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Pronghorn Winter Resource Selection Before and After Wind Energy Development in South-Central Wyoming☆

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ABSTRACT

Few studies have evaluated the response of ungulate populations to wind energy development. Recent demand for wind-generated electricity coupled with a tendency for wind-energy facilities to be sited within suitable pronghorn *(Antilocapra americana)* winter range make this a critical issue for conservation of this icon of western North America. We evaluated pronghorn response to wind energy development at the winter home range scale, as well as within individual winter home ranges using data collected from 47 adult female pronghorn equipped with Global Positioning System transmitters. At both scales, we developed separate resource selection models for pronghorn before (winter 2010) and after (winters 2011 and 2012) development of the Dunlap Ranch wind energy facility in south-central Wyoming to evaluate the potential impacts of wind energy infrastructure on pronghorn winter resource selection. In general, pronghorn winter resource selection was correlated with greater sagebrush (*Artemisia* spp.) cover, lower snow depth, and lower slopes before and after wind energy development at both scales. At the larger scale, pronghorn selected home ranges closer to wind turbines during all winters. Within home ranges, pronghorn selected areas closer to future locations of wind turbines at Dunlap Ranch during 2010 before turbine erection. However, we found evidence that pronghorn avoided wind turbines in winters after development within their winter home ranges. This relationship was most evident during winter 2011, which coincided with the most severe winter of our study. Long-term replicated studies will be necessary to make inferences for pronghorn populations exposed to wind energy development in different environments and scales than we evaluated. Nonetheless, in the absence of additional information on how ungulates respond to wind energy development, our finding that pronghorn avoided wind turbines within their winter home ranges has important implications for future wind development projects, particularly in areas known to fulfill important seasonal requirements of pronghorn populations.

Introduction

Recent research assessing the impacts of energy development to ungulate populations has focused largely on impacts of oil and natural gas to these iconic species. Ungulate responses to oil and natural gas development include avoidance and altered movement patterns in developed areas (Bradshaw et al. 1997; Dyer et al. 2001; Sawyer et al. 2006, 2009; Webb et al. 2011; Beckmann et al. 2012; Buchanan et al. 2014). Avoidance behaviors are commonly associated with human presence and development intensity (Sawyer et al. 2013; Buchanan et al. 2014) and appear to persist long after development is implemented (Sawyer et al. 2017). Research on pronghorn *(Antilocapra americana)* has documented mixed responses to oil and gas development, which may be partially explained by the season when pronghorn were studied, the physical footprint of development, and the scale of selection that was addressed. At broader scales, pronghorn did not avoid oil and gas infrastructure during summer in North Dakota or south-central Wyoming (Christie et al. 2017; Reinking et al. 2019), but pronghorn exposed to oil and gas development on winter range in western Wyoming abandoned highly disturbed areas, presumably resulting in indirect loss of high-quality habitats (Beckmann et al. 2012). At a finer scale, avoidance of oil and natural gas wells occurred during daytime in winter, but avoidance was not evident during summer (Reinking et al. 2019). Displacement from areas developed for

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energy extraction could be an energetically costly behavior for pronghorn, particularly during winter when ungulates are already experiencing stressful environmental conditions (Parker et al. 1984; Reinking et al. 2018).

Pronghorn winter range is characterized by extreme environmental conditions where individuals are challenged with negotiating energy intake and reducing overall energy costs (Schwartz et al. 1977; Parker et al. 1984; Byers 1997). Pronghorn have higher energy demands relative to body mass than most domestic ruminants, resulting in higher stress during periods of food deprivation (Wesley et al. 1970). Pronghorn may respond by increasing time spent foraging during winter months (Byers 1997); however, high mortality rates are still common during this time (Martinka 1967; Barrett 1982; O'Gara 2004; Pyrah 1987). Malnutrition is a proximate cause of winter mortality and reduced pregnancy rates for many ungulate species (Barrett 1982; Boertje and Garder 1998; Pyrah 1987; Bishop et al. 2005), and exposure to higher levels of human activity and associated energy development may exacerbate fitness costs when individuals are on winter range. Consequently, to understand potential impacts of energy development on wintering pronghorn, it is crucial to consider how different types of energy development may affect pronghorn populations.

It remains largely unknown whether impacts to ungulates in general, and pronghorn in particular, associated with oil and gas development are comparable with other forms of development (Northrup and Wittemyer 2013). A recent goal set by the Department of Energy to promote expansion of wind energy in the United States has resulted in a rapidly growing industry with wind energy projected to contribute 6.3% of total US electricity generation by 2018 (EIA 2017). Wyoming currently ranks 15th in installations and has the most undeveloped wind energy potential (AWEA 2017). Differences in physical infrastructure between wind energy (wind turbines, transmission lines, meteorological towers, substations, etc.) and oil and gas development (well pads, compressor stations, pumps, pipelines, etc.) are readily apparent. Both types of development result in increased human activity during construction and production phases, albeit likely at greater rates with oil and gas development. Oil and gas and wind energy developments have similar infrastructure densities and direct habitat loss per unit area (Jones and Pejchar 2013; Jones et al. 2015), yet the potential impacts to ungulate behavior in response to wind infrastructure remains unclear.

Along with the recent expansion of wind energy development comes uncertainty related to the response of pronghorn populations in the face of this rapidly growing industry (AWEA 2017; EIA 2017). Development of the Dunlap Ranch wind energy facility on pronghorn winter range in south-central Wyoming created a unique opportunity to study the relationship between coexisting wind energy development and wintering ungulates before and after development. Our research at the Dunlap Ranch facility did not detect a relationship between pronghorn winter mortality risk and exposure to wind energy development (Taylor et al. 2016). However, deleterious effects to ungulates resulting from energy development are often difficult to detect (Beckman et al. 2016; Reinking et al. 2018), particularly if developed areas are being avoided. We evaluated pronghorn winter resource selection of seasonal home ranges (second-order resource selection; Johnson 1980) and within seasonal home ranges (third-order resource selection; Johnson 1980) before and after the construction of Dunlap Ranch turbines. We built alternative models to test our predictions that wind energy development influenced pronghorn winter resource selection at each scale. Specifically, we predicted that pronghorn would not avoid the Dunlap Ranch wind facility when selecting home ranges, but avoidance would be evident within home ranges during winters after construction of turbines. Our predictions mirror previous research on multiscale resource selection of pronghorn exposed to energy development (Christie et al. 2017; Reinking et al. 2019).

Methods

Study Area

We evaluated winter pronghorn resource selection near the Dunlap Ranch wind energy facility located ~12 km north of Medicine Bow in Carbon County, Wyoming (42.01°N, 106.19°W). Our study focused on the Dunlap Ranch (36.5-km^2) sited within a larger area that included 1 452 km^2 of rangelands delineated by the Wyoming Game and Fish Department as crucial winter range for pronghorn (22.6% Bureau of Land Management, 7.6% state of Wyoming, and 69.7% private ownership). The region was marked by flats, high hills, and low mountains with Wyoming big sagebrush (*Artemisia tridentata wyomingensis* Nutt.), the most prevalent cover type. Other shrub species included black sagebrush (*Artemisia nova* A. Nelson), Gardner's saltbush (*Atriplex gardneri* [Moq.] D. Dietr.), greasewood (*Sarcobatus vermiculatus* [Hook.] Torr.), and rabbitbrush (*Chrysothamnus* Nutt. and *Ericameria nauseosa* [rubber rabbitbrush; Pall. ex Pursh] G.L. Nesom & Baird). Understory herbaceous vegetation was primarily composed of short- and mid-statured grasses including bluebunch wheatgrass (*Pseudoroegneria spicata* [Pursh] Á. Löve), prairie junegrass (*Koeleria macrantha* [Ledeb.] Schult.), Sandberg bluegrass (*Poa secunda* J presl), and western wheatgrass (*Pascopyrum smithii* [Rydb.] Á. Löve), as well as a minor forb component including scarlet globemallow (*Sphaeralcea coccinea* [Nutt.] Rydb.). Elevation ranged from 2 000 to 2 530 m. Total snowfall for winter 2010 (November 2009–April 2010) was 136.6 cm, for winter 2010–2011 (November 2010–April 2011) it was 212.6 cm, and for winter 2011–2012 (November 2011–April 2012) it was 90.7 cm. Average minimum and maximum temperatures for winter 2010 were −10.2°C and 3.2°C, for winter 2010–2011 they were −8.8°C and 2.9°C, and for winter 2011–2012 they were −9.7°C and 5.4°C (HPRCC 2012).

PacifiCorp owned and operated the Dunlap Ranch wind energy facility, which included the construction of 74 General Electric Company 1.5-MW wind turbine generators (119 m tall), 28.3 km of access roads, 3 meteorological towers (79.9 m tall), an onsite 34.5/230-kV substation, and onsite maintenance buildings from September 2009 to September 2010. Turbines were erected from May to September 2010 (PacifiCorp Energy 2009). Daily traffic within the Dunlap Ranch ranged from 0.9 to 3.6 with an average of 1.8 (95% confidence interval [CI]: 1.4–2.3) traffic events per day during 6 December 2011–30 January 2012 and 1.9 (95% CI: 1.5–2.4) during 29 February–27 April 2012 (Taylor 2014). Highway 487 extends north and south through the center of the Dunlap Ranch and pronghorn crucial winter range.

Capture and Monitoring

We captured 35 and 17 adult female pronghorn using helicopter net gunning (Leading Edge Aviation, Lewiston, ID) in early January 2010 and December 2011, respectively. Capture and handling protocols were approved by the University of Wyoming Institutional Animal Care and Use Committee (protocol 01012010) and Wyoming Game and Fish Department (Chapter 33 Permit ID 742). Each captured animal was fitted with an Advanced Telemetry System (Isanti, MN 55040) store-on-board Global Positioning System neck collar (model G2110B) in or within the general vicinity of Dunlap Ranch. Mean distance of captured individuals to the Dunlap Ranch was 4.1 km (range: 0.0–10.9 km). Collars were programmed to fix locations every 7 h from 16 November to 15 May. Locations were collected from January 2010 through May 2012. Aerial flights were conducted four times annually to record the status of study animals and to aid in our recovery of collars transmitting a mortality signal to download location data collected up to time of death. A release mechanism installed on each collar caused remaining collars to deploy in late April 2012, and they were recovered by late May 2012.

Resource Selection Study Design and Analysis

We acquired spatial layers for big sagebrush and shrub height from remotely sensed products (Homer et al. 2012). Because sagebrush is the primary component of winter diets for many pronghorn populations in northern latitudes (Bayless 1969; Beale and Smith 1970; Mitchell and Smoliak 1971), we focused on sagebrush as the primary land cover category. We acquired daily snow depth measurements for the study area from meteorological distribution and snow-evolution models (750-m resolution; Liston and Elder 2006a, 2006b), which have been validated within the western United States and internationally (Hiemstra et al. 2002; Liston and Hiemstra 2011). We summarized daily snow depth measurements to obtain an average snow depth at each pixel during each winter (1 January to 31 March; described later). We used a 10-m digital elevation map (DEM; US Geological Survey 2011) to calculate slope. We summarized big sagebrush cover, shrub height, and slope within 980 m (median step length between 7-h fixes) around each use or available location for analysis. We digitized fences using the 2009 National Agriculture Imagery Program (km/km^2; US Department of Agriculture 2010) to develop a spatial layer for fence density (km/km^2). We calculated the Euclidean distance to state, county, US highways, or interstate roads (O'Donnell et al. 2014), excluding minor two-track roads because they received little use during winter. To represent the impact of wind energy development on pronghorn, we used wind turbine layers to calculate distance to nearest wind turbine.

We estimated seasonal resource selection functions (RSFs) for pronghorn on the basis of winter home ranges (second-order resource selection; Johnson 1980) and within winter home ranges (third-order resource selection; Johnson 1980) during winters 2010, 2011, and 2012 separately with binomial generalized mixed models with package lme4 in R (Bates et al. 2015). We used individual as a random intercept term in all models to account for individual variation and an unbalanced design (Gillies et al. 2006). Individuals who had 80 or more locations during each winter were included in analyses. We defined winter as 1 January to 31 March because individuals were on winter range during this time in all winters (Taylor 2014), and this time interval standardized the winter period for individuals in all models. To evaluate seasonal home range resource selection, we generated 95% fixed kernels around all pronghorn locations during each winter (default bivariate kernel smoothing parameter; Worton 1989) to delineate study population home ranges. We randomly selected 25 available locations per pronghorn use location within the population home range to compare with locations used within individual seasonal home ranges. To characterize available habitats within seasonal home ranges, we generated 95% fixed kernels for each pronghorn during each winter. For within–winter home range analyses, we only included individuals with 95% fixed kernels that overlapped a 5-km buffer around Dunlap Ranch infrastructure to ensure that use of the Dunlap Ranch was actually available to the individual. We randomly generated 25 times the number of used locations for each pronghorn within each pronghorn's 95% fixed kernel to represent available habitats. Pronghorn relocations used in analyses were consistent across the two scales. At both scales, we ensured that the number of available locations adequately characterized the distribution of used locations (Northrup et al. 2013).

Table 1
Models used to assess winter home range (second order) pronghorn resource selection relative to wind energy development in Carbon County, Wyoming, for winters 2010, 2011, and 2012. *K* is the number of parameters in the model (including individual as a random intercept term), *ΔAICc* is the change in Akaike's information criterion adjusted for small sample sizes from the top model, and w_i is the Akaike weight.

Model	K	ΔAIC	w_i
Winter 2010			
Env Covs[1] + Road + FenceDens + Wind	9	0.00	1.00
Env Covs[1] + Wind	7	86.24	0.00
Env Covs[1] + Road + FenceDens	8	17 172.53	0.00
Env Covs[1]	6	19 660.68	0.00
NULL	2	39 079.05	0.00
Env Covs[1,2] + Road + FenceDens + Wind[3]	10	—	—
Env Covs[1,2] + Wind[3]	8	—	—
Winter 2011			
Env Covs[1] + Road + FenceDens + Wind[3]	10	0.00	1.00
Env Covs[1] + Road + FenceDens +Wind	9	25.04	0.00
Env Covs[1] + Wind[3]	8	974.75	0.00
Env Covs[1] + Wind	7	979.69	0.00
Env Covs[1] + Road + FenceDens	8	1 813.32	0.00
Env Covs[1]	6	2 475.37	0.00
NULL	2	4 045.90	0.00
Winter 2012			
Env Covs[1] + Road + FenceDens + Wind[3]	10	0.00	1.00
Env Covs[1] + Road + FenceDens + Wind	9	465.03	0.00
Env Covs[1] + Wind[3]	8	1 545.01	0.00
Env Covs[1] + Wind	7	2 128.17	0.00
Env Covs[1] + Road + FenceDens	8	8 629.58	0.00
Env Covs[1]	6	10 798.64	0.00
NULL	2	13 673.57	0.00

[1] Env Covs include BigSage, ShrubH, Slope, and Snow.
[2] Failed to converge.
[3] Model included quadratic term for wind.

We created 5 candidate models for each scale (home range and within home range) and period of development (before [2010] and after [2011 and 2012]) to test our prediction that wind energy infrastructure influenced pronghorn winter resource selection. The null model included only the random intercept term. Environmental models contained sagebrush cover, shrub height, slope, and snow depth and represented the hypothesis that anthropogenic features did not influence winter resource selection. Anthropogenic models included distance to road and fence density in addition to variables in the environmental model. The anthropogenic models represented the hypothesis that environmental and anthropogenic factors, except wind infrastructure, influenced winter resource selection. Wind infrastructure models included variables in the environmental model, plus distance to wind turbines to test whether wind infrastructure improved model fit. Full models included covariates in environmental models plus distance to road, fence density, and distance to wind turbines to test the hypothesis that environmental and anthropogenic factors, including wind infrastructure, influenced pronghorn winter resource selection. We also assessed variants of wind infrastructure and full models by including a quadratic term for distance to wind infrastructure to assess potential nonlinear relationships between pronghorn winter resource selection and distance to wind infrastructure. We used the future location of wind turbines in 2010 wind infrastructure and full models. We scaled and centered variables before modeling to ensure model convergence (Becker et al. 1988). We ranked candidate models with Akaike information criterion adjusted for small sample sizes (AICc; Burnham and Anderson 2002) and considered candidate models within 4 AICc points from the top model to be competitive. If the distance to wind infrastructure covariate was included in the competitive model set, we evaluated whether wind infrastructure was predictive of pronghorn resource selection if the variable coefficient had a 95% confidence interval excluding zero.

Table 2
Variable coefficients, standard errors (SE), and 95% confidence intervals (Lower [LCL] and Upper [UCL]) from winter home range (second order) pronghorn resource selection relative to wind energy infrastructure in Carbon County, Wyoming, for winters 2010–2012.

Parameter	Winter 2010				Winter 2011				Winter 2012			
	Estimate	SE	LCL	UCL	Estimate	SE	LCL	UCL	Estimate	SE	LCL	UCL
Snow	−0.596	0.065	−0.723	−0.469	−0.862	0.022	−0.906	−0.819	−0.943	0.026	−0.995	−0.892
Bigsage	0.601	0.033	0.536	0.666	0.086	0.022	0.043	0.129	0.068	0.028	0.013	0.124
ShrubH	−0.476	0.055	−0.584	−0.369	0.091	0.027	0.038	0.145	0.119	0.031	0.058	0.179
Slope	−1.514	0.038	−1.589	−1.438	−0.416	0.023	−0.460	−0.372	0.064	0.019	0.027	0.101
Road	−0.138	0.022	−0.180	−0.096	0.413	0.013	0.388	0.439	−0.801	0.023	−0.845	−0.756
Fencedens	−0.112	0.015	−0.142	−0.083	−0.007[1]	0.015	−0.036	0.023	−0.114	0.015	−0.144	−0.085
Wind	−6.338	0.110	−6.553	−6.123	−0.910	0.022	−0.954	−0.866	−1.400	0.020	−1.439	−1.361
Wind[2]	—	—	—	—	0.102	0.019	0.064	0.140	0.462	0.021	0.421	0.503

[1] Parameter estimate with 95% confidence intervals including zero.
[2] Quadratic term.

Results

We used data from 47 individual females during winters 2010–2012 (average locations per pronghorn-winter = 272; range: 100–312). Due to mortalities and timing of capture events, not all individuals from initial captures were used in all analyses. For home range analyses, we used locations from 32 individuals in winter 2010 (8 812 locations), 22 individuals in winter 2011 (5 214 locations), and 23 individuals in winter 2012 (6 340 locations). We used 27 individuals in winter 2010 (7 399 locations), 12 individuals in winter 2011 (2 858 locations), and 19 individuals in winter 2012 (5 174 locations) for within–home range analyses.

Home Range Resource Selection

Full models were the most supported models explaining pronghorn selection of home ranges during all winters, and no other models were competitive with these models (w_i = 1.00; Table 1). During all winters, pronghorn resource selection was correlated with greater big sagebrush cover, less snow depth, and lower fence densities (Table 2). Selection for shrub height, slope, and distance to roads varied across winters. The relative probability of selection by pronghorn at the home range scale was greatest closer to Dunlap Ranch wind turbines during all years (Fig. 1A). We found the most support for a linear effect of distance to wind turbines in winter 2010, but models including a quadratic term for distance to wind turbines had the most support during winters 2011 and 2012.

Within–Home Range Resource Selection

Full models were the most supported models explaining within–home range pronghorn resource selection during all winters (Table 3). During all winters, pronghorn resource selection was correlated with greater big sagebrush cover, lower shrub height, and lower slopes. However, 95% confidence intervals around parameter estimates for shrub height overlapped zero in winters 2011 and 2012 (Table 4). Pronghorn selected areas closer to roads and with lower fence density during winters 2010 and 2012; however, pronghorn selected areas farther from roads with higher fence density during 2011. The relative probability of selection by pronghorn at the within–home range scale was greatest closer to Dunlap Ranch wind turbines during winter 2010 (see Fig. 1B). During winters 2011 and 2012 following construction of turbines, the relative probability of selection was greatest farther from Dunlap Ranch turbines (see Fig. 1B).

Discussion

We evaluated multiscale winter resource selection by pronghorn before and after wind energy development in central Wyoming. During all winters at home range and within–home range scales, full models received the most support indicating that pronghorn resource selection was correlated with

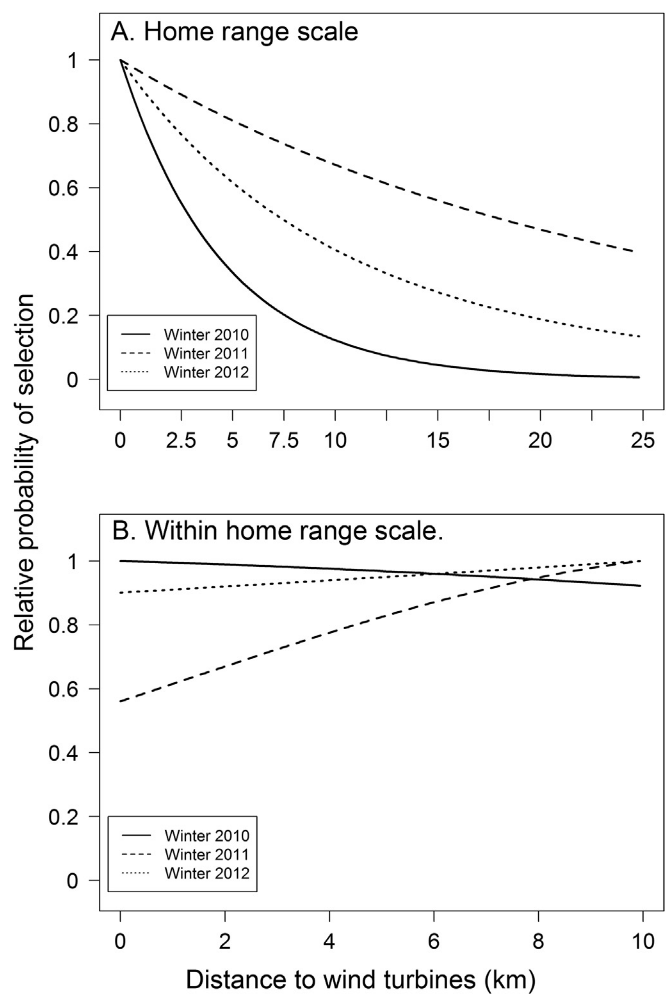

Figure 1. Relative probability of pronghorn winter resource selection at winter home range (**A**) and within winter home range (**B**) scales as a function of distance to wind turbines during winters before (2010) and after (2011 and 2012) development of the Dunlap Ranch wind energy facility, Carbon County, Wyoming. Relative probability of selection was standardized for each scale and winter by dividing predicted values by their maximum.

Table 3
Models used to assess within winter–home range (third-order) pronghorn resource selection relative to wind energy development in Carbon County, Wyoming, for winters 2010, 2011, and 2012. *K* is the number of parameters in the model (including individual as a random intercept term), *ΔAICc* is the change in Akaike's information criterion adjusted for small sample sizes from the top model, and w_i is the Akaike weight.

Model	K	ΔAIC	w_i
Winter 2010			
Env Covs[1] + Road + FenceDens + Wind[2]	10	0.00	1.00
Env Covs[1] + Road + FenceDens + Wind	9	15.40	0.00
Env Covs[1] + Road + FenceDens	8	47.28	0.00
Env Covs[1] + Wind[2]	8	96.94	0.00
Env Covs[1] + Wind	7	124.31	0.00
Env Covs[1]	6	150.32	0.00
NULL	2	989.99	0.00
Winter 2011			
Env Covs[1] + Road + FenceDens + Wind[2]	10	0.00	1.00
Env Covs[1] + Road + FenceDens + Wind	9	130.05	0.00
Env Covs[1] + Road + FenceDens	8	153.86	0.00
Env Covs[1] + Wind[2]	8	361.05	0.00
Env Covs[1] + Wind	7	450.03	0.00
Env Covs[1]	6	518.04	0.00
NULL	2	1 135.92	0.00
Winter 2012			
Env Covs[1] + Road + FenceDens + Wind	9	0.00	0.73
Env Covs[1] + Road + FenceDens + Wind[2]	10	1.98	0.27
Env Covs[1] + Road + FenceDens	8	31.65	0.00
Env Covs[1] + Wind	7	117.56	0.00
Env Covs[1] + Wind[2]	8	118.77	0.00
Env Covs[1]	6	169.80	0.00
NULL	2	1 169.78	0.00

[1] Env Covs include BigSage, ShrubH, Slope, and Snow.
[2] Model included quadratic term for wind.

environmental and anthropogenic factors, including wind energy infrastructure. Our model predictions suggested that, at both scales, winter resource selection within the vicinity of the Dunlap Ranch was relatively high. Wind turbines were sited within designated pronghorn winter range in habitats considered high value to pronghorn. The Dunlap Ranch had greater average sagebrush cover, less snow depth, and lower slopes compared with the rest of the study area. Pronghorn selected areas with greater sagebrush cover and lower snow depths at both scales during all winters. Pronghorn also selected lower slopes at both scales during all winter, with the exception of winter 2012 at the home range scale. At the home range scale, pronghorn selected areas closer to wind turbines during all winters. At the finer, within–home range scale, pronghorn selected areas closer to the Dunlap Ranch during 2010 before turbine erection. However, we found evidence that pronghorn avoided wind turbines in winters following development and that relationship was most pronounced during winter 2011.

Our finding that pronghorn resource selection was related to distance to wind turbines in winters after development was similar to previous research documenting avoidance by ungulates during operational phases of oil and gas development (Bradshaw et al. 1997; Dyer et al. 2001; Webb et al. 2011; Beckmann et al. 2012; Sawyer et al. 2017). While our results also indicated that pronghorn were selecting areas farther from turbines during winter 2012, relative probability of selection was still rather high in areas closer to turbines during this time. Several explanations for this phenomenon are possible. For instance, Helldin et al. (2012) suggested that ungulates temporarily avoid wind energy facilities during construction phases, which may partially explain the differences we found during winters after development. However, to our knowledge, there is little empirical evidence to support this claim. Sawyer et al. (2017) found persistent avoidance of oil and gas development by mule deer *(Odocoileous hemionus)* over a 15-yr period of energy development, with no evidence to suggest that mule deer habituated to this form of development. In the same energy field, mule deer avoided all types of well pads on winter range, but avoidance of well pads was greater at those experiencing higher traffic volumes (Sawyer et al. 2009). Indeed, ungulate avoidance of oil and gas development is most often associated with increased traffic and human presence (Dyer et al. 2001; Sawyer et al. 2009; Beckmann et al. 2012; Buchanan et al. 2014), which tends to be greater in oil and gas fields compared with wind energy production facilities (Jones and Pejchar 2013). Average daily traffic on the Dunlap Ranch during operation was lower than that at liquid gathering system (LGS; 3.3–3.6 detections/d) well sites, non-LGS wells (7.3–8.4 detections/d), and active drilling pads (85.3–112.4 detections/d) within the Pinedale Anticline Project Area in southwestern Wyoming (Sawyer et al. 2009). Traffic levels on the Dunlap Ranch do not act as a direct comparison to oil and gas field traffic levels; however, they provide a general assessment for understanding potential differences in wind energy and oil and gas traffic levels. Paired with less overall length of access roads and a smaller physical development footprint, lower traffic rates observed within the Dunlap Ranch may explain why avoidance was less pronounced during winter 2012 compared with winter 2011.

Our findings were inherently confounded by yearly environmental variation driving pronghorn resource selection. Increased snow depth during more severe winters, such as winter 2011, may have altered the availability of resources and led to greater avoidance of wind turbines during winter 2011. In support, pronghorn selected lower fence densities at both scales, except during winter 2011. This was unexpected because fences may contribute to direct mortalities and create barriers by restricting access to important winter habitats used during harsh weather events (Oakley and Riddle 1974; O'Gara 2004; Harrington and Conover 2006). Thus, it is conceivable that snow was a primary

Table 4
Variable coefficients, standard errors (SE), and 95% confidence intervals (LCL and UCL) from within–winter home range (third-order) pronghorn resource selection relative to wind energy infrastructure in Carbon County, Wyoming, for winters 2010–2012.

Parameter	Winter 2010				Winter 2011				Winter 2012			
	Estimate	SE	LCL	UCL	Estimate	SE	LCL	UCL	Estimate	SE	LCL	UCL
Snow	−0.220	0.028	−0.274	−0.166	−0.285	0.027	−0.337	−0.232	−0.443	0.021	−0.484	−0.402
Bigsage	0.242	0.017	0.208	0.277	0.333	0.033	0.269	0.398	0.148	0.021	0.107	0.189
ShrubH	−0.061	0.020	−0.101	−0.022	−0.060[1]	0.037	−0.134	0.013	−0.039[1]	0.026	−0.090	0.011
Slope	−0.184	0.017	−0.217	−0.150	−0.504	0.031	−0.564	−0.444	−0.390	0.021	−0.432	−0.349
Road	−0.139	0.014	−0.167	−0.112	0.568	0.031	0.507	0.629	−0.138	0.018	−0.174	−0.102
Fencedens	−0.042	0.012	−0.066	−0.017	0.121	0.019	0.083	0.159	−0.131	0.015	−0.161	−0.102
Wind	−0.141	0.029	−0.198	−0.084	0.174	0.057	0.063	0.286	0.116	0.020	0.077	0.155
Wind[2]	−0.042	0.011	−0.063	−0.020	−0.399	0.036	−0.469	−0.329	—	—	—	—

[1] Paramerter estimate with 95% confidence intervals including zero.
[2] Quadratic term.

driver of pronghorn habitat selection during winter 2011. Previous studies have documented pronghorn selection for less snow accumulation during winter (Beckmann et al. 2012). Selection for lower snow depth is a beneficial survival strategy considering pronghorn mortality rates are elevated during winters with increased snow accumulation (Barrett 1982; Pyrah 1987; Reinking et al. 2018). Longer-term studies will be necessary to determine how environmental stochasticity influences pronghorn response to wind energy development.

Our study was a before-after quasiexperiment, limiting inferences to those detected from temporal change alone (Green 1979). Unfortunately, we did not have a control site or spatial replication to perform a more rigorous quasiexperiment, such as a before-after, control-impact (BACI) analytical approach (Green 1979). Insufficient time and spatial replication are common weaknesses for studies that have evaluated impacts of development on ungulates (Hebblewhite 2011). In addition, our results cannot be directly applied to pronghorn populations exposed to larger wind energy projects, during other seasons, or where traffic levels and environmental conditions at wind energy facilities differ from the Dunlap Ranch. However, our results do support our prediction that pronghorn would avoid wind turbines within their home ranges during winters after construction. This finding has implications in consideration of developing other areas with wintering pronghorn or other ungulates. Pronghorn likely tolerate some levels of human activities, and mortality risk studies have not found a relationship between energy development and female mortality (Taylor et al. 2016; Reinking et al. 2018). Differences in individual condition was also not apparent with pronghorn exposed to natural gas development (Beckmann et al. 2016). However, detecting demographic change in ungulate populations exposed to energy development is inherently difficult (Polfus and Krausman 2012). Special consideration must be given when contemplating further development to landscapes used by pronghorn during winter as they are already predisposed to high mortality rates on winter range due to harsh environmental conditions and high energy demands (Wesley et al. 1970; Byers 1977; Parker et al. 1984; Schwartz et al. 1997).

Implications

Our results indicated that pronghorn avoided wind turbines within their winter home ranges during the operational phase after development. Avoidance of wind turbines by pronghorn has important implications for future development, particularly in areas known to fulfill important seasonal requirements for pronghorn populations. Although we detected avoidance of wind energy development on the Dunlap Ranch for two winters following construction, the Dunlap Ranch was still predicted to have relatively high probability of selection at both home range and within−home range scales, indicating that this area functioned as important pronghorn winter habitat throughout our study. However, there remains limited information on how ungulates respond to wind energy development over longer time periods, warranting further investigation. Nonetheless, managers should expect some loss of otherwise functional habitat when siting wind energy projects in pronghorn winter range.

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