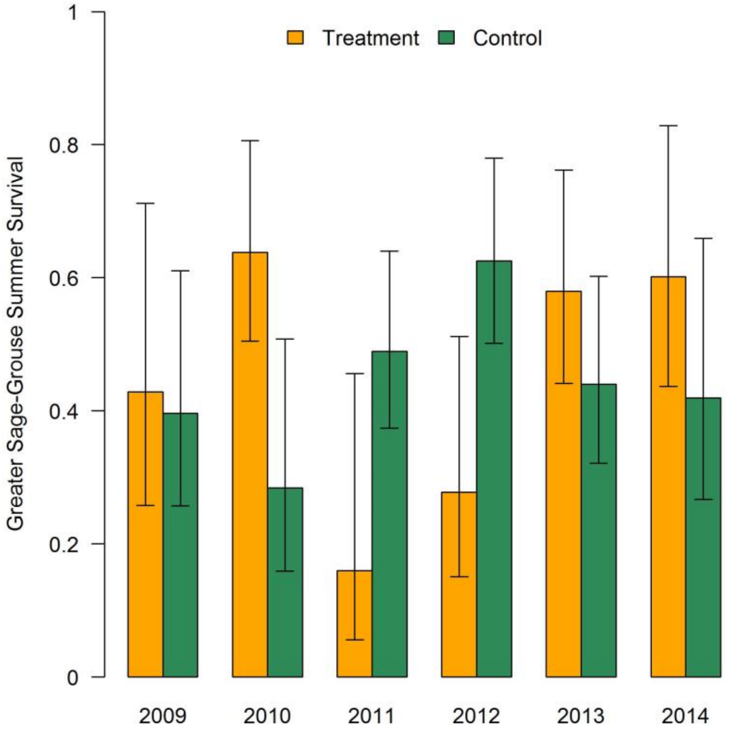


Figure 28. Mean sage-grouse female summer survivorship and 90% confidence levels at each study area and year, calculated from the terminus of respective Kaplan-Meier curves within the Seven Mile Hill study area, Carbon County, Wyoming, USA, 2009–2014.

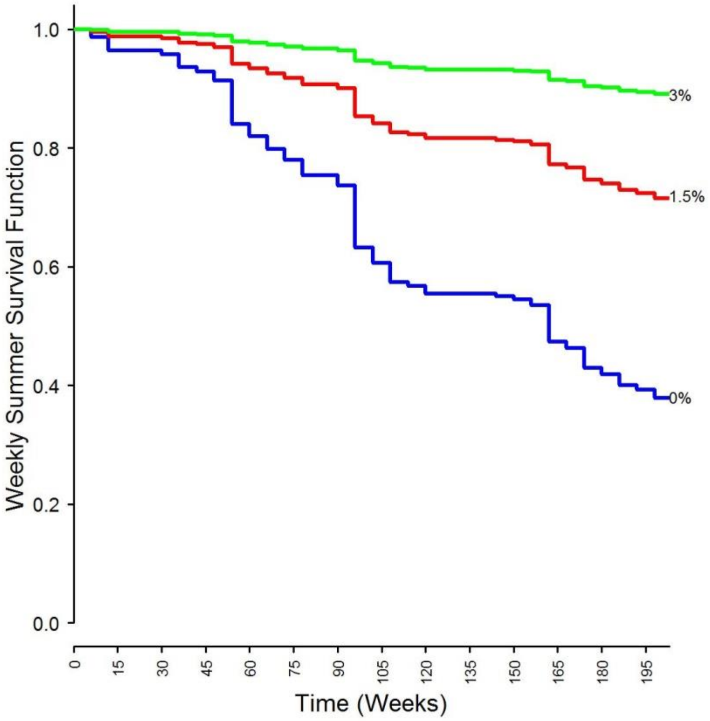


Figure 29. Sage-grouse female summer survival predicted from the top proportional hazards model containing, bare ground, CTI, herbaceous cover, terrain ruggedness, TPI, distance to capture lek, and percentage of disturbance in 2012 within the Seven Mile Hill study area, Carbon County, Wyoming, USA. All covariates where held at their median values except percentage of disturbance.

CONCLUSION

Our study is the first to estimate the impacts of wind energy development on sage-grouse habitat selection patterns and fitness parameters. Female sage-grouse selection of seasonal habitats was variable relative to the infrastructure associated with SWEF, but fitness parameters appear not to be negatively influenced by the infrastructure. LeBeau et al. (2014) detected a negative effect of wind energy development on nest and brood survival 2-years following development. The additional years of data collection and use of different covariates likely provided a better explanation of the variation in survival relative to wind turbines long term compared to the short term. The long term patterns similar to this study was similar to greater prairie-chicken response to a wind energy facility (McNew et al. 2014, Winder et al. 2014a) but opposite of sage-grouse response to oil and gas development (e.g., Dzialak et al. 2011, Holloran 2005). Ideally, we would have preconstruction data to identify changes in the population and decipher mechanisms in sage-grouse response to infrastructure; however, we are confident that if such impacts to habitat selection and survival did occur then we would have been able to detect these changes over the 6-year study period.

Selected nest locations were not influenced by the presence of the SWEF. Nor did we detect any potential time lags in nest site selection associated with the presence of the facility, suggesting that juveniles recruited to the population over the study period continued to select habitats in close proximity to the facility. The variability in daily nest survival was influenced more by habitat features than the presence of the SWEF.

We did detect a negative impact of the SWEF on sage-grouse brood-rearing habitat. It appears that once sage-grouse have completed their nesting cycle they move broods farther from turbines to habitats that are more suitable and this affect was more prominent during the fourth through sixth year post-development, suggesting a lag in this response (Table 9). This movement away from turbines and associated lag response is likely avoidance of infrastructure and/or the activity associated with the wind development and not an issue of unsuitable habitat in close proximity to turbines. Females nesting in close proximity to the facility during initial stages of our study suggest that the avoidance measure may have been confounded by poor brooding habitat. Similar to nest survival, we did not detect any influence of the SWEF on brood-rearing survival. Like many environmental studies, it is difficult to consider all possible variables that could influence survival. Interestingly, brood survival had frailty effects associated with the lek at which the female was captured, suggesting that survival was related to the lek at which the female bred; this is likely a proxy for some environmental features that we were unable to model. However, if the covariates that we used did not adequately assess brood survival relative to the SWEF then we would have expected significant frailty effects associated with treatment area leks and we did not detect such influences suggesting the covariates we considered adequately assessed survival relative to the turbines.

Similar to the brood-rearing habitat selection, we detected a negative impact on sage-grouse habitat selection during the summer period where female sage-grouse avoided habitats within 1.2 km of the SWEF (Table 9). It is unclear if the avoidance of the facility was related to the SWEF or the available suitable summer habitat that was located in close proximity to the SWEF. Summer female survival was higher in habitats that were closer to the SWEF. This relationship was similar to greater prairie-chickens in Kansas (Winder et al. 2014a). The unique ecosystems that each species occupies make it difficult to draw comparisons between the two; however, avian predators are the main source of predation in both species. We did estimate lower avian predator density in habitats closer to the SWEF relative to habitats farther away which might suggest that avian predators were avoiding the wind turbines therefore reducing risk of predation. This interaction could be similar in greater prairie-chicken ecosystems. Nonetheless, we did not detect a negative impact on female survival relative to the SWEF.

The lack of other studies investigating impacts from wind energy development to sage-grouse habitat selection and survival limits our ability to make inferences about the cumulative impacts of wind energy development on sage-grouse, but we were able to describe some of the impacts that wind energy developments may have on sage-grouse populations. Although we attempted to account for possible confounding factors, there is the chance that we did not detect important interactions between environmental features and habitat selection and survival patterns. The lack of preconstruction data may have produced some uncertainty in the interpretation of our results. Nonetheless, our results demonstrate that wind energy development has some implications to sage-grouse populations during the brood-rearing and summer periods.

Table 9. Summary of the impacts from the Seven Mile Hill Wind Energy Facility during different annual sage-grouse cycles within the Seven Mile Hill study area, Carbon County, Wyoming, USA, 2009–2014.

	Annual Period					
SWEF Impact	**Nesting Period**		**Brood-rearing**		**Summer**	
	Selection	**Survival**	**Selection**	**Survival**	**Selection**	**Survival**
Positive						<0.81 km
Negative			<1.20 km		<1.20 km	
None	X	X		X		

MANAGEMENT IMPLICATIONS

Future wind energy developments should consider the potential impacts of wind energy development on sage-grouse habitat selection patterns and survival parameters. Current US Fish and Wildlife Service Land-Based Wind Energy Guidelines do not have specific prairie grouse avoidance measures for wind energy developers but the Guidelines do suggest impacts will be similar to those from other anthropogenic structures (USFWS 2012). Based on our analysis, we recommend facilities that are similar in size that occupy similar habitats as our study be placed 1.20 km from any occupied nesting, brood-rearing, or summer habitats. We recommend that future research consider predator-prey mechanisms by estimating avian and mammalian predator densities to understand better the impacts of wind energy development on sage-grouse fitness parameters and to develop appropriate mitigation measures. We also recommend that future studies investigating fitness consequences and habitat selection patterns of sage-grouse relative to wind energy development consider habitat covariates not currently available in GIS including (e.g., residual grass cover and height, forb cover and diversity etc.)

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