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Kelly, C. S., Plains sharp-tailed grouse response to wind energy development in northeastern South Dakota, M.S., Department of Ecosystem Science and Management, December 2023.

ABSTRACT

The number of wind turbines on the landscape has increased sharply over the past decade. The rapid accumulation of wind energy structures has created a pressing issue for wildlife managers to find ways to balance renewable energy with conservation of the wildlife residing in these areas. The plains sharp-tailed grouse (*Tympanuchus phasianellus jamesi*; hereafter, 'sharp-tailed grouse') is a subspecies of sharp-tailed grouse with a range stretching across the grasslands of north-central United States. As grassland bird populations decline, managers look to sharp-tailed grouse due to their status as an indicator and umbrella species for grassland habitats. Previous research on prairie grouse and wind energy development has focused on habitat obligate species, however understanding how these species may respond to habitat change may be more predictable due to their relationships with specific habitat features. However, sharp-tailed grouse are a habitat generalist, and the response of this species may be less predictable due to their plasticity when selecting habitats. A greater understanding of how sharp-tailed grouse respond to wind energy development is needed to make management decisions specific to this species. My thesis evaluated resource selection and survival of sharp-tailed grouse during the breeding season in northeastern South Dakota, using GPS location data collected from April to August 2020–2022. My research included 1) modeling resource selection across 3 life stages for individuals in close proximity to wind energy development, and 2) evaluating survival across 2 life stages near cumulative wind energy infrastructure.

In Chapter 1, I conducted a review of literature published over the last 23 years (2000–2023) focused on prairie grouse (sharp-tailed grouse and prairie chickens [*T. cupido* {greater}, and *T. pallidicinctus* {lesser}]) and greater sage-grouse (*Centrocercus urophasianus*) responses to wind energy development. The purpose of this chapter was to identify changes in survival or resource selection related to wind energy development and describe current management recommendations. Of the 14 papers I identified, 14% reported a decrease in survival, 14% described an increase in survival, and 42% identified changes in resource selection. Some recent management recommendations include siting wind turbines in cropland and outside of nesting and brood-rearing habitat.

In Chapter 2, my research focused on identifying changes in resource selection and survival of sharp-tailed grouse relative to a wind energy facility. I used spatial and demographic data collected from 130 GPS-marked female sharp-tailed grouse in northeastern South Dakota during the April to August breeding season over a 3-year period from 2020–2022. I found that females avoided areas of wind energy development during the brood-rearing and breeding season, but selection was not altered when selecting nest sites. I did not detect an effect of wind energy infrastructure on nest survival but found a slight negative affect on adult female survival, however confidence intervals overlapped zero indicating these effects were not informative. Understanding how the construction of a wind energy facility affects sharp-tailed grouse is essential for making science based and species-specific management decisions.

PLAINS SHARP-TAILED GROUSE RESPONSE TO WIND ENERGY DEVELOPMENT IN NORTHEASTERN SOUTH DAKOTA

By:

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DEDICATION

I dedicate this thesis to my husband, Mike, for his limitless support, patience, and understanding while I spent months away at a time chasing grouse through South Dakota's grasslands, followed by long nights hunkered down in front of my computer. I also dedicate this thesis to my family and friends, for their support sustained me throughout my degree. My parents, who never wavered in their support as I chased the next dream, and my brothers, for their comedic relief during the hard times. My friends, Alix and Desiree, for their encouragement while they also pursued their own rigorous degrees.

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CHAPTER 1: PRAIRIE GROUSE AND WIND ENERGY DEVELOPMENT

ABSTRACT

To offset the effects of climate change, industries have been developing renewable energy sources, such as wind energy. The increase of wind energy infrastructure on the landscape has led wildlife managers to develop guidelines based on the best available science from peer-reviewed literature. However, research evaluating wildlife responses to wind energy is relatively new (< 15 years) and species responses may vary based on the type and quantity of wind energy structures on the landscape, habitat conditions prior to development, and unique sensitivities of each species. I conducted a review of all literature published on prairie and sage (*Centrocercus urophasianus*) grouse resource selection and survival in response to wind energy infrastructure. I identified and reviewed 14 papers published between 2000 and 2023; 7 included studies on both resource selection and survival, 4 evaluated resource selection, and 3 focused on survival. Research generally has found minimal impacts of wind energy development on nest site selection and survival, instead vegetation composition may be more informative. Survival during the brood-rearing period may decrease near wind energy development and avoidance of wind energy infrastructure may increase. However, female survival doesn't appear to be affect by the presence of wind energy development, but adult resource selection as a function of wind energy is mixed. Some recent recommendations include placing turbines in cultivated croplands, outside of grouse habitat.

INTRODUCTION

Human activities since the Industrial Revolution have resulted in increasing levels of carbon dioxide and other greenhouse gases, such as methane and nitrous oxide in the atmosphere.

Greenhouse gasses trap heat in the atmosphere, leading to stronger and more frequent storms, drought, rising sea levels (Manabe 2019), and wildlife extinctions (Wiens 2016). The combustion of fossil fuels has been identified as the leading contributor of U.S. greenhouse gas emissions resulting in climate change (USGCRP 2009). As the severity of climate change increases, pressure is placed on industries that burn fossil fuels, such as oil and gas, to reduce carbon emissions. Oil and gas disturbance has been found to alter resource selection for many species including greater sage-grouse (*Centrocercus urophasianus*; Doherty et al. 2010, Walker et al. 2022) and mule deer (*Odocoileus hemionus*; Sawyer et al. 2009, Northrup et al. 2016), and decrease abundance of obligate bird species (Gilbert and Chafoun 2011, Maguire and Papeş 2021). Moreover, oil and gas development has resulted in declines in habitat use or changes to migratory routes (Sawyer et al. 2020) that may result in a division between food resources and movement while migrating (Aikens et al. 2022). Reducing reliance on fossil fuels could significantly reduce such negative impacts to wildlife. To reduce carbon emissions, energy producers and consumers are switching to renewable energy sources like wind, hydropower, and solar energy. Renewable energy sources now (2022) account for 21% of all electricity generated in the U.S., with wind energy accounting for 10.2% of the total power generated in the U.S. (EIA 2023). However, as renewable energy increases across the landscape, there remains much uncertainty about how wildlife will respond to renewable energy development.

Wind energy developers often target open landscapes with the greatest potential for high wind speeds, typical of the Great Plains region of the U.S., which contains more than 75% of the total U.S. wind-energy generating capacity (Ott et al. 2021). Over the last decade, the growth in wind energy has sparked concerns surrounding habitat loss, degradation, and fragmentation in the Great Plains due to the conversion of grassland habitats (Pruett et al. 2009), raising concerns for grassland birds, which are sensitive to fragmentation (Herkert 1994). Each wind turbine, the associated turbine pad, and access road require approximately 1.2 ha, which, if not properly sited, can result in habitat loss, fragmentation, and increased edge effects (Ott et al. 2021). Studies evaluating whether habitat loss or fragmentation are more detrimental to species abundance and occurrence yield mixed results. Some suggest habitat loss may cause more adverse effects than fragmentation, such as species extinction (Fahrig 1997) and decreases in biodiversity (Fahrig 2003) and population size (Wiegand et al. 2005). However, this comes with caveats such as the quality and functional connectivity of the habitat and species-specific distributions (Wiegand eta al. 2005, Betts et al. 2014). Fragmentation may increase edge habitat, which has been linked to decreased species occurrence (Herse et al. 2020), and richness (Herkert 1994), and increased nest predation (Herkert et al. 2003), and displacement (Brennan and Kuvlesky 2005, Shaffer and Buhl 2015).

As renewable energy development increases on the landscape, understanding the potential impacts on wildlife is crucial. The conversion of land by anthropogenic development in the Great Plains has caused a sharp and continuous decline in grassland bird species, making them the fastest declining avian group (NABCI 2022). To study these trends among grassland birds, there has been an increasing amount of research conducted on prairie grouse (*Tympanuchus* spp.) as they are often considered an umbrella species (Pruett et al. 2009, Carlisle et al. 2018). Conservation of umbrella species may result in higher species richness and abundance of accompanying species, making prairie grouse a critical avian group to study and conserve (Branton and Richardson 2010). Wind energy can directly affect grassland birds through habitat loss and collisions with turbines and indirectly through behavioral avoidance of habitat (Johnson et al. 2004, Drewitt and Langston 2006, Loss et al. 2013). Although direct effects, such as collisions, on prairie grouse are likely low, collision mortalities have occurred in ruffed grouse (*Bonasa umbellus*; Jain et al. 2009), sharp-tailed grouse (*T. phasianellus*; Graff et al. 2016), black grouse (*Lyrurus tetrix*; Zeiler and Grünschachner-Berger 2009) and Cantabrian capercaillie (*Tetrao urogallus cantabricus*; González 2018). Indirect effects, such as avoidance of otherwise suitable habitat are common and may temporarily mask demographic affects (Zeiler and Grünschachner-Berger 2009, Hovick et al. 2014, Winder et al. 2014). The current literature investigating the effects of wind energy development on prairie grouse populations has focused on greater sage-grouse, greater prairie-chickens (*T. cupido*), lesser prairie-chickens (*T. pallidicinctus*), and Columbian sharp-tailed grouse (*T. p. columbianus*). There is currently no literature on wind energy effects on Gunnison sage-grouse (*C. minimus*), likely due to the species restricted range.

Power lines (transmission and distribution lines) associated with wind energy infrastructure also have the potential to affect grouse populations directly and indirectly. Although rare, direct mortality caused by collisions with power lines has been documented (Beck et al. 2006, Wolfe et al. 2007) and indirect effects could include displacement and survival consequences similar to wind energy infrastructure. In Nevada, greater sage-grouse resource selection was negatively associated with a 345-kilovolt (kV) transmission line (Gibson et al. 2018). Studies that assessed lesser prairie-chicken home range placement relative to power lines found that home ranges were farther from power lines than expected by chance (Pruett et al. 2009a, Hagen et al. 2011, Plumb et al. 2019), and other studies have found that lesser prairie-chicken avoided nesting near power lines (Pruett et al. 2009, Plumb et al. 2019). Londe et al. (2022) found that greater prairie chicken avoided crossing power lines during the post-nesting and non-breeding seasons and increased movement rates near power lines. A study in the same area found that female greater prairie-chickens avoided transmission lines throughout the year (Londe et al. 2019).

As wind energy development increases on the landscape, understanding how the associated anthropogenic features (e.g., turbines, roads, transmission lines, etc.) affect wildlife and their habitats has become increasingly important. Literature reviews have been conducted on similar topics, focusing on grouse responses to wind energy development internationally (Coppes et al. 2020), and more specifically prairie grouse of North America (Lloyd et al. 2021). To better understand how birds respond to anthropogenic change, researchers may start with grouse because they are ubiquitous and migrate small distances, making it easier to study an individual throughout their life cycle. Non-migratory species make landscape level movements that result in dispersal, seasonal shifts in home range, and within home range movements (Harris and Reed 2002). Disruption to such localized movements may alter population genetics (Wilson et al. 2015), changes in home range size (Xu et al. 2023) and reduce access to resources (Beyer et al. 2016). To better understand how North American prairie grouse respond to wind energy development I conducted a review of the current scientific literature. My objectives for this review were to 1) summarize the current literature on grouse and wind energy development, and 2) describe the current management recommendations found in scientific literature. The results from this chapter may in turn be used to inform future research on prairie grouse.

METHODS

Research investigating the responses of prairie and sage-grouse to wind energy development first emerged in the literature in 2009 (Pruett et al. 2009a, 2009b). I therefore set a temporal range when searching for literature to the most recent 23 years (2000–2023). I gathered literature using combinations of search terms; “prairie grouse,” “prairie chicken,” “sage grouse,” “sharp-tailed grouse," "habitat selection," "resource selection," "survival," "wind energy development, and "turbines." I included studies on juvenile and adult grouse to better understand effects across all life stages. For articles describing resource selection, I required that methods included use of resource selection function models with a used-to-available design. For articles on survival, I required that methods included Cox proportional hazards models (Cox 1972) or known-fate models (Program MARK; White and Burnham 1999). The movement papers that were included used either integrated step selection analysis (Thurfjell et al. 2014; Londe et al. 2022) or step selection functions (Fortin et al. 2005; LeBeau et al. 2023).

RESULTS

I identified and reviewed 14 papers, 7 included studies on both resource selection and survival relative to wind energy facilities, 4 only on resource selection, and 3 only on survival, published between 2000–2023. The reviewed literature included 4 taxa of prairie and shrubland grouse, Columbian sharp-tailed grouse, greater prairie-chicken, greater sage-grouse, and lesser prairie-chicken.

Prairie grouse survival and wind energy development

Current research on prairie grouse suggests minimal impacts of wind energy development on nest survival (Table 1.1). Instead, local habitat characteristics may be better predictors of nest survival. Studies conducted in Nebraska and Kansas found that nest survival of greater prairie-chickens was not affected by proximity to wind energy development (McNew et al. 2014, Harrison et al. 2017). Instead, nest survival was influenced by vegetation cover (McNew et al. 2014) and structure (Harrison et al. 2017). Similar results were reported for studies of Columbian sharp-tailed grouse and lesser prairie-chickens—nest survival was not altered by wind energy infrastructure, rather survival was influenced by vegetation cover (LeBeau et al. 2023, Proett et al. 2019). LeBeau et al. (2014) found that greater sage-grouse nest and brood survival were lower closer to turbines within 2 years of development of a wind energy facility. However, in a 6-year study at the same wind facility, there was no detectable effect of wind energy on nest or brood survival (LeBeau et al. 2017). Few studies have quantified the effects of wind energy development on prairie grouse broods and have yielded mixed results. No effects have been found on brood survival of greater prairie-chickens (Harrison 2015). However, in Idaho, survival of Columbian sharp-tailed grouse chicks decreased as turbine density increased (Proett et al. 2022). It is hypothesized that wind-energy infrastructure could increase predation on grouse chicks, which may explain decreased brood survival rates near turbines (LeBeau et al. 2014, Proett et al. 2022).

Studies investigating adult female survival relative to wind energy have failed to detect negative effects of wind energy infrastructure on female prairie grouse survival. In Kansas, survival of female greater prairie-chickens was nearly twice as high after the development of a wind energy facility (Winder et al. 2014a). Similar results were found with female greater sage-grouse, where survival was higher when surface disturbance associated with a wind energy facility increased from 0 to 3% (LeBeau et al. 2017). Adult survival may increase near wind energy facilities due to behavioral avoidance by avian predators (raptors) that may avoid turbines due to collision risk (Watson et al. 2018), and avoidance of anthropogenic disturbance from mammalian predators including American badgers (*Taxidea taxus*), coyotes (*Canis latrans*), raccoons (*Procyon lotor*), red fox (*Vulpes vulpes*), and striped skunks (*Mephitis mephitis*; Burr et al. 2017, Smith et al. 2017). Contrary to previous studies, LeBeau et al (2019) found that transmission lines had a negative effect on greater sage-grouse resource selection and survival across multiple life stages. Some studies have found no effect of wind energy infrastructure on adult survival of greater and lesser prairie-chickens (Harrison et al. 2017, Smith et al. 2017, LeBeau et al. 2023).

Prairie grouse resource selection and wind energy development

Understanding why prairie grouse select resources relative to wind energy development can be challenging as results may vary based on the extent of the anthropogenic disturbance, the type of development, and the individual's life stage. Studies on prairie grouse nest site selection have not detected an effect of wind energy infrastructure on nest site selection (McNew et al. 2014, Harrison et al. 2017, Proett et al. 2019, LeBeau et al. 2023; Table 1.2). Instead, vegetation structure and composition may be better predictors of resource selection for nesting sites. McNew et al. (2014) found that visual obstruction, proportion of grass cover, and distance from forest patches influenced nest-site selection for greater prairie-chickens more than anthropogenic disturbance. Individuals preferred vertical nesting cover and avoided woody cover, forest patches, and edges. Similarly, in Nebraska, greater prairie-chickens selected nesting sites based on habitat and landscape factors such as distance to road, visual obstruction, litter depth, and standing dead vegetation (Harrison et al. 2017). The development of a wind energy facility often includes improving existing roads and creating access roads. Multiple studies have found that prairie grouse and sage-grouse avoid nesting near roads within wind energy facilities (Pruett et al. 2009, LeBeau et al. 2017, Proett et al. 2019). In Oklahoma, greater prairie-chickens avoided roads and decreased their rate of movement near roads, which could result in negative fitness consequences if roads are influencing greater prairie-chicken space use (Londe et al. 2022). The strength of the avoidance may be related to road type and the associated traffic volume. For example, interstate and state highways with steady vehicle traffic may elicit more avoidance, compared to gravel roads with primarily residential traffic. Road avoidance was not observed with Columbian sharp-tailed grouse at a wind energy facility in Idaho (Proett et al. 2019), suggesting the distribution and planning of roads may be critical when developing a wind facility.

Avoidance and altered movement near development may reduce the amount of nesting habitat available, altering nest-site selection towards lower quality sites. Changes in habitat use, such as avoidance of otherwise suitable habitat near wind energy facilities, could have negative long-term fitness and demographic consequences (Lloyd et al. 2022). Wind turbines have not been found to alter nest-site selection for prairie grouse or greater sage-grouse. Complimentary to nest survival, vegetation composition may be more informative of nest placement. Columbian sharp-tailed grouse affected by wind-energy development selected nest sites based on vegetation structure and composition (Proett et al. 2019). Similarly, greater sage-grouse selected nest sites based on vegetation characteristics; however, individual grouse avoided nesting near linear anthropogenic features such as transmission lines and roads (LeBeau et al. 2017).

Limited research has been conducted on the effects of wind energy development on brood-rearing and adult resource selection by prairie grouse. Research on lesser prairie-chickens in Kansas found that across all life stages, individuals avoided areas with high amounts of cropland and contained high densities of wind turbines (LeBeau et al. 2023). However, turbines were largely sited in cultivated cropland, making it difficult to disentangle the two effects. Contrary to how lesser prairie-chickens may respond, adult greater prairie-chickens did not alter resource selection patterns after the construction of a wind-energy facility (Winder et al. 2014b). LeBeau et al. (2017) found female greater sage-grouse with broods shifted away from areas with a higher percentage of surface disturbance. This shift in avoidance was more pronounced in the final three years of the 6-year study, suggesting a delayed response to the development of the wind facility. This trend continued following the brood-rearing period, as female selection shifted away from areas with a higher percentage of surface disturbance associated with wind energy. The avoidance of surface disturbance by females after brood-rearing was consistent across the 6 years, unlike the shift observed in brood-rearing females. Female greater-sage grouse habitat use continued around the edges of the wind facility after brood-rearing but was lower within the facility (LeBeau et al 2017). No other studies have investigated resource selection for female prairie grouse with broods at a wind energy facility. The lack of information regarding resource selection of brood-rearing females could make interpreting broader impacts of wind energy development on prairie grouse challenging.

DISCUSSION

While utility companies that have previously relied on fossil fuels transition to renewable energy sources, wildlife managers are tasked with balancing a rapidly increasing number of wind energy facilities on the landscape, potentially compromising wildlife conservation. Due to expansive open space and capacity for high wind speeds, much of the United States' major wind generating capacity is concentrated in the Great Plains (Ott et al. 2020). The development of the Prairie Pothole Region for wind resources has raised concerns about the continuous decline of grassland birds and how wind energy development may continue to threaten these sensitive species (NABCI 2022). To study trends among grassland birds, researchers have turned to prairie grouse as they may function as an umbrella species (Pruett et al. 2009, Carlisle et al. 2018) and indicator species for grassland ecosystems (Roersma 2001).

While information is available regarding impacts of wind energy development to grouse, the results remain mixed. For example, in Wyoming, LeBeau et al. (2014) reported lower nest and brood survival for greater sage-grouse in habitats closer to wind turbines 2 years following development. However, over a 6-year period after development at the same facility, LeBeau et al. (2017b) failed to detect negative effects on greater sage-grouse nest, brood, or summer female survival. In Idaho, nest survival for Columbian sharp-tailed grouse was not influenced by proximity to turbines (Proett et al. 2019); however, turbine density was negatively associated with chick survival (Proett et al. 2022). These studies highlight the variability of effects on survival; however, avoidance behaviors may mask the ability to detect changes in survival and resource selection.

RESEARCH FOCUS

Although the range-wide population of sharp-tailed grouse has remained relatively stable (IUCN 2023), understanding how local populations of this species respond to wind energy development is crucial as the industry continues to increase within sharp-tailed grouse habitats. While some information exists on the effects of wind energy infrastructure on prairie grouse populations, no studies have directly measured plains sharp-tailed grouse behavioral and demographic responses to wind energy infrastructure. My findings will be used to identify management practices to minimize impacts to sharp-tailed grouse exposed to wind energy development.

My thesis is focused on understanding the behavioral and demographic responses of sharp-tailed grouse to wind energy development in the Prairie Pothole Region of South Dakota, using GPS location data from individual grouse during the 2020, 2021, and 2022 breeding seasons. My objectives were to 1) evaluate potential changes in nest survival and adult survival during the breeding season and 2) assess whether resource selection during the nesting, brood rearing, or adult breeding season was influenced by the presence of a wind energy facility.

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Table 1.1. Summary of literature evaluating greater sage-grouse, greater prairie-chicken, lesser prairie-chicken, and Columbian sharp-tailed grouse survival across 3 unique life stages in relation to wind energy infrastructure from 2000–2023. Effects are represented as increase (+), decrease (-), and no effect (0).

		Nesting				Brood rearing				Breeding season			
		Distance to transmission line	Distance to turbine	Transmission line length	Turbine Density	Distance to transmission line	Distance to turbine	Transmission line length	Turbine Density	Distance to transmission line	Distance to turbine	Transmission line length	Turbine Density
Study	Species												
Harrison 2015	Greater prairie-chicken										+		
Harrison et al. 2017	Greater prairie-chicken	0	0										
LeBeau et al. 2014	Greater sage-grouse	+	+			0	+			0	0		
LeBeau et al. 2017	Greater sage-grouse	0	0							0	0		
LeBeau et al. 2019	Greater sage-grouse	-	0							-	0		

LeBeau et al. 2023	Lesser prairie-chicken									0	0	0	0
McNew et al. 2014	Greater prairie-chicken	0	0										
Proett et al. 2019	Columbian sharp-tailed grouse		0		0								
Proett et al. 2022	Columbian sharp-tailed grouse						0		-				
Winder et al. 2014a	Greater prairie-chicken												

Table 1.2. Summary of literature on greater sage-grouse, greater prairie-chicken, lesser prairie-chicken, and Columbian sharp-tailed grouse resource selection across 3 unique life stages influenced by wind energy infrastructure from 2000–2023. Effects are represented as selection (+), avoidance (-), and no effect (0).

		Nesting				Brood rearing				Breeding season			
		Distance to transmission line	Distance to turbine	Transmission line length	Turbine Density	Distance to transmission line	Distance to turbine	Transmission line length	Turbine Density	Distance to transmission line	Distance to turbine	Transmission line length	Turbine Density
Study	Species												
Harrison 2015	Greater prairie-chicken		0				0						
Harrison et al. 2017	Greater prairie-chicken	0	0										
LeBeau et al. 2017	Greater sage-grouse	0	0			0	0			-	0		
LeBeau et al. 2019	Greater sage-grouse	-	0			-	0			-	0		
LeBeau et al. 2023	Lesser prairie-chicken									-	+	0	-

Londe et al. 2022	Greater prairie-chicken									-	
McNew et al. 2014	Greater prairie-chicken	0	0								
Pitman et al. 2005	Lesser prairie-chicken									-	
Proett et al. 2019	Columbian sharp-tailed grouse		0		0						
Pruett et al. 2009b	Greater and Lesser prairie-chickens									-	
Winder et al. 2014b	Greater prairie-chicken										0

CHAPTER 2: RESOURCE SELECTION AND SURVIVAL OF PLAINS SHARP-TAILED GROUSE AT A WIND ENERGY FACILITY

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ABSTRACT

As the demand for wind energy development increases across much of the Great Plains region, there is a need to understand how this type of energy generation may impact wildlife. Due to their extensive range across areas with high wind energy capacity, their economic importance, and status as an indicator species for grassland ecosystems, plains sharp-tailed grouse (*Tympanuchus phasianellus james*i) represent a valuable species to evaluate responses associated with wind energy development. We used spatial and demographic data collected from radio-marked female sharp-tailed grouse to evaluate the effects of a wind energy development on resource selection (nest, brood-rearing, and breeding season) and survival (nest and female) during the April to August breeding season over a 3-year period from 2020–2022 in north-eastern South Dakota, USA. We captured 130 females at 8 leks over the study period. We did not find evidence that females selected nest sites in relation to wind energy infrastructure but found that females with broods and during the breeding season avoided areas near high densities of wind turbines within their home ranges at the 1.0 and 5.0 km scales, respectively. We found consistent selection for lower lengths of transmission lines across all life stages at the home range scale. We did not detect a statistically significant effect of wind energy infrastructure on nest or female survival, but caution that the potential relationship between female survival and

wind turbine density may be biologically meaningful. Given the relative stability of the local sharp-tailed grouse population, as indexed by trends in yearly lek counts, potential avoidance behaviors in areas with relatively high densities of wind turbines did not appear to result in population level declines over the short-term following development, a result consistent with other studies evaluating the response of grouse to wind energy development. Based on the results of our study, siting wind turbines at low densities within 5.0 km of sharp-tailed grouse breeding habitat may represent an important siting tool to minimize avoidance of otherwise suitable habitats.

KEYWORDS energy development, grouse, renewable energy, resource selection, survival, *Tympanuchus phasianellus*

Concerns about global climate change have placed mounting pressure on transitioning from conventional to renewable sources of energy generation in the United States. A reduction in carbon emissions by increased use of alternative renewable energy sources, such as wind energy generation, has important implications for wildlife inhabiting the Great Plains region of the central U.S., which contains more than 75% of the total U.S. wind energy generating capacity (Ott et al. 2021). The increased demand for wind energy has sparked concerns surrounding habitat loss, degradation, and fragmentation of remaining grassland habitats in the Great Plains (Pruett et al. 2009); yet much uncertainty remains regarding how wildlife may respond to development of renewable energy infrastructure (Northrup and Wittemyer 2023). Each wind turbine, associated turbine pad, and access road requires approximately 1.2 ha of land (Ott et al. 2021), which, if not properly sited, may increase loss and fragmentation of important habitat occupied by wildlife in this region.

Steep declines in grassland bird populations have prompted efforts to better understand how to mitigate the effects of rapidly changing landscapes (NABCI 2022, Pavlacky et al. 2022). Grassland-obligate birds are sensitive to fragmentation and require large, contiguous intact habitats (Herkert 1994). Fragmentation may increase edge which is associated with decreased species occurrence (Herse et al. 2020), and richness (Herkert 1994), and increased nest predation (Herkert et al. 2003), and displacement (Brennan and Kuvlesky 2005, Shaffer and Buhl 2015). Several studies have identified displacement and avoidance of grassland birds resulting from energy development; however, impacts vary among species utilizing different life history strategies (Stevens et al. 2013, Hale et al. 2014, Shaffer and Buhl 2015). Waterfowl occupying prairie pothole wetlands across the Great Plains, for example, avoid wetlands closer to wind energy infrastructure (Loesch et al. 2012), but shorebirds and other waterbirds do not appear to avoid nesting habitat near wind energy infrastructure (Niemuth et al. 2013). Furthermore, the magnitude of responses to energy infrastructure may vary by habitat quality (Hatchett et al. 2013, Mahoney and Chalfoun 2016), potentially confounding our ability to detect potential negative impacts associated with energy infrastructure.

Concerns regarding how grouse respond to wind energy development have been recognized globally. Studies to better understand the direct and indirect impacts of wind energy infrastructure on grouse have been conducted in 8 countries (Coppes et al. 2020). Five species of North American grouse (tribe Tetraonini) reside in grassland habitats and have received considerable conservation attention as a result of declining populations (Storch 2007). Studying grouse not only increases the current understanding on potential impacts of wind energy development to nonmigratory wildlife, but may also inform wildlife managers on how to better conserve grassland species as a whole (Branton and Richardson 2010). Direct effects of energy infrastructure, such as collisions, on prairie grouse are likely low, although indirect effects, such as avoidance of otherwise suitable habitat have been documented (Hovick et al. 2014). Generally, impacts to prairie grouse and greater sage-grouse (*Centrocercus urophasianus*) nest and adult survival from wind energy infrastructure have not been detected (Winder et al. 2014, Harrison et al. 2017, LeBeau et al. 2017b, Smith et al. 2017, Proett et al. 2019); however, brood survival may decrease following development, at least over a short period (LeBeau et al. 2014, LeBeau et al. 2017b, Proett et al. 2022). Avoidance behaviors by grouse in relation to their exposure to wind energy infrastructure could possibly mask the ability to detect potential survival consequences. Such behaviors have been documented during the breeding season (Winder et al. 2014, LeBeau et al. 2017b) and suggest that avoidance of wind energy infrastructure could result in indirect loss of potentially suitable habitats. Power lines (transmission and distribution lines) often associated with wind energy infrastructure also can directly and indirectly affect grouse populations. Although rare, direct mortality caused by collisions with power lines has been documented (Beck et al. 2006, Wolfe et al. 2007) and indirect effects could include displacement and demographic consequences similar to wind energy infrastructure (Gibson et al. 2018, LeBeau et al. 2019, Londe et al. 2019).

Previous research on grouse and wind energy development has primarily focused on habitat specialists or species with narrow geographic ranges. For example, greater sage-grouse are considered sagebrush (*Artemisia* spp.) obligates (Baker et al. 1976) and greater prairie-chicken (*Tympanuchus cupido*) require large, contiguous tallgrass prairie (McNew et al. 2013, 2015). Predicting risk as a result of anthropogenic habitat modification for these specialist species may be easier due to their obligate relationships with specific habitats (Owens and Bennett 2000). Predicting how habitat generalist species may respond to human-induced habitat changes, however, may be challenging because they are widespread and can utilize a variety of habitats to fulfill their life history needs. The sharp-tailed grouse (*T. phasianellus*) is a generalist grouse species comprising 6 subspecies distributed across much of central and northwestern North America (Connelly et al. 2020). The most widespread of the subspecies, and focus of this research, the plains sharp-tailed grouse (*T. p. jamesi*; hereafter 'sharp-tailed grouse') has been recognized as an indicator species for grassland ecosystems (Roersma 2001). Due to their extensive range across areas with high wind energy capacity, sharp-tailed grouse are exposed to the greatest number of wind turbines compared to other grouse species (Lloyd et al. 2022). However, no studies have directly measured potential impacts of wind energy development to sharp-tailed grouse.

Although sharp-tailed grouse are a species of least conservation concern (IUCN 2023), their preservation is of economic importance for the rural areas comprising the Northern Great Plains. South Dakota has been a popular destination for upland game bird hunting where the sport has consistently contributed millions of dollars annually to the economy through hunting license sales, lodging, dinning, and sporting goods (Erickson and Wiebe 1973, South Dakota Game Fish and Parks 2017, Gascoigne et al. 2021). Therefore, an understanding of how sharp-tailed grouse respond to wind energy development will be necessary for stakeholders tasked with conserving this important species. The goal of our study was to evaluate the effects of a wind energy development on sharp-tailed grouse resource selection and survival over a 3-year period from 2020–2022. We used spatial and demographic data collected from observations of lek trends and GPS-marked females. Specifically, our objectives were to evaluate 1) resource selection by female sharp-tailed grouse associated with wind energy infrastructure during nesting, brood-rearing, and the breeding season, and 2) nest and female survival relative to wind energy infrastructure. We used lek count data, as an index of the local sharp-tailed grouse population, as an additional means to qualitatively assess population trends over the short-term following wind energy development. Our research is the first to evaluate the effects of wind energy on plains sharp-tailed grouse. These results will assist wildlife managers to make conservation decisions based on science and not need to rely on inferences from other studies of other prairie grouse species.

STUDY AREA

Our study area was located in Grant, Codington, and Deuel counties, South Dakota. We defined our study by buffering the Crowned Ridge I and Crowned Ridge II Wind Energy Facilities by 10 km (Figure 1). This region contained all previously known sharp-tailed grouse leks and included large swaths of grassland. Crowned Ridge I consisted of 87, 2.3-MW turbines that were constructed prior to the study in 2019. Crowned Ridge II consisted of 88, 2.3-MW turbines that became operational in 2020. Other wind energy facilities in the region included Dakota Range I, II (72, 2.2–4.5-MW turbines operational in 2021), and III (32, 4.5-MW turbines operational in 2021), Deuel Harvest North (101, 2.8-MW turbines operational in 2019), and Tatanka Ridge (50, 2.8-MW turbines and 6, 2.3-MW turbines operational in 2021). The number of turbines in the study area ranged from 102 in April 2020 to 258 at the end of the study in August 2022.

Classified as tallgrass prairie within the Northern Great Plains Region (Johnson and Larson 2007), the study area was almost entirely privately owned land managed for cattle grazing and crop agriculture production. Several small state and federally managed wildlife management areas and waterfowl production areas intersperse the region. Topography was characteristic of the Prairie Coteau ecoregion, consisting of rolling hills and numerous wetlands (Johnson and Larson 2007). Elevations ranged from 294–635 m (US Geological Survey [USGS]

2023) and annual precipitation from 61.0–71.1 cm (30-year average; PRISM Climate Group 2021). Characteristic grasses include big bluestem (*Andropogon gerardi*), Indiangrass (*Sorghastrum nutans*), little bluestem *(Schizachyrium scoparium*), porcupine grass *(Hesperostipa spartea*), sideoats grama (*Bouteloua curtipendula*), and switchgrass (*Panicum virgatum*). Common forbs included American licorice (*Glycyrrhiza lepidota*), blazing star (*Liatris pycnostachya*), Canada goldenrod (*Solidago canadensis*), downy phlox (*Phlox pilosa*), false boneset (*Brickellia eupatorioides*), giant goldenrod (*S. gigantea*), ground plum (*Astragalus crassicarpus*), heath aster (*Symphyotrichum ericoides*), New England aster (*S. novae-angliae*), purple prairie clover *(Dalea purpurea*), purple coneflower (*Echinacea purpurea*), pussytoes (*Antennaria neglecta*), silverleaf scurfpea *(Pediomelum argophyllum*), and common sunflower (*Helianthus annuus*). Dominant shrubs included lead plant (*Amorpha canescens*) and prairie rose (*Rosa arkansana*; Johnson and Larson 2007). Common crops included alfalfa (*Medicago sativa*), corn (*Zea mays*), soybeans (*Glycine max*), and wheat (*Triticum*).

METHODS

Field methods

We searched for previously undocumented leks (i.e., 2 or more displaying males) each spring and visited known leks to count the number of individual sharp-tailed grouse in attendance. We surveyed all known leks 3–4 times each spring using ground-based lek counts during the lekking period. We conducted aerial lek surveys in 2020 to search for previously unknown leks and to supplement ground-based surveys. Lek surveys followed standardized protocols (South Dakota Game Fish and Parks 2022). We targeted leks for capture based on the number of males observed on leks, proximity to turbines, and landowner access.

We targeted female sharp-tailed grouse for captures, given their contribution to population growth rates (Milligan et al. 2018). We captured females from leks using walk-in drift traps during the spring lekking period, March–late April (Haukos et al. 1990). We sexed each grouse based on tail feather striation and color of crown feathers and aged them as juveniles or adults based on the shape and condition of the ninth and tenth primary feathers (Ammann 1944, Henderson et al. 1967). We fit captured adult and yearling females with Global Positioning System (GPS)-Ultra High Frequency (UHF) solar-powered telemetry units (Ecotone Harrier GPS-UHF, Saker GPS-GSM model L) with a modified rump-mounting harness (Kirol et al. 2020). Telemetry units weighed approximately 17 g (less than 3% body weight; Phillips et al. 2003).

GPS units were programmed to collect locations every 15 min and uploaded via 3G cellular transmission. We masked locations recorded from each individual immediately following capture and assumed that individuals acclimated to the GPS transmitters after 2 days. GPS units were also equipped with VHF transmitters (model RI-2B, Holohil Systems Ltd., Ontario, Canada) to allow for manual tracking when necessary. We manually located sharp-tailed grouse on the ground beginning in May each year using a R4000 (Isanti, Minnesota) receiver (Advanced Telemetry Systems, Isanti, Minnesota, USA) and 3- or 5-element Yagi antennas to estimate demographic parameters (described below). We used fixed-wing aircraft flights to locate any individuals that went missing. In the event locations were localized for more than a day indicating a mortality, we visited the location to retrieve the GPS transmitter and determine cause of death when possible.

We located nests by visually inspecting location data that indicated homing by females to a single location (± GPS location error). We considered the nest to have failed if a female left the nest location prior to the 23-d incubation period (Johnsgard 1983). We visited each nest to confirm fate and considered a nest successful when at least 1 egg hatched (Rotella et al. 2004). We manually tracked the bird with VHF telemetry to confirm nest fate by visually observing chicks or brooding behavior by the female (e.g., distraction displays or injury feigning; Kirol et al. 2015). We monitored all females throughout the study period irrespective of nest fate.

Spatial predictors

We considered both habitat and wind energy infrastructure variables to assess sharp-tailed grouse resource selection and survival (Table 1). We used land cover data from the U. S. Department of Agriculture (USDA) National Agricultural Statistical Service (USDA 2023) to estimate the proportion of canopy cover of alfalfa, corn, herbaceous wetland, grassland, soybeans, total crop cover (included alfalfa, corn, and soybeans), and developed areas (including roads, dwellings, and associated infrastructure [USDA 2023]). We selected major crop cover variables (corn, alfalfa, and soybeans) based on their abundance in the study area and visual observations of sharp-tailed grouse use. Land cover data were available each year; therefore, we temporally matched sharp-tailed grouse locations to the appropriate year to reflect land cover when locations were recorded.

We used a digital elevation model (USGS 2023) to create a Terrain Roughness Index (TRI) and Terrain Positioning Index (TPI). We calculated TRI as the mean difference between a raster cell and the 8 surrounding cells (Wilson et al. 2007). TPI compared the elevation of each cell to the mean elevation of the 8 surrounding cells. Positive and negative TPI values represent areas that were higher or lower than their surrounding areas, respectively (Guisan et al. 1999). We calculated distance to roads using spatial data from the South Dakota Department of

Transportation (2022), Minnesota Department of Transportation (2012), and service roads to wind turbines that were manually digitized.

Wind energy and transmission line covariates (hereafter, collectively referred to as wind energy infrastructure variables) included distance to turbine (km), distance to transmission line (km), turbine density (count of turbines), and length of transmission lines (km; transmission line density). We obtained locations of turbines from the United States Wind Turbine database (Hoen et al. 2018). We verified information on timing of construction and commercial operation dates by direct communication with wind energy facility operators. We obtained transmission and distribution line data from the Department of Homeland Security (2022). Transmission and distribution line voltage ranged from 69–345 kilovolts. We time-stamped wind energy covariates to accurately reflect when infrastructure was present on the landscape.

We assessed all habitat covariates (excluding those describing Euclidean distance) within 6 circular scales: 0.2-km, 0.5-km, 1.0-km, 1.3-km, 3.2-km, and 5.0-km radii. We assessed wind energy infrastructure variables within 1.0-km, 1.3-km, 3.2-km, and 5.0-km. We also assessed TPI and TRI at the local scale (raster pixel). We determined scales based on previous research on survival and spatial use patterns of sharp-tailed grouse (Milligan et al. 2020b, Runia et al. 2021, Proett et al. 2022) and current management recommendations for wind energy development siting (North Dakota Game and Fish Department 2021).

Experimental design and analysis

We evaluated the potential influence of wind energy infrastructure on sharp-tailed grouse behavior and demography using resource selection and survival analyses. We evaluated resource selection of female sharp-tailed grouse nests, broods, and during the breeding season (1 Apr to 15 Aug), and survival of nests and females. In each analysis, we related sharp-tailed grouse locations to spatially explicit covariates (Table 1). We performed all statistical analyses in R version 4.1.3 (R Core Team 2022). We used second-order Akaike's Information Criterion (AICc) to assess model support for all models (Burnham and Anderson 2002). Prior to model development, we ran univariate models and retained variables when they were more informative than random intercept only models. We removed variables from further consideration if 85% confidence intervals surrounding coefficient estimates included 0 (Hosmer and Lemeshow 2000). For non-Euclidean distance-based variables that were assessed at multiple scales, we retained the variable scale that had the lowest AICc score. We completed variable screening procedures independently for each model.

We used a variable subsetting approach (Arnold 2010) to evaluate the influence of wind energy infrastructure variables on female sharp-tailed grouse. We first explored all combinations of uncorrelated ($|r| > 0.6$) habitat variables retained after univariate screening that excluded wind energy infrastructure variables. We set the maximum number of habitat variables in any model to 6 to limit potential model overfitting (Burnham and Anderson 2002). We used AICc to rank models and considered the most parsimonious model to be the base model for comparison with models containing wind energy infrastructure variables. We used a similar variable screening procedure for wind energy infrastructure variables. We then compared the base model to models that included habitat variables in the base model plus all combinations of uncorrelated ($|r| < 0.6$) wind energy infrastructure variables. This modelling approach allowed us to determine whether models containing wind energy infrastructure variables were more predictive of sharp-tailed grouse resource selection or survival compared to models only containing habitat covariates in the base model. Candidate models were fitted with package *MuMIn* in R (Bartoń 2022). We allowed each model to compete and selected the most parsimonious model based on AICc

(Burnham and Anderson 2004). We considered covariates in final models that had 95% confidence intervals that included 0 to be uninformative.

We conducted *post hoc* assessments of final models in 2 ways. First, we tested for interactions between grassland and turbine density or distance to wind turbines if these wind energy covariates were present in final models. We selected grassland because it was included in all final models and the importance of grassland habitats is well understood across life stages (Proett et al. 2019, Runia et al. 2021). We surmised that selection and survival in relation to wind energy infrastructure may covary with the amount of grassland habitat. Second, we evaluated final models that contained wind energy infrastructure variables and had parameter estimates that indicated behavioral avoidance or survival consequences to test for potential thresholds in sharp-tailed grouse responses. We investigated quadratic and ramped thresholds for all wind energy infrastructure variables. A ramped threshold describes a gradient of the effect of a specified covariate and identifies a break point where the response to the covariate plateaus (Powell et al. 2017). To determine potential ramped threshold values to assess, we used 10% quantile intervals (ranging from 10 to 90%) based on the distribution of sharp-tailed grouse use locations relative to wind energy infrastructure. Therefore, we tested up to 9 ramped thresholds and 1 quadratic threshold for each wind energy infrastructure variable included in final models. We used AICc to assess support for including both interactions and nonlinear terms in final models.

We used binomial generalized linear mixed models to estimate the relative probability of female sharp-tailed grouse nest site, brood-rearing (from hatch to 5 weeks), and breeding season (1 Apr to 15 Aug) resource selection within the study area. Models included a random intercept term identifying individual grouse nested within year to account for variation among individuals and across years (Gillies et al. 2006). We rarified used locations to 10 locations per day to minimize spatial autocorrelation (Valcu and Kempenaers 2010). We evaluated resource selection at the home-range (second-order) and within home range (third-order) scales using resource selection functions (RSFs; Johnson 1980, Manly et al. 2002). The home-range scale analyses evaluated resource selection at the population level (selection given available habitat occupied by all marked females), whereas the within home range analyses evaluated resource selection at the individual level (an individual's selection given habitat within each female's seasonal range). For all home-range scale analyses, we used 25 times the number of available locations per used location. We restricted available locations to a 99% fixed kernel (KDE; Worton 1989) surrounding all sharp-tailed grouse locations during the breeding season at this scale. For within home range analyses, we generated available points within a 99% KDE that was created using locations used by each individual. For the within home range nest analysis, we used locations obtained during the 3-week period preceding nest incubation to determine the area to generate available locations. We assumed that a 3-week period represented the time period when a female was choosing a nest location prior to initiation. We used locations obtained during the 5-week period following hatch or during the breeding season to determine the area to generate available locations for the within home range brood-rearing and breeding season analyses, respectively. We restricted the brood-rearing resource selection analysis to individuals that were known to have broods. We generated available locations at a rate of 25 times the number of used locations for within home range analyses.

We evaluated the predictability of the most parsimonious home range scale breeding season RSF using a 5-fold cross-validation (Boyce et al. 2002, Johnson et al. 2006). We binned predictions into 5 equal-area (quartile) intervals (Wiens et al. 2008). We performed model validations with linear regressions run on the number of observed locations from test groups compared to expected locations generated from each RSF bin. We considered models to be good predictors when linear regressions had high coefficients of determination ($r^2 > 0.9$) and 95% confidence intervals of slope estimates that excluded 0 and included 1 (Howlin et al. 2004). We mapped the most predictive RSF across the study area using coefficients from the top model and distributed predictions into 5 equal area bins corresponding with increasing relative probability of selection. We also mapped the most predictive base model RSF to visually compare spatial predictions that did not include the additive effects of wind energy infrastructure variables.

We evaluated nest and breeding season female survival using Cox proportional hazards regression models to relate hazard of death to predictor variables using the *coxme* package in R (Cox 1972, Therneau and Grambsch 2000). We assessed nest survival over a 23-day incubation period (Johnsgard 1983). We only included first nest attempts because renests may not have been independent of first nests and comprised a relatively small sample (n = 8). We assessed female survival from 1 April to 15 August (19 weeks) to be consistent with other studies (Manzer and Hannon 2008, Milligan et al. 2020b). We excluded individuals that died within 2 days of capture from the analysis to remove possible bias associated with potential capture-related mortality. We modelled female risk during the breeding season using the Andersen-Gill formulation of the Cox proportional hazards regression to accommodate left and right censoring of data (Andersen and Gill 1982). We tested the assumption of proportional hazards using Schoenfeld residuals of the covariates included in the final model (Schoenfeld 1982).

RESULTS

We completed lek counts from 11 Mar to 25 Apr each year. Nineteen sharp-tailed grouse leks were known prior to initial surveys in 2020 and 12 previously undocumented leks were identified during ground and aerial based surveys (Figure 1). The average maximum male sharp-tailed grouse count at leks was 6 (range = 0–23), 9 (range = 0–31), and 8 (range = 0–29) in 2020, 2021, and 2022, respectively (Figure 2). We captured 130 female sharp-tailed grouse at 8 leks over the study period. We masked 11 individuals because they died within 2 days of capture. Resource selection models included 75 nests, 5,364 brood rearing-locations from 17 broods, and 72,453 breeding season locations (Figure 3). Our survival analyses included 65 first nest attempts, and 112 females with complete survival histories.

Resource selection

At the home range scale, the addition of wind energy infrastructure variables improved model fit compared to base models (Table A1). The final model suggested that female sharp-tailed grouse selected nest sites with greater proportion of grassland within 0.2 km, less herbaceous wetland within 3.2 km, lower TPI within 5.0 km, lower TRI within 3.2 km, and lower length of transmission lines within 5.0 km (Table 2). The addition of threshold terms to describe length of transmission lines within 5.0 km did not improve model fit compared to a model that only contained the linear model term. At the within home range scale, sharp-tailed grouse selected nest sites with greater proportion of grassland within 0.2 km, and lower TPI at the local scale (Table 2). Models containing wind energy infrastructure variables did not improve model fit compared to base models (Table A1).

The addition of wind energy infrastructure variables in models evaluating brood rearing resource selection improved model fit compared to base models at both scales of selection (Table A2). The final model describing brood site selection at the home range scale, suggested that brood-rearing females selected locations with more alfalfa within 5.0 km, less corn within 5.0 km, less developed land within 1.3 km, greater proportion of grassland within 0.5 km, greater proportion of herbaceous wetland within 1.0 km, lower TPI within 5.0 km, lower length of transmission lines within 5.0 km, areas closer to turbines, and with higher density of turbines within 1.3 km (Table 3). A nonlinear relationship of length of transmission lines within 5.0 km suggested that females with broods avoided areas once the length of transmission lines exceeded approximately 3.0 km within 5.0 km (Figure 4). Threshold terms considered for wind turbine density did not improve model fit. At the within home range scale, females selected brood-rearing locations with greater proportion of developed land within 1.0 km, greater proportion of grassland within 0.2 km, greater proportion of herbaceous wetland within 1.3 km, lower TPI, higher TRI, and areas closer to transmission lines (Table 3). A quadratic term describing wind turbine density within 1.0 km suggested that brood rearing sharp-tailed grouse avoided areas once the number of turbines within 1.0 km exceeded approximately 4 (Figure 4). At both scales of selection, an interaction between the proportion of grassland and turbine density improved model fit; models suggested that females with broods were less likely to avoid higher densities of wind turbines within 1.3 km at the home range scale ($\beta = 0.96$, 95% CI = 0.89 to 1.02), and within 1.0 km at the within home range ($\beta = 1.54$, 95% CI = 1.35 to 1.72; Figure 6) in areas with greater proportions of grassland, respectively.

The density of used and available locations in relation to wind infrastructure covariates to assess breeding season resource selection at the home range and within home range scales are in Appendix A (Figures A1 and A2). Models that contained wind energy infrastructure variables were more informative than base models during the breeding season (Table A3). The final home range scale model suggested that female sharp-tailed grouse selected areas with less developed land within 0.5 km, closer to roads, greater proportion of grassland within 0.2 km, less herbaceous wetland within 3.2 km, less soybean within 3.2 km, lower TPI within 5.0 km, areas farther from turbines and transmission lines, but greater turbine densities within 3.2 km (Table

4). The final model was improved by an interaction term describing the proportion of grassland within 0.2 km and distance to turbine ($\beta = 0.006$, 95% CI = 0.002 to 0.01; Figure 6), suggesting that females during the breeding season were less likely to avoid turbines at nearer distances in areas with greater proportion of grassland. The addition of a quadratic term describing distance to turbines suggested that the relative probability of selection by sharp-tailed grouse during the breeding season increased positively as distance to turbines increased up to approximately 14 km, after which relative probability of selection declined (Figure 5). Of note, however, is that only 6% of used locations were farther than 14 km from a turbine.

The spatial prediction of the RSF was a strong predictor of female home range resource selection during the breeding season (Figure A3). When we partitioned validation testing and training groups by individual, average $r^2 = 0.98 \pm < 0.01$ SE. In general, the relative probability of selection increased slightly in areas near turbines based on final model predictions (FigureA3B) relative to base model predictions (Figure A3A). There was a general shift where areas around turbines were considered to have higher predicted relative probability of selection when turbine covariates were included in final model predictions, suggesting that relative probability of selection was not reduced in areas near wind turbines at the home range scale (Figure A4).

At the within home range scale during the breeding season, the addition of turbine covariates improved model fit compared to base models (Table A3). The final model suggested that females selected breeding season locations within home ranges with less corn within 0.2 km, less developed land within 0.5 km, greater proportion of grassland within 0.2 km, less herbaceous wetland within 3.2 km, lower TPI, lower TRI within 3.2 km, areas closer to transmission lines, but lower lengths of transmission lines within 1.0 km. The addition of an interaction improved model fit ($\beta = 0.004$, 95% CI = 0.003 to 0.006; Figure 6), suggesting that females during the breeding season were less likely to avoid areas within 5.0 km with higher densities of wind turbines in areas with greater amounts of grassland within 0.2 km; however, the effect was marginal. A quadratic term describing turbine density within 5.0 km suggested that during the breeding season sharp-tailed grouse avoided areas within their home ranges that contained wind turbines within 5.0 km. The strongest avoidance occurred once an area exceeded approximately 20–35 wind turbines within 5.0 km (Figure 5B).

Nest and adult survival

The final nest survival model indicated that nest survival was negatively associated with the proportion of grassland within 1.3 km (Table 5). The addition of wind energy infrastructure did not improve model fit (Table A4). The addition of wind energy infrastructure covariates improved the female survival model fit compared to the base model (Table A4). The final model suggested that female survival was negatively associated with the proportion of developed land within 3.2 km, positively associated with the proportion of soybeans within 0.5 km, negatively associated with TPI within 5.0 km, and negatively associated with the density of wind turbines within 5.0 km (Table 5). However, we considered turbine density within 5.0 km to be uninformative because confidence intervals surrounding the parameter estimate overlapped 0.

DISCUSSION

Wildlife managers have been tasked with understanding how to mitigate the effects of energy development to prevent further declines in grassland bird populations. However, current literature evaluating grassland bird responses to wind energy development is generally mixed and provides limited context for conservation planning. Our study addressed an important knowledge gap focused on a wide-ranging, habitat generalist, the plains sharp-tailed grouse. We did not find evidence that females selected nest sites in relation to wind energy infrastructure but found that females with broods and during the breeding season avoided areas near high densities of wind turbines within their home ranges. Given the relative stability of the local sharp-tailed grouse population over the 3-year period of our study, as indexed by trends in yearly lek counts, potential avoidance behaviors in areas with relatively high densities of wind turbines did not appear to result in population level declines over the short-term following development of wind energy infrastructure. Our findings will be useful for identifying management practices to minimize impacts to sharp-tailed grouse exposed to future wind energy facilities.

Consistent with other studies, female sharp-tailed grouse selected areas with higher amounts of grassland across all life stages (Proett et al. 2019, Milligan et al. 2020a), highlighting the importance of conserving large intact grassland habitats for sharp-tailed grouse conservation (Runia et al. 2021). The median proportion of grassland used by sharp-tailed grouse during the breeding season in our study was relatively high and greater than 0.52 at used locations within all circular regions that were assessed (Figure A5). Another study reported the percentage of grassland and pasture hay within a 1.2-km radius was a strong positive predictor of sharp-tailed grouse occurrence and density in North and South Dakota (Runia et al. 2021). In Montana and western North Dakota, female sharp-tailed grouse selected a greater proportion of grassland habitats within their home ranges during the breeding season (Milligan et al. 2020a). Contrary to other studies, we found that sharp-tailed grouse nest survival decreased with higher proportions of grassland within 1.3 km. This negative relationship may be related to the local predator population, which we did not measure. For example, red foxes (*Vulpes vulpes*) displayed more foraging behavior in pastureland, compared to cropland (Philips et al. 2004). We also found that sharp-tailed grouse selected areas with more alfalfa during brood-rearing, a finding consistent with other studies (Goddard et al. 2009). Forb rich cultivated crop fields may function as preferred forage (Sullins et al. 2018) and potentially provide concealment structure. We found that sharp-tailed grouse selected nesting and brood-rearing habitats in depressions on the landscape (as indexed by TPI and TRI), characteristic of the prairie pothole region, which may further act as concealment from predators, provide higher soil moisture and concomitant vegetation productivity, and potentially provide thermal refugia (Raynor et al. 2018). Although other studies have found that prairie grouse generally avoid roads (Pitman et al. 2005, Pruett et al. 2009, Harrison et al. 2017), we found that sharp-tailed grouse selected areas near roads during the breeding season at the home-range scale. A potential explanation is that our study area contained mostly gravel roads used primarily by residential traffic as opposed to more heavily traveled roads.

We did not detect an effect of wind turbine distance or density on nest site selection at either scale that we assessed, a finding consistent with other studies evaluating prairie grouse response to wind energy development (McNew et al. 2014, Harrison et al. 2017, Proett et al. 2019, LeBeau et al. 2023). In addition, we found little evidence that females with broods avoided areas influenced by wind turbines at either scale of selection. Females with broods selected areas closer to turbines and with more turbines within 1.3 km at the home range scale. At the within home range scale, females with broods selected areas with up to approximately 4 turbines within 1.0 km. The addition of the interaction term at each scale further supported this relationship, suggesting that females with broods were more likely to use areas with greater densities of wind turbines, provided they were in areas with sufficient grassland. We are unaware of any prairie grouse studies that have evaluated brood-rearing resource selection relative to wind turbines, but

LeBeau et al. (2017b) found that female greater sage-grouse with broods avoided areas with higher density of wind turbines.

We found some evidence that resource selection by females during the breeding season was influenced by wind energy infrastructure. Females selected areas farther from wind turbines, but in areas with greater turbine density within 3.2 km at the home range scale. The spatial predictions of the home range breeding season RSF model, which also accounted for other attributes of sharp-tailed grouse habitat in the model, however provided limited support that wind turbines resulted in strong avoidance by sharp-tailed grouse at this scale. When considering the base RSF, 52.3% of wind turbines were in areas that were predicted to be in areas of medium-high or high relative probability of breeding season resource selection. Based on final model predictions that included wind energy infrastructure variables, 66.3% of wind turbines were in areas predicted to be in medium-high or high relative probability of selection, indicating that the additive effect of wind energy infrastructure did not reduce the relative probability of sharp-tailed grouse selection. In support, we also found that females during the breeding season were more likely to select areas closer to turbines, provided they were in areas with adequate grassland.

In contrast, we found that female sharp-tailed grouse selection was negatively associated with the count of wind turbines within 5.0 km at the within home range scale. This is contrary to the responses of lesser prairie chickens (*T. pallidicinctus*), which selected habitats closer to wind turbines when turbine densities were low (LeBeau et al. 2023). A count of 20–35 wind turbines within 5.0 km represented a potential threshold where sharp-tailed grouse avoidance of wind turbines was lowest. The model predicted an approximate 85 to 93% reduction in relative probability of selection when the number of wind turbines increased from 0 to 20 or 0 to 35 wind turbines within 5.0 km, respectively. The average number of turbines within 5.0 km of a point on the landscape within the study area was 9 (range: 0–57) and areas with greater than 20 wind turbines represented approximately 19% of the study area.

We found consistent selection for lower length of transmission lines across all life stages at the home range scale. Mounting evidence indicates that avoidance of transmission lines is a consistent behavior by prairie grouse at multiple spatial scales (Pruett et al. 2009, Londe et al. 2019, Plumb et al. 2019). It is hypothesized that grouse may avoid transmission lines because they can act as perches for avian predators, increasing raptor abundance and predation risk for grouse (Hagen et al. 2011, Gibson et al. 2018). That we generally failed to detect a consistent effect of transmission line length or distance across life stages at the within home range scale likely indicates that sharp-tailed grouse were primarily selecting habitats at the larger scale, wherein fewer transmission lines were available to be avoided within home ranges. Vegetation characteristics and topography appeared to be more important to sharp-tailed grouse when selecting habitats at the finer scale. While most studies have evaluated prairie grouse responses as a function of distance to transmission lines, Sullins et al. (2019) found a similar avoidance of length of transmission lines by lesser prairie-chickens when assessed within a 2.0 km radius.

Similar to other studies evaluating grouse responses to wind energy development, we did not detect an effect of wind energy infrastructure on nest survival (McNew et al. 2014, Harrison et al. 2017, LeBeau et al. 2017b, Proett et al. 2019, LeBeau et al. 2023). Other studies at wind energy facilities have documented vegetation characteristics related to concealment or visual obstruction to influence nest survival, suggesting the importance of concealment from predators and foraging opportunities (McNew et al. 2014, Proett et al. 2019, LeBeau et al. 2023). Interestingly, we found that nest survival was negatively associated with the amount of grassland within 1.3 km. This relationship is contrary to other research and may be an artifact of the spatial scales that were assessed (e.g., unmeasured factors such as grassland patch sizes or habitat heterogeneity) in this study system. We did not evaluate brood survival relative to wind energy infrastructure; however, there is evidence that brood success and chick survival of Columbian sharp-tailed grouse (*T. p. columbianus*) is negatively associated with wind turbine density (Proett et al. 2022), warranting further investigation. Based on our analysis criteria, we did not find evidence that female survival during the breeding season was associated with wind energy infrastructure. However, this may be a biologically meaningful effect. We cannot rule out the possibility that unmeasured environmental factors influenced survival, which could have potentially been uncovered with a longer-term dataset. Other studies have found that adult survival increased (Winder et al. 2014, LeBeau et al. 2017b) or was not influenced by wind energy infrastructure (Smith et al. 2017, LeBeau et al. 2023) following construction. Addressing the uncertainty in the effect of turbine density on female survival will be necessary to fully understand how wind energy infrastructure may impact sharp-tailed grouse.

Although we observed avoidance behavior associated with wind energy infrastructure during the breeding season, relatively stable lek trends over our 3-year study suggest that this behavioral response has not resulted in population level declines. This is based on an assumption that lek counts are suitable indices of grouse population trends, which is supported by greater sage-grouse population modeling (Dahlgren et al. 2016). Other prairie grouse research has found that population trends, indexed by lek counts, are not negatively impacted by wind energy infrastructure (LeBeau et al. 2017a), although there is evidence that lek persistence may be lower closer to turbines (Winder et al. 2015). Nonetheless, our findings support the existing body of evidence that prairie grouse may not experience population level impacts over the short-term following development of wind energy facilities (Lloyd et al. 2022).

The lack of other studies investigating the effects of wind energy development on sharp-tailed grouse resource selection and survival limits our ability to make predictions about how sharp-tailed grouse may respond to wind energy development over a longer period. In addition, we lacked pre-development data to understand how sharp-tailed grouse utilized our study area prior to construction of the wind energy facilities, which is an unfortunate shortcoming in most wildlife-impact studies (Hebblewhite 2011, Conkling et al. 2020). It has been suggested that grouse may exhibit a 3 or more-year lagged response to renewable and conventional energy development (e.g., Walker et al. 2007, Green et al. 2017, LeBeau et al 2017a), and 10 or more years of data may be necessary to fully understand and detect population level impacts (*sensu* Harju et al. 2010). While most studies have failed to detect negative effects of wind energy on grouse populations, long-term replicated studies are necessary to adequately address the impacts associated with wind energy development (Coppes et al. 2020, Lloyd et al. 2022).

MANAGEMENT IMPLICATIONS

Based on the results of our study, siting wind turbines in a manner that does not exceed 20–35 wind turbines within 5.0 km of sharp-tailed grouse breeding habitat may represent an important siting threshold to minimize sharp-tailed grouse avoidance. If development of new transmission lines is necessary for a wind energy facility, collocation with existing infrastructure and in areas outside of sharp-tailed grouse breeding habitat should be encouraged to minimize sharp-tailed grouse avoidance. Sharp-tailed grouse breeding habitat occurs in close proximity to lek locations, which are typically centered on large intact grasslands (Merrill et al. 1999, Hanowski et al. 2000, Niemuth 2000). In our study, 95% of female breeding season locations (including nest and brood-rearing) occurred within 4.3 km of an active lek (50% of locations were with 1.4 km) and 95% were located in areas that contained greater than 28% grassland (50% of locations contained greater than 52% grassland) within all scales that we assessed. Minimizing placement of wind energy infrastructure within intact grasslands (e.g., greater than 28% regardless of scale) and within 5 km of a lek would limit avoidance by sharp-tailed grouse occupying habitats during the breeding season. Although we did not detect population level declines because of avoidance behaviors, future research employing long-term datasets and robust study designs will be necessary to determine additional management prescriptions especially in areas where available habitat differs from our study. Our results will be useful for future siting of wind energy facilities occurring in similar habitats as our study through informed management recommendations to minimize impacts to sharp-tailed grouse.

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ETHICS STATEMENT

All grouse captures adhered to protocols of a South Dakota Game, Fish and Parks scientific collection permit (Permit No. 14) to minimize handling time and capture related stress.

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FIGURE CAPTIONS

Figure 1. Study area located in Grant, Codington, and Deuel counties, South Dakota, USA, including locations of wind turbines, land cover types, sharp-tailed grouse leks monitored during the 2020–2022 breeding seasons, and leks where grouse captures occurred within the study area.

Figure 2. Trends in sharp-tailed grouse leks monitored during the 2020–2022 breeding seasons within the study area in Grant, Codington, and Deuel counties, South Dakota, USA. Points connected by dashed lines represent individual leks. The solid black line connects the mean maximum lek count for each year. Points that are not connected by dashed lines were not monitored in previous years.

Figure 3. Nest, brood-rearing, and breeding season locations of female sharp-tailed grouse within the study area in Grant, Codington, and Deuel counties, South Dakota, USA, during the 2020–2022 breeding seasons.

Figure 4. Relative probability of brood-rearing female sharp-tailed grouse selection at the home range (A) and within home range (B) scales as a function of length of transmission lines within 5.0 km and count of wind turbines within 1.0 km near the study area in Grant, Codington, and Deuel counties, South Dakota, USA, during the 2020–2022 breeding seasons. Dashed lines represent 95% confidence intervals surrounding predictions.

Figure 5. Relative probability of female sharp-tailed grouse breeding season selection at the home range (A) and within home range (B) scales as a function of distance to transmission lines and count of wind turbines within 5.0 kilometers in Grant, Codington, and Deuel counties, South Dakota, USA, during the 2020–2022 breeding seasons. Dashed lines represent 95% confidence intervals surrounding predictions.

Figure 6. Estimated coefficients and 95% confidence intervals (CI) for interactions describing breeding season home range (panel A), breeding season within home range (panel B), brood-rearing home range (panel C) and brood-rearing within home range (panel D) selection.

Table 1. Spatial predictor variables used to assess sharp-tailed grouse resource selection and survival in Grant, Codington, and Deuel counties, South Dakota, USA, from 2020–2022.

Covariate[a]	Description	Biological Significance	Citation
Habitat variables			
Alfalfa	Alfalfa canopy cover (%; US Department of Agriculture [USDA] 2023)	Forb dense crop that may act as preferred forage	Goddard et al. 2009, Sullins et al. 2018
Corn	Corn canopy cover (%; USDA 2023)	May act as a preferred forage	Roy and Chen 2023
Grassland	Grassland canopy cover (%; USDA 2023)	Prairie grouse have strong selection for grasslands across all life stages	Proett et al. 2019, Milligan et al. 2020a, Runia et al. 2021
Herbaceous wetland	Herbaceous wetland (%; USDA 2023)	May provide dense vegetation for concealment and a source of invertebrates	McDonald and Reese 1998
Soybeans	Soybean canopy cover (%; USDA 2023)	May act as a preferred forage	Roy and Chen 2023
Total crop	Combined canopy cover of alfalfa, corn, miscellaneous crop, and soybeans (%; USDA 2023)	Higher proportions of cropland may result in decreases in survival	Milligan et al. 2020b
Distance to roads	Euclidean-distance to road (km; South Dakota Department of Transportation 2022, Minnesota Department of Transportation 2012)	Vehicle noise may increase perceived risk	Pitman et al. 2005, Pruett et al. 2009, Harrison et al. 2017, Londe et al. 2022
Terrain Positioning Index (TPI)	Mean terrain positioning index (Positive values = area higher than surroundings; negative values = area lower than surroundings; Guisan et al. 1999) derived from a digital elevation model (US Geological Survey [USGS] 2023).	Lower TPI values may act as concealment and provide thermal refugia	Raynor et al. 2018
Terrain Roughness Index (TRI)	Mean topographic ruggedness index (Positive values = area more rugged than surroundings, example: ridges; negative values = area less rugged than surroundings, example: depressions; Wilson et al. 2007) derived from a digital elevation model (USGS 2023).	Lower TRI values (depressions) may catch water resulting in higher soil moisture and more vegetation growth for concealment	Raynor et al. 2018
Wind energy infrastructure variables			

Distance to transmission line	Euclidean-distance to transmission or distribution line (69–345 kilovolt; km; Department of Homeland Security [DHS] 2022)	May act as perches for aerial predators and increase risk and avoidance by grouse	Hagen et al. 2011, Pruett et al. 2009, Londe et al. 2019, Plumb et al. 2019
Distance to turbine	Euclidean-distance to turbine (km; Hoen et al. 2018)	Presence of turbines may result in avoidance of otherwise suitable habitat	Winder et al. 2014, LeBeau et al. 2017
Transmission line length	Length of transmission line (km; DHS 2022)	Higher densities may result in higher perceived risk	Sullins et al. 2019
Turbine density	Count of wind turbines (Hoen et al. 2018)	Number of turbines may affect the strength of avoidance behaviors	LeBeau et al. 2023

[a] Non-Euclidean distance habitat variables were estimated across 0.2, 0.5, 1.0, 1.3, 3.2, and 5.0-kilometer (km) radii circular scales. Wind energy infrastructure variables were estimated across 1.0, 1.3, 3.2, and 5.0 km radii scales.

Table 2. Coefficient estimates and 95% confidence intervals (CI) for covariates in models describing sharp-tailed grouse nest site selection at home range (second order) and within home range (third order) scales in Grant, Codington, and Deuel counties, South Dakota, USA, 2020–2022.

Model and variable	**Scale (km)**	**Coefficient**	**Lower CI**	**Upper CI**
Home range scale (second order)				
Corn	0.2	-1.31	-2.77	0.15
Developed	0.5	-0.36	-0.73	0.02
Grassland	0.2	1.11	0.65	1.57
Herbaceous wetland	3.2	-0.40	-0.72	-0.08
TPI	5.0	-0.63	-0.93	-0.32
TRI	3.2	-0.70	-1.12	-0.28
Transmission line length	5.0	-0.80	-1.23	-0.37
Within home range scale (third order)				
Corn	0.2	-0.56	-1.34	0.22
Grassland	0.2	0.44	0.09	0.79
TPI	NA	-0.23	-0.45	-0.01

Table 3. Coefficient estimates and 95% confidence intervals (CI) for covariates in models describing sharp-tailed grouse brood-rearing site selection at the home range (second order) and within home range (third order) scales in Grant, Codington, and Deuel counties, South Dakota, USA, 2020–2022.

Model and variable	Scale (km)	Coefficient	Lower CI	Upper CI
Home range scale (second order)				
Alfalfa	5.0	0.21	0.20	0.23
Corn	5.0	-1.31	-1.34	-1.29
Developed	1.3	-0.58	-0.59	-0.56
Grassland	0.5	1.03	1.01	1.05
Herbaceous wetland	1.0	0.34	0.32	0.35
TPI	5.0	-0.82	-0.84	-0.80
Distance to turbine	NA	-0.26	-0.29	-0.23
Transmission line length	5.0	1.15	1.02	1.27
Transmission line length[a]	5.0	-10.02	-10.48	-9.57
Turbine density	1.3	0.46	0.43	0.48
Within home range scale (third order)				
Developed	1.0	0.07	0.04	0.09
Grassland	0.2	0.21	0.20	0.23
Herbaceous wetland	1.3	0.71	0.64	0.77
Soybeans	1.3	-0.02	-0.05	0.01
TPI	NA	-0.31	-0.32	-0.30
TRI	NA	0.18	0.16	0.19
Distance to transmission line	NA	-0.51	-0.59	-0.44
Turbine density	1.0	0.73	0.67	0.79
Turbine density[a]	1.0	-0.34	-0.39	-0.29

[a] Quadratic term.

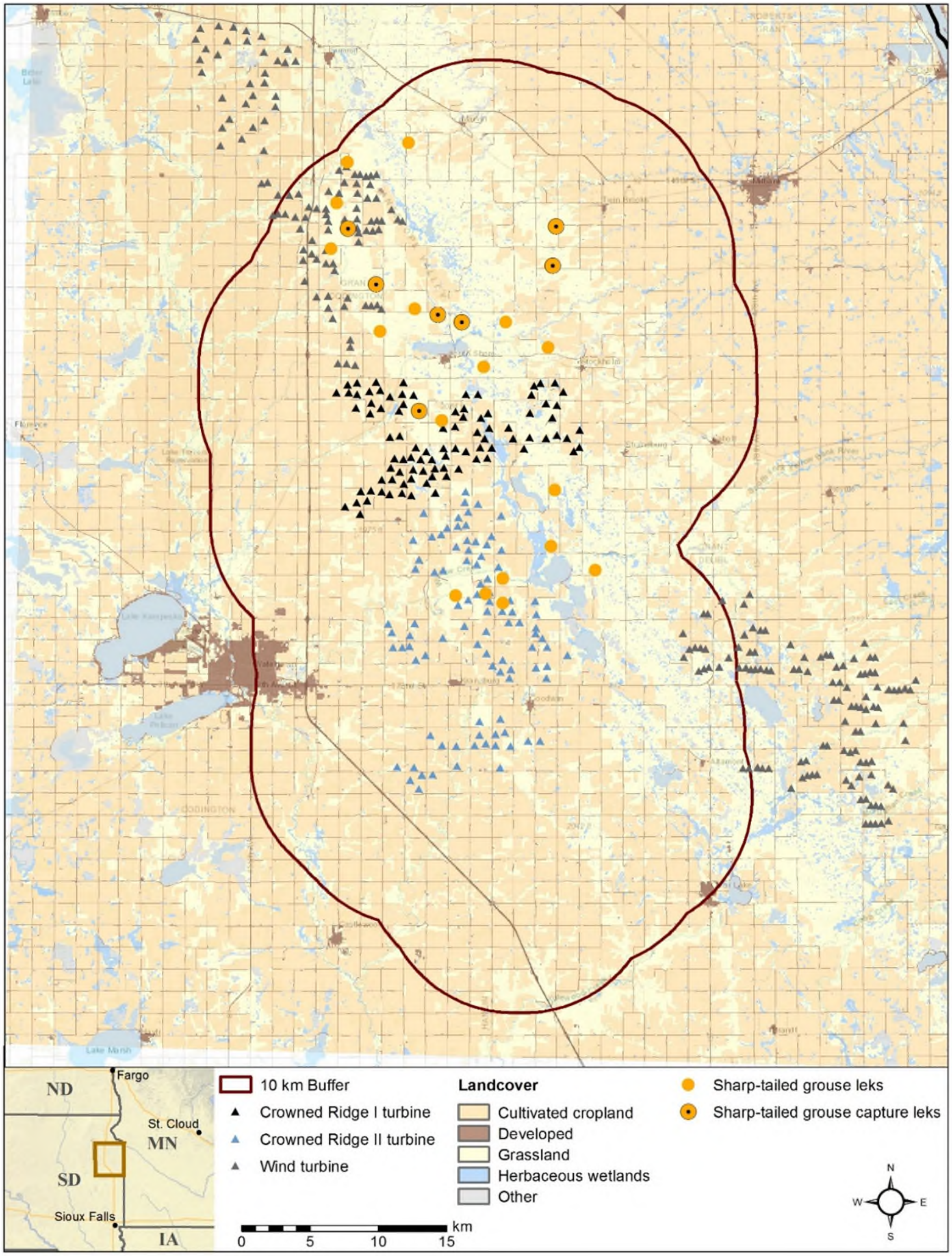
Table 4. Coefficient estimates and 95% confidence intervals (CI) for covariates in models describing female sharp-tailed grouse breeding season (April 1 through August 15) site selection at the home range (second order) and within home range (third order) scales in Grant, Codington, and Deuel counties, South Dakota, USA, 2020–2022.

Model and variable	**Scale (km)**	**Coefficient**	**Lower CI**	**Upper CI**
Home range scale (second order)				
Developed	0.5	-0.61	-0.62	-0.59
Distance to road	NA	-0.25	-0.26	-0.24
Grassland	0.2	0.54	0.53	0.55
Herbaceous wetland	3.2	-0.28	-0.30	-0.27
Soybeans	3.2	-0.34	-0.36	-0.33
TPI	5.0	-0.16	-0.17	-0.15
Distance to transmission line	NA	0.60	0.59	0.61
Distance to turbine	NA	1.73	1.68	1.78
Distance to turbine[a]	NA	-1.52	-1.58	-1.46
Turbine density	3.2	0.80	0.79	0.82
Within home range scale (third order)				
Corn	0.2	-0.25	-0.26	-0.24
Developed	0.5	-0.26	-0.27	-0.25
Grassland	0.2	0.24	0.23	0.26
Herbaceous wetland	3.2	-0.17	-0.18	-0.16
TPI	NA	-0.08	-0.08	-0.07
TRI	3.2	-0.04	-0.06	-0.03
Distance to transmission line	NA	-0.18	-0.20	-0.17
Transmission line length	1.0	-0.02	-0.03	-0.01
Turbine density	5.0	-0.78	-0.83	-0.72
Turbine density[a]	5.0	0.59	0.54	0.65

[a] Quadratic term.

Table 5. Coefficient estimates and 95% confidence intervals (CI) for covariates in models describing sharp-tailed grouse nest and female survival in Grant, Codington, and Deuel counties, South Dakota, USA, 2020–2022. A positive coefficient indicated a greater risk of nest failure or female mortality.

Model and variable	**Scale (km)**	**Coefficient**	**Lower CI**	**Upper CI**
Nest survival				
Grassland	1.3	2.89	0.02	5.77
Adult survival				
Developed	3.2	88.15	42.97	133.32
Soybeans	0.5	-3.14	-5.56	-0.72
TPI	5.0	0.91	0.06	1.75
Turbine density	5.0	0.01	-0.02	0.03



ND
Fargo
St. Cloud
MN
SD
Sioux Falls
IA
10 km Buffer
Crowned Ridge I turbine
Crowned Ridge II turbine
Wind turbine
Landcover
Cultivated cropland
Developed
Grassland
Herbaceous wetlands
Other
Sharp-tailed grouse leks
Sharp-tailed grouse capture leks
0 5 10 15 km
N
W
E
S

Figure 1.

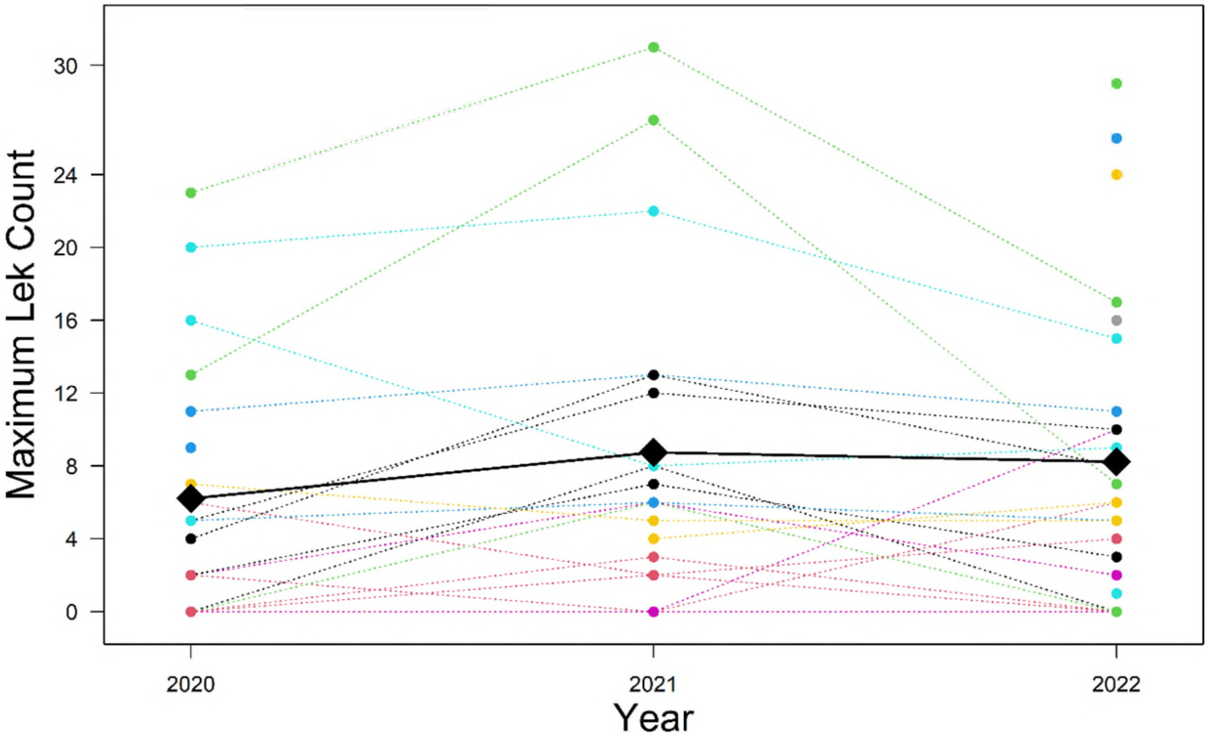


Figure 2.

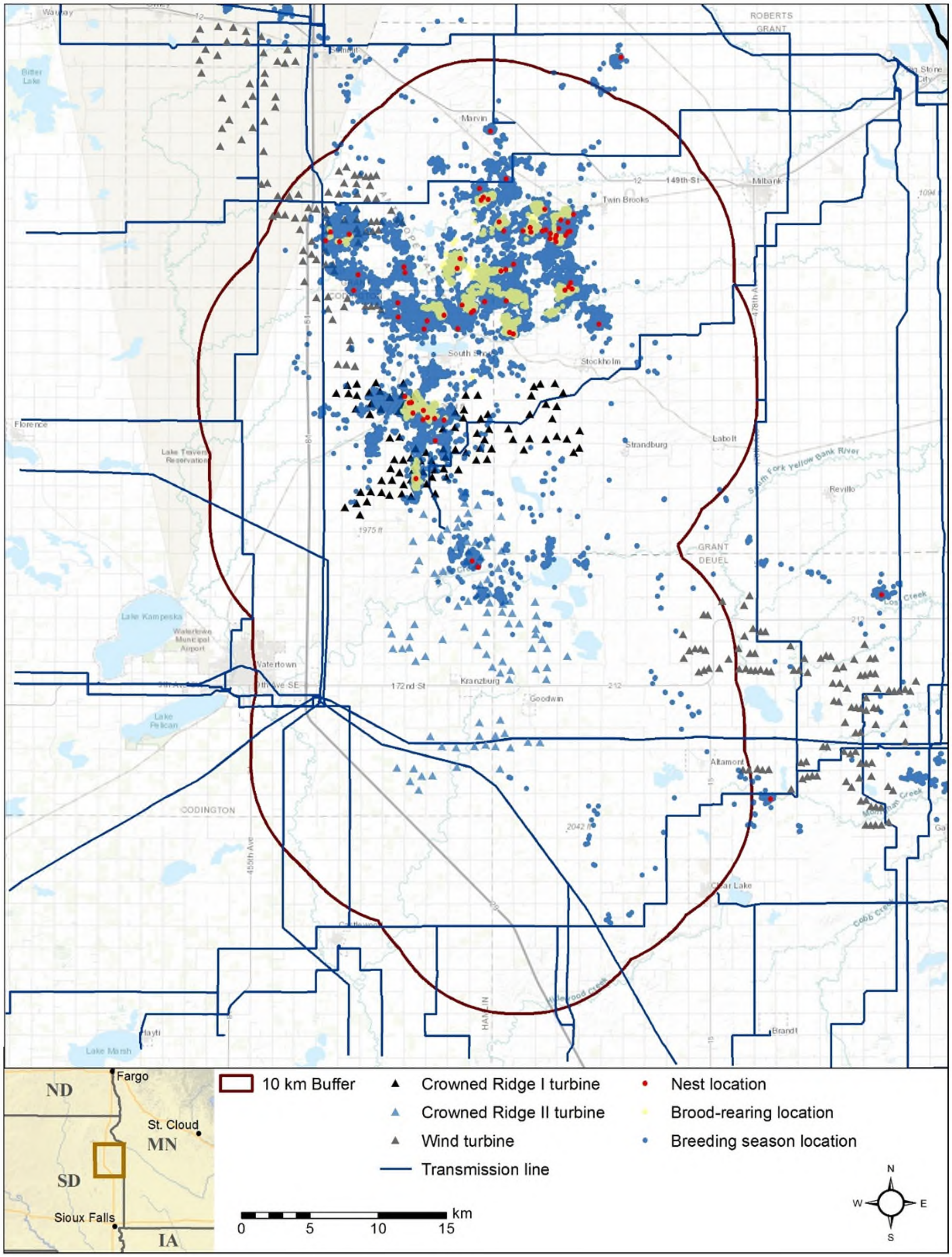
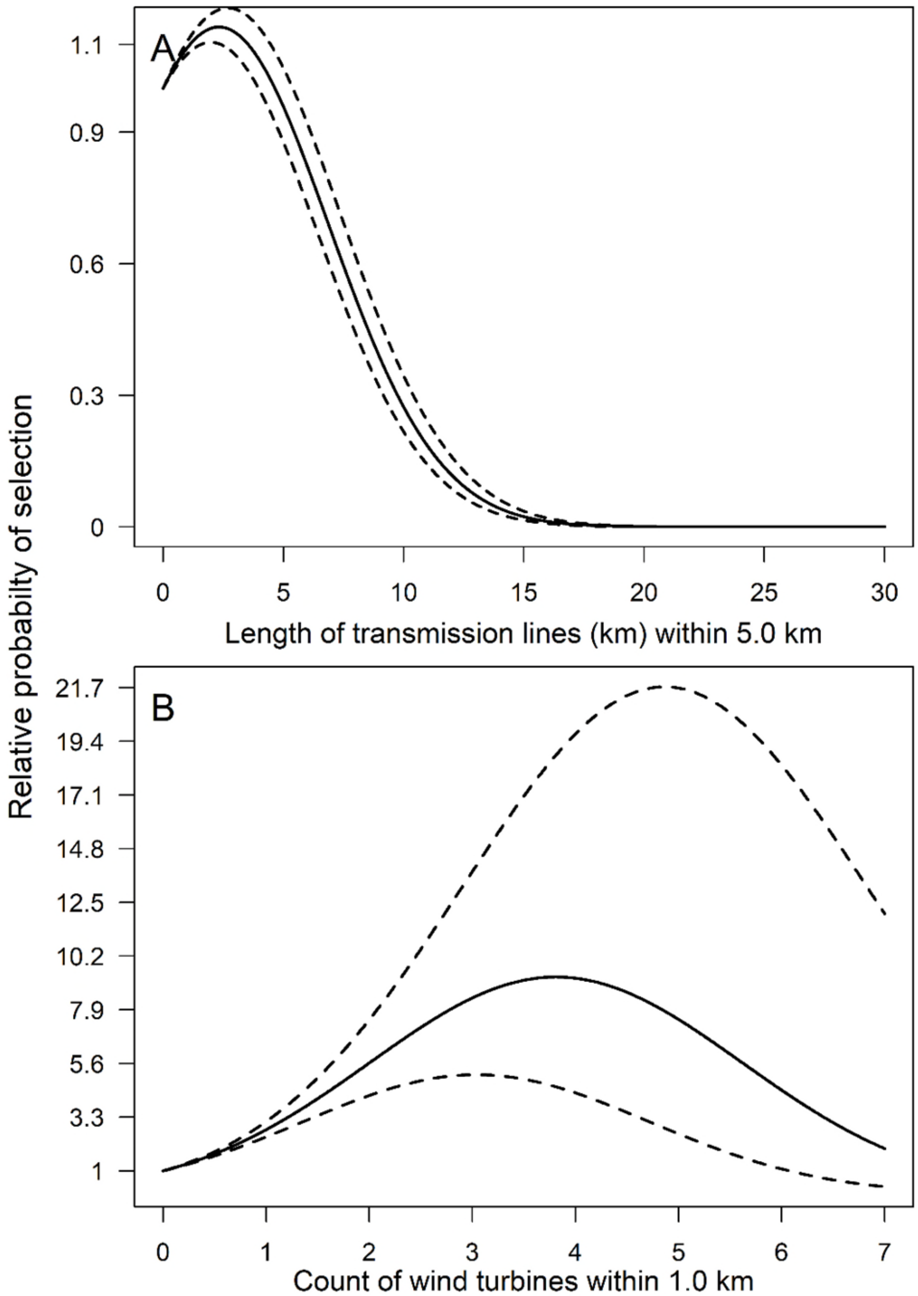

10 km Buffer
Crowned Ridge I turbine
Crowned Ridge II turbine
Wind turbine
Transmission line
Nest location
Brood-rearing location
Breeding season location
km
0
5
10
15
N
S
E
W
ND
SD
MN
IA
Fargo
St. Cloud
Sioux Falls
ROBERTS
GRANT
DEUEL
CODINGTON
HAMLIN
Marvin
Milbank
Twin Brooks
149th St
Stockholm
Strandburg
Labolt
Revillo
South Fork Yellow Bank River
Florence
Lake Traverse Reservation
Lake Kampeska
Watertown Municipal Airport
Watertown
Lake Pelican
172nd St
Kranzburg
Goodwin
Altamont
Clear Lake
Brandt
Hayti
Lake Marsh
Bitter Lake
1975 ft
2042 ft

Figure 3.



A
1.1
0.9
0.6
0.3
0
0
5
10
15
20
25
30
Length of transmission lines (km) within 5.0 km
Relative probabilty of selection
B
21.7
19.4
17.1
14.8
12.5
10.2
7.9
5.6
3.3
1
0
1
2
3
4
5
6
7
Count of wind turbines within 1.0 km

Figure 4.

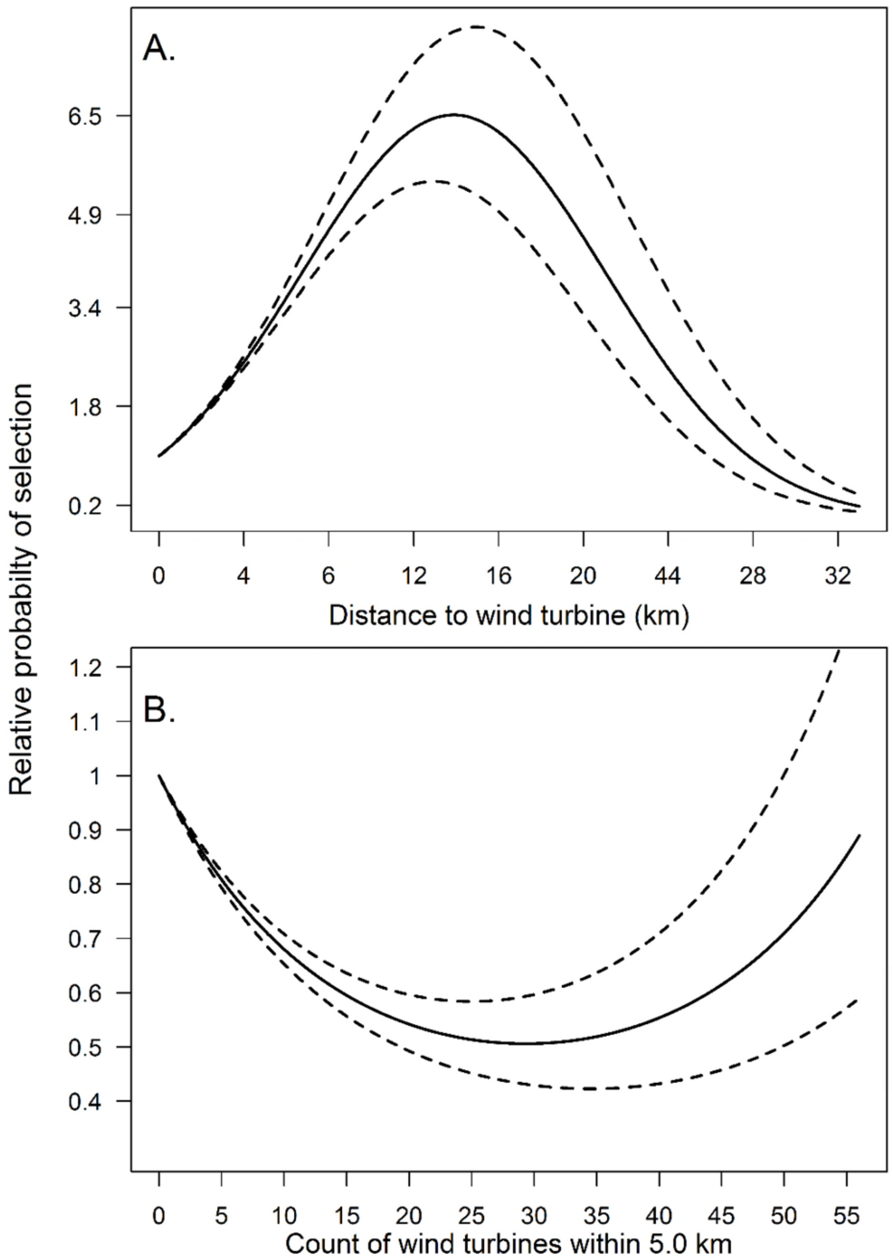
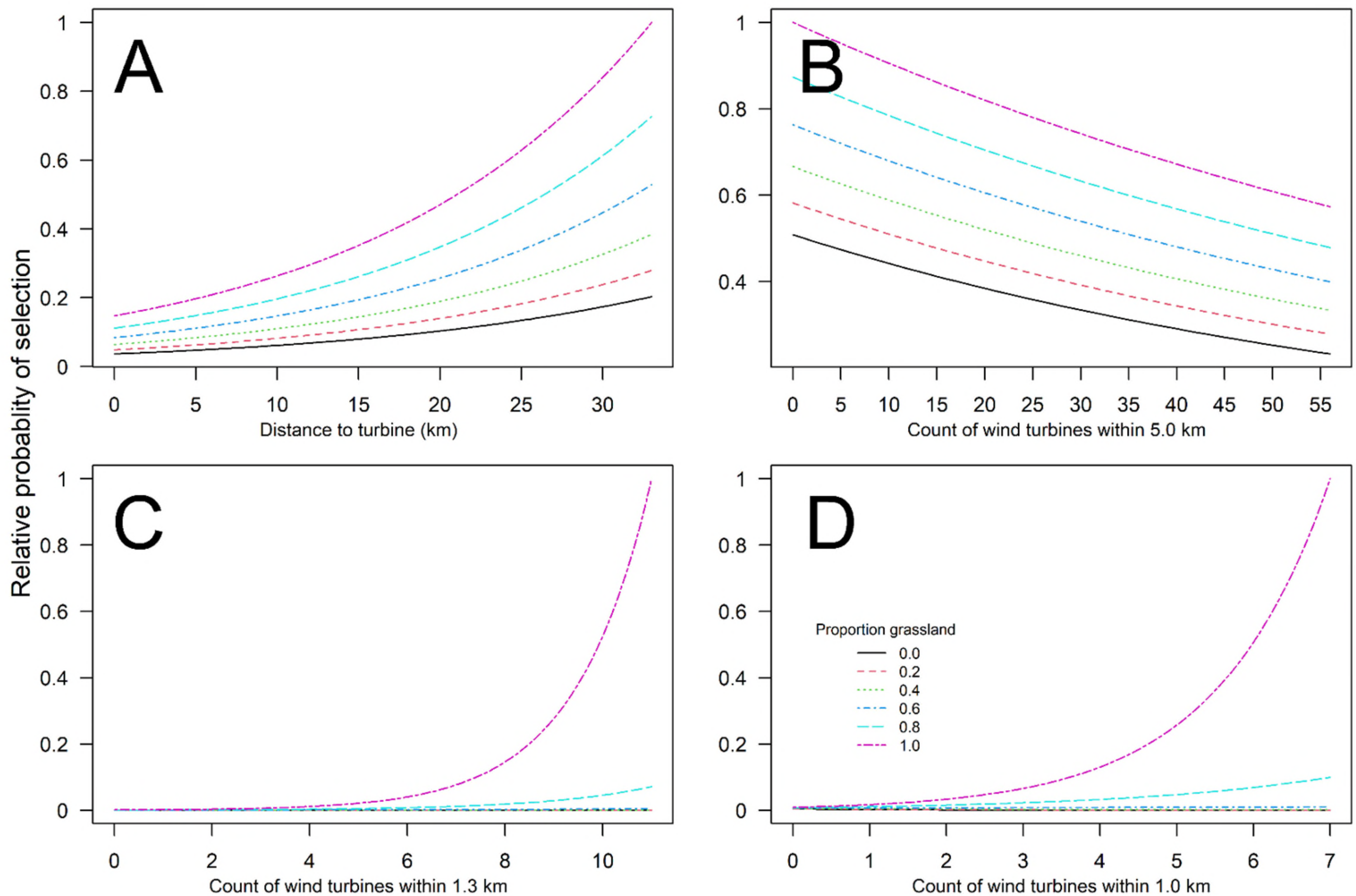

A.
B.
Relative probability of selection
6.5
4.9
3.4
1.8
0.2
0
4
6
12
16
20
44
28
32
Distance to wind turbine (km)
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0
5
10
15
20
25
30
35
40
45
50
55
Count of wind turbines within 5.0 km

Figure 5.



A
B
C
D
Relative probablity of selection
Distance to turbine (km)
Count of wind turbines within 5.0 km
Count of wind turbines within 1.3 km
Count of wind turbines within 1.0 km
Proportion grassland
0.0
0.2
0.4
0.6
0.8
1.0

Figure 6.

Appendix A. Additional supporting information

Table A1. Top 5 (if applicable) models used to assess sharp-tailed grouse nest site selection in Grant, Codington, and Deuel counties, South Dakota, USA, 2020–2022. Base models were included for comparison if not in the top 5 models.

	Model fit statistics[a]		
Model	**K**	**ΔAIC**	$\boldsymbol{w_i}$
Home range scale[b]			
Base model parameters + length of transmission line$_{5.0km}$	8	0.00	0.68
Base model parameters + length of transmission line$_{5.0km}$ + turbine density$_{1.3km}$	9	2.00	0.25
Base model parameters + distance to transmission line	8	5.34	0.05
Base model parameters + distance to transmission line + turbine density$_{1.3km}$	9	7.31	0.02
Base model parameters	7	19.58	0.00
Within home range scale[c]			
Base model parameters[d]	4	NA	NA

[a]Number of parameters (K), change in AICc (ΔAICc), and Akaike weights (w_i).

[b]Base model parameters include proportion corn within 0.2 km, proportion developed within 0.5 km, proportion grassland within 0.2 km, proportion herbaceous wetland within 3.2 km, TPI within 5.0 km, and TRI within 3.2 km.

[c]Base model parameters include proportion corn within 0.2 km, proportion grassland within 0.2 km, and TPI at the local scale.

[d]No wind energy infrastructure variables were retained following initial variable screening.

Table A2. Top 5 (if applicable) models used to assess female sharp-tailed grouse brood-rearing resource selection in Grant, Codington, and Deuel counties, South Dakota, USA, 2020–2022. Base models were included for comparison if not in the top 5 models.

	Model fit statistics[a]		
Model	**K**	**ΔAIC**	w_i
Home range scale[b]			
Base model parameters + length of transmission line$_{5.0km}$ + turbine density$_{1.3km}$ + distance to turbine	10	0.00	1.00
Base model parameters + length of transmission line$_{5.0km}$ + turbine density$_{1.3km}$	9	155.47	0.00
Base model parameters + length of transmission line$_{5.0km}$ + distance to turbine	9	1,613.21	0.00
Base model parameters + length of transmission line$_{5.0km}$	8	2,348.78	0.00
Base model parameters + distance to transmission line + turbine density$_{1.3km}$ + distance to turbine	10	6,210.53	0.00
Base model parameters	7	17,320.18	0.00
Within home range scale[c]			
Base model parameters + distance to transmission line + turbine density$_{1.0km}$	9	0.00	0.70
Base model parameters + distance to transmission line + turbine density$_{1.0km}$ + distance to turbine	10	1.71	0.30
Base model parameters + length of transmission line$_{5.0km}$ + turbine density$_{1.0km}$ + distance to turbine	10	74.42	0.00
Base model parameters + turbine density$_{1.0km}$ + distance to turbine	9	84.83	0.00
Base model parameters + length of transmission line$_{5.0km}$ + turbine density$_{1.0km}$	9	111.53	0.00
Base model parameters	7	920.11	0.00

[a] Number of parameters (K), change in AICc (ΔAICc), and Akaike weights (w_i).

[b] Base model parameters include proportion alfalfa within 5.0 km, proportion corn within 5.0 km, proportion developed within 1.3 km, proportion grassland within 0.5 km, proportion herbaceous wetland within 1.0 km, and TPI within 5.0 km.

[c] Base model parameters include proportion developed within 1.0 km, proportion grassland within 0.2 km, proportion herbaceous wetland within 1.3 km, proportion soybeans within 1.3 km, TPI at the local scale, and TRI at the local scale.

Table A3. Top 5 (if applicable) models used to assess female sharp-tailed grouse breeding season resource selection in Grant, Codington, and Deuel counties, South Dakota, USA, 2020–2022. Base models were included for comparison if not in the top 5 models.

	Model fit statistics[a]		
Model	**K**	**ΔAIC**	w_i
Home range scale[b]			
Base model parameters + distance to transmission line + turbine density$_{3.2km}$ + distance to turbine	10	0.00	1.00
Base model parameters + distance to transmission line + turbine density$_{3.2km}$	9	2,218.26	0.00
Base model parameters + length of transmission line$_{5.0km}$ + turbine density$_{3.2km}$ + distance to turbine	10	3,490.71	0.00
Base model parameters + length of transmission line$_{5.0km}$ + turbine density$_{3.2km}$	9	4,317.01	0.00
Base model parameters + distance to transmission line + distance to turbine	9	5,903.48	0.00
Base model parameters	7	22,200.54	0.00
Within home range scale[c]			
Base model parameters + length of transmission line$_{1.0km}$ + distance to transmission line + turbine density$_{5.0km}$	10	0.00	1.00
Base model parameters + distance to transmission line + turbine density$_{5.0km}$	9	18.34	0.00
Base model parameters + length of transmission line$_{1.0km}$ + distance to transmission line + distance to turbine	10	181.66	0.00
Base model parameters + distance to transmission line + distance to turbine	9	191.01	0.00
Base model parameters + length of transmission line$_{1.0km}$ + distance to transmission line	9	365.63	0.00
Base model parameters	7	700.34	0.00

[a] Number of parameters (K), change in AICc (ΔAICc), and Akaike weights (w_i).

[b] Base model parameters include proportion developed within 0.5 km, proportion grassland within 0.2 km, proportion herbaceous wetland within 3.2 km, distance to road, proportion soybean within 3.2 km, and TPI within 5.0 km.

[c] Base model parameters include proportion corn within 0.2 km, proportion developed within 0.5 km, proportion grassland with 0.2 km, proportion herbaceous wetland within 3.2 km, TPI at the local scale, and TRI within 3.2 km.

Table A4. Top 5 (if applicable) models used to assess sharp-tailed nest and female survival in Grant, Codington, and Deuel counties, South Dakota, USA, 2020–2022. Base models were included for comparison if not in the top 5 models.

	Model fit statistics[a]		
Model	**K**	**ΔAIC**	w_i
Nest survival[b]			
Base model parameters	1	0.00	0.57
Base model parameters + distance to turbine	2	0.53	0.43
Female survival[c]			
Base model parameters + turbine density$_{5.0km}$	4	0.00	0.60
Base model parameters	3	1.95	0.23
Base model parameters + distance to turbine	4	2.49	0.17

[a] Number of parameters (K), change in AICc (ΔAICc), and Akaike weights (w_i).

[b] Base model parameters include proportion grassland within 1.3 km.

[c] Base model parameters include proportion developed within 3.2 km, proportion soybean within 0.5 km, and TPI within 5.0 km.

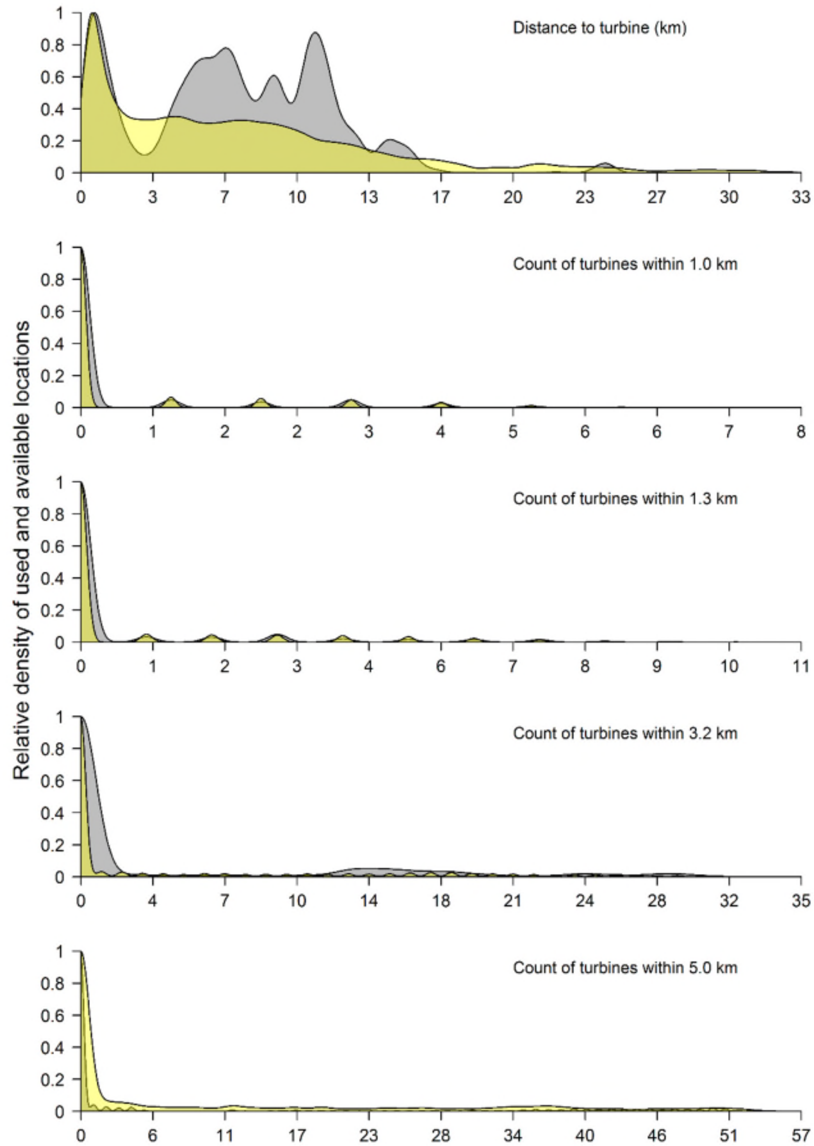


Figure A1. Relative density of locations used by female sharp-tailed grouse (gray) and what was available at the home range scale (yellow) relative to distance to wind turbines and count of wind turbines within 1.0, 1.3, 3.2, and 5.0 km radii in Grant, Codington, and Deuel counties, South Dakota, USA, during the 2020–2022 breeding seasons.

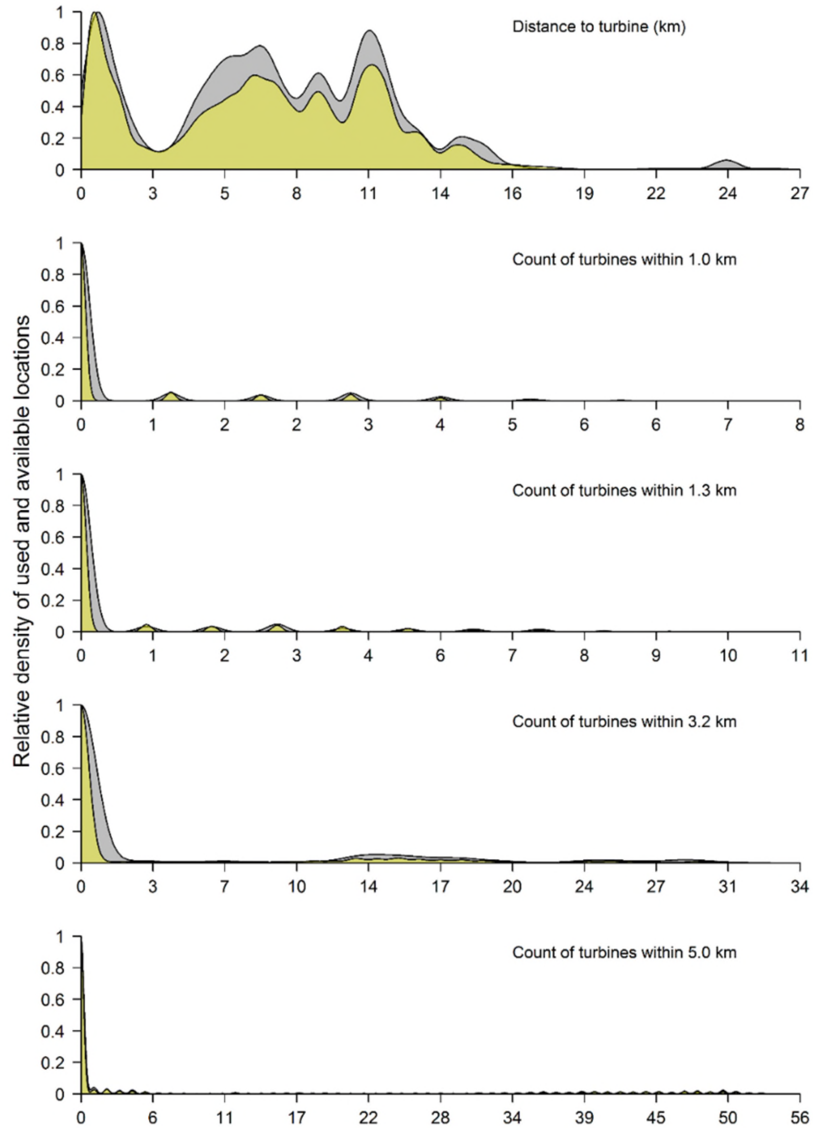


Figure A2. Relative density of locations used by female sharp-tailed grouse (gray) and what was available at the within home range scale (yellow) relative to distance to wind turbines and count of wind turbines within 1.0, 1.3, 3.2, and 5.0 km near the Crowned Ridge I and Crowned Ridge II Wind Energy Projects during 2020–2022 breeding seasons.

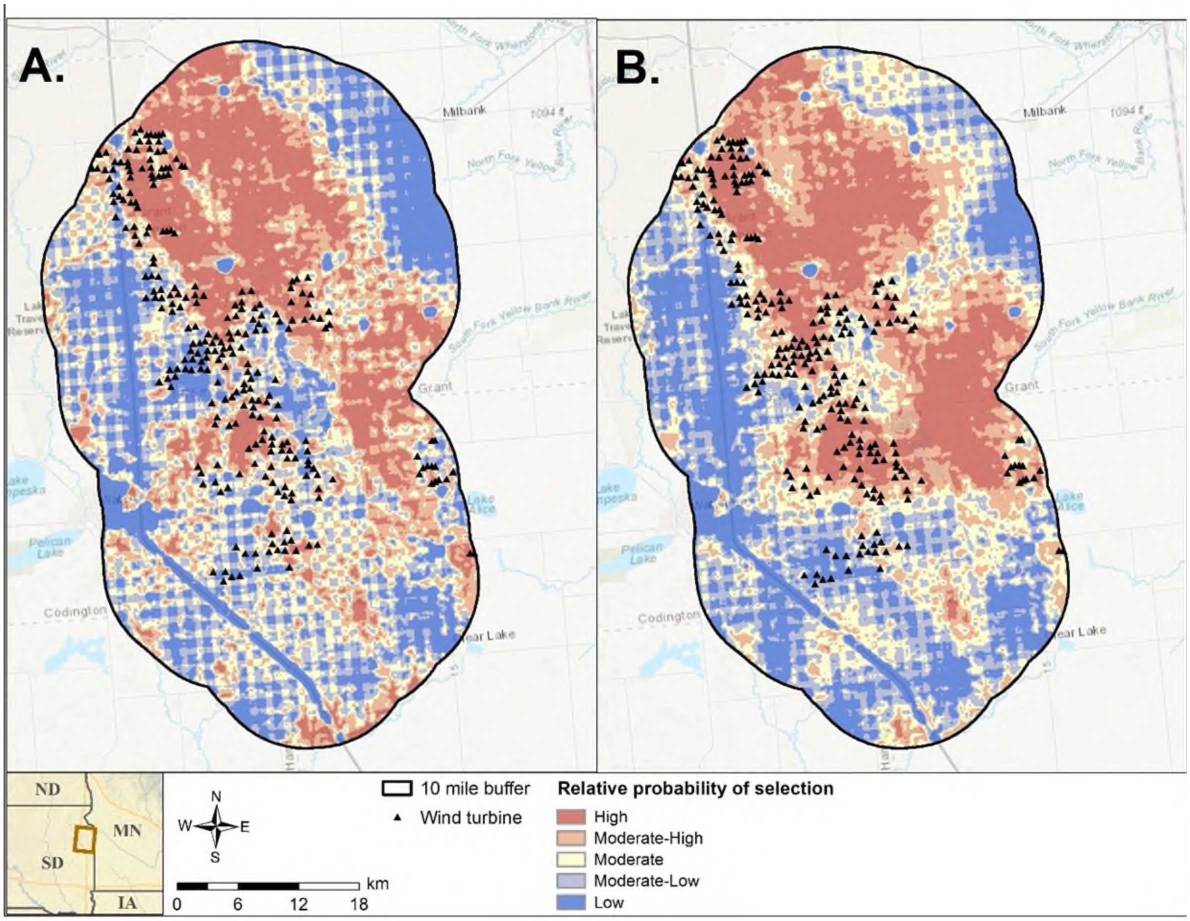


Figure A3. Predicted relative probability of female sharp-tailed grouse breeding season selection at the home range scale from models that did not (A) and models that did (B) include wind energy infrastructure variables in Grant, Codington, and Deuel counties, South Dakota, USA, during the 2020–2022 breeding season. Predictions were generated within the study area.

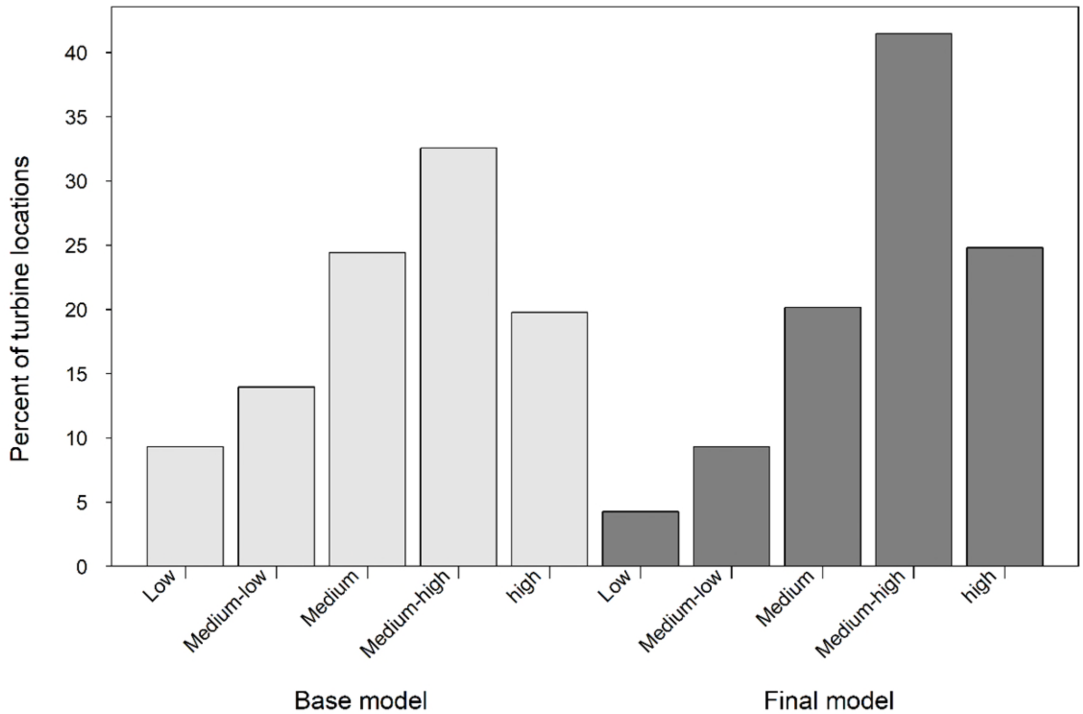


Figure A4. Percent of Crowned Ridge I and Crowned Ridge II wind turbine locations within each resource selection function (RSF) model-predicted bin from the lowest predicted probability of selection (left-most bins) to the highest predicted probability of selection (right-most bins). RSF models were developed using female sharp-tailed grouse locations in Grant, Codington, and Deuel counties, South Dakota, USA, during the 2020–2022 breeding seasons and represented models that included (final model) or did not include (base model) wind energy covariates.

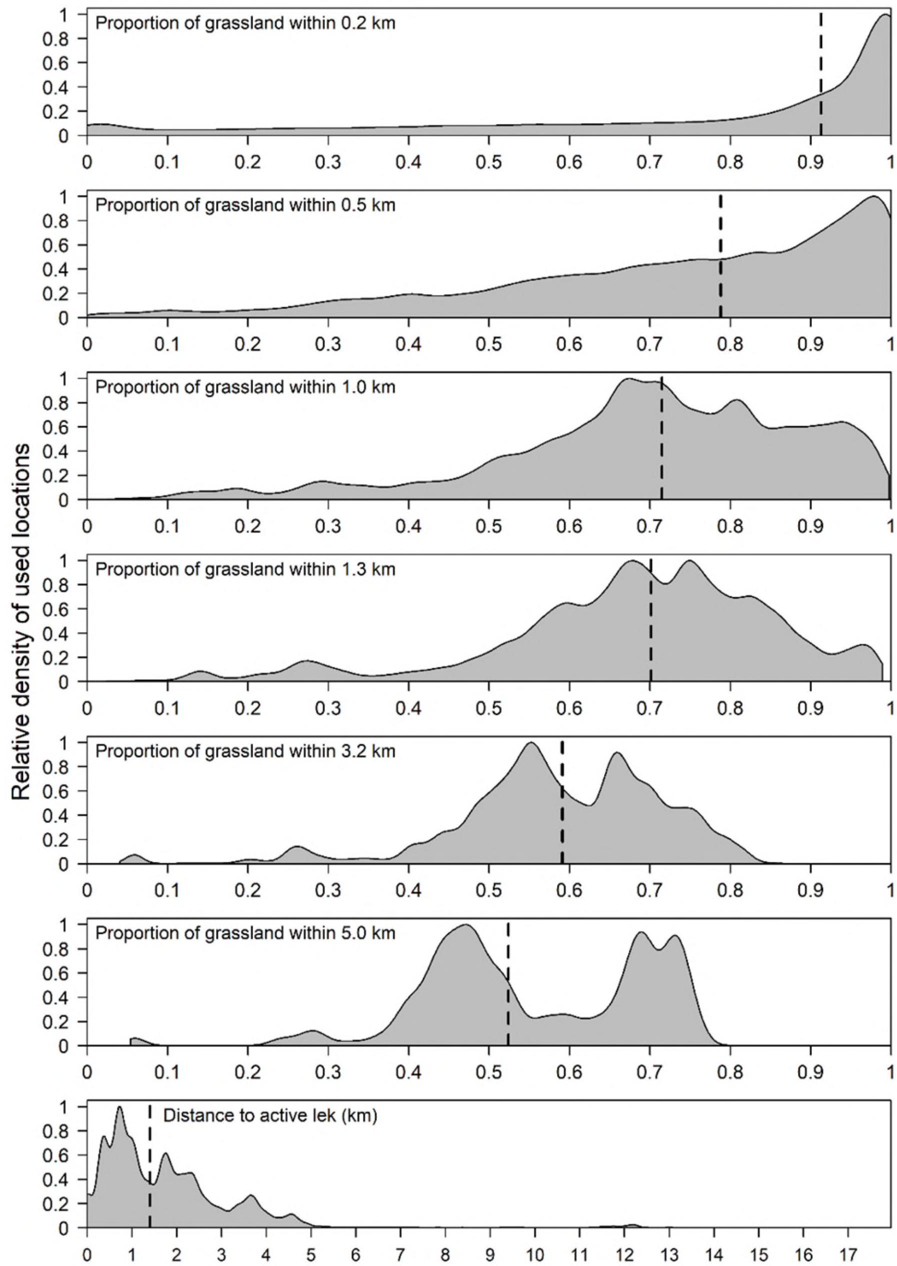


Figure A5. Density of locations used by female sharp-tailed grouse during the breeding season relative to the proportion of grassland within 0.2, 0.5, 1.0, 1.3, 3.2, and 5.0-km radii scales as well as distance to active leks in Grant, Codington, and Deuel counties, South Dakota, USA, during 2020–2022 breeding seasons. Vertical dashed lines within each panel represent the mean value of sharp-tailed grouse use locations within respective buffers.