



Effects of Power Lines on Habitat Use and Demography of Greater Sage-Grouse (*Centrocercus urophasianus*)

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ABSTRACT Energy development and its associated infrastructure, including power lines, may influence wildlife population dynamics through effects on survival, reproduction, and movements of individuals. These infrastructure impacts may be direct or indirect, the former occurring when development acts directly as an agent of mortality (e.g., collision) and the latter when impacts occur as a by-product of other processes that are altered by infrastructure presence. Functional or numerical responses by predators to power-line corridors are indirect impacts that may suppress demographic rates for certain species, and perceived predation risk may affect animal behaviors such as habitat selection. Greater sage-grouse (*Centrocercus urophasianus*) are a species of conservation concern across western North America that may be affected by power lines. Previous studies, however, have not provided evidence for causal mechanisms influencing demographic rates. Our primary objective was to assess the influence of power lines on multiple sage-grouse vital rates, greater sage-grouse habitat selection, and ultimately greater sage-grouse population dynamics. We used demographic and behavioral data for greater sage-grouse collected from 2003 to 2012 in central Nevada, USA, accounting for sources of underlying environmental heterogeneity. We also concurrently monitored populations of common ravens (*Corvus corax*), a primary predator of sage-grouse nests and young. We focused primarily on a single 345 kV transmission line that was constructed at the beginning of our study; however, we also determined if similar patterns were associated with other nearby, preexisting power lines. We found that numerous behaviors (e.g., nest-site selection, brood-site selection) and demographic rates (e.g., nest survival, recruitment, and population growth) were affected by power lines, and that these negative effects were predominantly explained by temporal variation in the relative abundance of common ravens. Specifically, in years of high common raven abundance, avoidance of the transmission line was extended farther from the line, re-nesting propensity was reduced, and nest survival was lower near the transmission line relative to areas more distant from the transmission line. Additionally, we found that before and immediately after construction of the transmission line, habitats near the footprint of the transmission line were generally more productive (e.g., greater reproductive success and population growth) than areas farther from the transmission line. However, multiple demographic rates (i.e., pre-fledging chick survival, annual male survival, *per capita* recruitment, and population growth) for groups of individuals that used habitats near the transmission line declined to a greater extent than for individuals using habitats more distant in the years following construction of the transmission line. These decreases were correlated with an increase in common raven abundance. The geographical extent to which power lines negatively influence greater sage-grouse demographic processes was thus contingent on local raven abundance and behavior. In this system, we found that effects of power lines, depending on the behavior or demographic rate, extended 2.5–12.5 km, which exceeds current recommendations for the placement of structures in areas around sage-grouse leks. Nests located 12.5 km from the transmission line had 0.06 to 0.14 higher probabilities of hatching in years of average to high levels of raven abundance, relative to nests located within 1 km of the transmission line. Similarly, leks located 5 km from the transmission line had 0.02 to 0.16 higher rates of population growth (λ) in years of average to high levels of raven abundance, relative to leks located within 1 km of the transmission line. Our finding that negative impacts of the transmission line were associated with common raven abundance suggest that management actions that decouple this association between common raven abundance and power lines may reduce the negative indirect impacts of power lines on greater sage-grouse population dynamics. However, because the removal of common ravens or the use of perch deterrents on power lines has not been demonstrated to be consistently effective in

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reducing common raven predation rates on greater sage-grouse nests, we recommend preferential treatment to mitigation strategies that reduce the number of elevated structures placed within 10 km of critical greater sage-grouse habitat. © 2018 The Wildlife Society.

KEY WORDS anthropogenic disturbances, *Centrocercus urophasianus*, common ravens, *Corvus corax*, demographic rates, elevated structures, environmental heterogeneity, habitat selection, indirect anthropogenic effects, population dynamics, power lines, sage-grouse, transmission lines.

Efectos de Líneas Eléctricas en el Uso de Hábitat y la Demografía del Gallo de Salvia (*Centrocercus urophasianus*)

RESUMEN El desarrollo de energías, así como de su infraestructura asociada (incluyendo líneas eléctricas) puede afectar la dinámica poblacional de la vida silvestre debido a sus efectos en supervivencia, reproducción y movimiento. Estos efectos causados por la infraestructura pueden ser directos, o indirectos, los primeros, cuando la infraestructura actúa como un agente o causa de mortalidad (e.g., colisiones), y la segunda, cuando los efectos ocurren derivados de procesos que son alterados por la presencia de infraestructura. Respuestas funcionales o numéricas por depredadores a corredores de líneas eléctricas son considerados impactos indirectos que pueden reducir las tasas demográficas de ciertas especies. La percepción del riesgo de depredación puede afectar conductas tales como la selección de hábitat. El Gallo de Salvia (*Centrocercus urophasianus*) es una especie de preocupación para la conservación en el oeste de Norteamérica, que puede ser afectada por líneas eléctricas. Sin embargo, estudios previos no han proporcionado evidencia de los mecanismos causales que influyen las tasas demográficas. Utilizamos datos demográficos y conductuales del gallo de salvia recogidos del 2003 al 2012 en la zona centro de Nevada, USA, contemplando fuentes de heterogeneidad ambiental subyacente. Concurrentemente, monitoreamos poblaciones del cuervo común (*Corvus corax*), un depredador primario de nidos y jóvenes del gallo de salvia. Nos enfocamos principalmente en una línea de transmisión de 345kV que fue construida al inicio del estudio; sin embargo, también exploramos si patrones similares estaban asociados con otras líneas eléctricas cercanas. Encontramos que numerosas conductas (e.g., selección del sitio de anidación, y selección del sitio de crianza) y tasas demográficas (e.g., supervivencia del nido, reclutamiento, y crecimiento poblacional) fueron afectados por líneas eléctricas, y que estos efectos negativos fueron explicados predominantemente por variaciones temporales en la abundancia relativa del cuervo común. Específicamente, en años de alta abundancia del cuervo común, se incrementó la conducta de evitar las líneas eléctricas, la propensión a repetir un sitio de anidación se redujo, y la supervivencia en el nido se redujo en zonas cercanas a líneas eléctricas. Adicionalmente, encontramos que antes, e inmediatamente después de la construcción de la línea eléctrica, hábitats cercanos a la huella de la línea eléctrica fueron generalmente más productivos (e.g., mayor éxito reproductivo y crecimiento poblacional) en comparación con áreas alejadas de la línea de alta tensión. Sin embargo, múltiples tasas demográficas (e.g., supervivencia de juveniles, supervivencia anual de los machos, reclutamiento per cápita, y crecimiento poblacional) disminuyeron en mayor grado para grupos de individuos que utilizaron hábitats cercanos a las líneas de transmisión que para individuos que utilizaron hábitats más lejanos a las líneas de transmisión. Estas disminuciones estuvieron correlacionadas con un incremento en la abundancia del cuervo común. La extensión geográfica en que las líneas eléctricas tuvieron una influencia negativa en los procesos demográficos del gallo de salvia estuvo condicionada a la abundancia y conducta del cuervo común. En este sistema, encontramos que los efectos de las líneas eléctricas, dependiendo de la conducta o tasa demográfica, se extendieron 2.5–12.5 km, lo cual excede recomendaciones actuales para la colocación de estructuras en áreas alrededor de leks del gallo de salvia. Nidos encontrados a 12.5 km de la línea de transmisión tuvieron una probabilidad de eclosión en años de alta abundancia 0.06 a 0.14 mayor que nidos localizados a 1 km de la línea de transmisión. De manera similar, leks localizados a 5 km de la línea de transmisión, en años de alta abundancia de cuervos, tuvieron tasas de crecimiento poblacional (λ) 0.02 a 0.16 mayores que leks localizados a 1 km de la línea de transmisión. Nuestro descubrimiento de que los impactos negativos de las líneas de transmisión estaban asociados con la abundancia de cuervos, sugieren que las acciones de manejo que separen esta asociación entre la abundancia del cuervo común y las líneas de transmisión pueden reducir los impactos negativos de las líneas eléctricas sobre la dinámica poblacional del gallo de salvia. Sin embargo, debido a que no se ha demostrado consistentemente la efectividad de la remoción de cuervos o el uso de disuasivos de percha de aves en las líneas de transmisión en la reducción de la depredación por cuervos en el gallo de salvia, recomendamos un tratamiento preferencial a las estrategias de mitigación que reduzcan el número de estructuras elevadas colocadas en un radio de 10 km de hábitat crítico del gallo de salvia.

Les effets des lignes électriques sur l'utilisation de l'habitat et la démographie des tétras des armoises (*Centrocercus urophasianus*)

RÉSUMÉ Le développement énergétique et les infrastructures associées, dont les lignes électriques, peuvent influencer les dynamiques de la vie sauvage par des effets sur la survie, la reproduction et les mouvements des individus. Ces impacts des infrastructures peuvent être directs ou indirects, ce premier ayant lieu quand le développement agit directement comme agent de mortalité (par exemple par collisions) et ce dernier quand les impacts sont le produit secondaire de l'altération d'autres processus par la présence d'infrastructures. Les réponses fonctionnelles et numériques des prédateurs aux couloirs de lignes électriques sont des impacts indirects qui pourraient écraser les taux démographiques pour certaines espèces. Aussi, perception d'un risque de prédation pourrait affecter certains comportements animaux comme la sélection d'habitat. Le tétras des armoises (*Centrocercus urophasianus*) est une espèce dont la conservation est préoccupante à travers l'Amérique du Nord-Ouest et qui pourrait être affectée par les lignes électriques. Cependant, les études passées n'ont pas fourni de preuves d'un mécanisme de cause à effet influençant les taux démographiques. Notre objectif premier a été d'évaluer l'influence des lignes électriques sur de multiples indices vitaux, sur la sélection d'habitat et enfin sur la dynamique de population du tétras des armoises. Nous avons utilisé des données démographiques et comportementales pour le tétras des armoises collectées de 2003 à 2012 dans le Nevada central, aux États-Unis, tenant compte des sources sous-jacentes d'hétérogénéité environnementale. Nous suivons aussi actuellement les populations de grands corbeaux (*Corvus corax*), le premier prédateur des nids et des petits. Nous nous sommes concentrés principalement sur une ligne de transmission à 345kV qui a été construite au début de notre étude. Cependant, nous avons déterminé si des tendances similaires étaient associées à d'autres lignes préexistantes voisines. Nous avons trouvé que nombre de comportements (par exemple la sélection du site de nidification et la sélection du site de couvée) et de taux démographiques (par exemple le succès de nidification, le recrutement et la croissance démographique) étaient affectés par les lignes électriques et que ces effets négatifs étaient principalement expliqués par la variation temporelle de l'abondance relative du grand corbeau. Plus spécifiquement, les années de forte abondance de grands corbeaux, l'évitement des lignes électriques s'étendait au-delà de la ligne et la propension de retour pour la nidification diminuait et la survie des nids était plus faible au voisinage de la ligne que dans les zones plus distantes de celle-ci. De plus, nous avons trouvé qu'avant et immédiatement après la construction de la ligne électrique, les habitats au voisinage de la trace de la ligne étaient généralement plus productifs (par exemple présentant un meilleur succès reproductif et une meilleure croissance démographique) que les zones plus loin de la ligne électrique. Cependant, de multiples taux démographiques (i.e., la survie des jeunes avant leur départ du nid, la survie annuelle des mâles, le recrutement par individu, et la croissance démographique) pour des groupes d'individus qui utilisaient les habitats proches de la ligne électrique ont diminué de façon plus importante que pour les individus utilisant des habitats plus distants dans les années qui suivirent la construction de la ligne de transmission. Ces diminutions ont été corrélées à une augmentation importante de l'abondance des grands corbeaux. L'étendue géographique sur laquelle les lignes électriques influencent négativement les processus démographiques des tétras des armoises était contingente avec l'abondance locale des grands corbeaux et leur comportement. Dans ce système, nous avons trouvé que les effets des lignes électriques, dépendant du comportement et du taux démographique, s'étendait sur 2.5 à 12.5 km, ce qui surpasse les recommandations actuelles pour le placement des structures dans des zones avoisinant des aires de parades de tétras des armoises. Des nids à 12.5 km des lignes électriques avaient une probabilité d'éclosion plus haute de 0.06 à 0.14 dans des années à haute abondance moyenne de grands corbeaux, comparé à des nids situés dans une zone de 1km autour de la ligne électrique. De façon similaire, les aires de parade situées à 5km de la ligne de transmission avaient un taux de croissance démographique (λ) plus élevé de 0.02 à 0.16 pour les années à haute abondance de corbeaux, relativement aux aires de parade situés dans une zone de 1km de la ligne électrique. Notre résultat indiquant l'effet négatif des lignes électriques était associé avec l'abondance de grands corbeaux suggère que les décisions de gestion qui dissocie cette association entre abondance de grands corbeaux et lignes électriques pourraient réduire l'impact négatifs indirect des lignes électriques sur la dynamique de populations du tétras des armoises. Cependant, comme le retrait des grands corbeaux proches des lignes, et l'utilisation de dispositifs anti-perchoir sur les lignes électriques n'ont pas montré d'efficacité constante pour la réduction du taux de prédation des nids de tétras des armoises, nous recommandons un traitement préférentiel pour des stratégies d'atténuation qui réduiraient le nombre de structures élevées placées dans les 10 km des habitats critiques du tétras des armoises.

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INTRODUCTION

Energy infrastructure has been associated with altering wildlife population dynamics by influencing survival, reproduction, and habitat use of individuals, exacerbating habitat fragmentation, and increasing spread of invasive species (Naugle et al. 2011a, Northrup and Wittemyer 2013). As of 2011, there were approximately 100,000 km of transmission lines in western North America (Copeland et al. 2011). Overhead power lines can negatively influence wildlife populations directly through the loss of habitat (i.e., the physical footprint of power-line towers and line rights of way; Jones et al. 2015) or increased mortality (e.g., bird collisions with guy wires, towers, or lines; Bevanger 1998; Janss 2000; Bevanger and Broseth 2001, 2004; Loss et al. 2014). Power-line towers, however, also may enhance habitat for avian predators by creating nesting (Steenhof et al. 1993, Howe et al. 2014) and perching habitat (Coates et al. 2014b). Although less studied, power lines are hypothesized to indirectly affect habitat use through avoidance behaviors beyond the physical footprint of the structure, potentially related to the increased presence of electromagnetic fields (Balmori and Hallberg 2007), avoidance of elevated structures, or increased harassment by predators associated with elevated structures (Pruett et al. 2009, Silva et al. 2010).

Power lines may indirectly suppress various vital rates such as nest success (DeGregorio et al. 2014) and adult survival (Hovick et al. 2014) for certain species because of increased predator abundance or changes in predator foraging behavior (Plumpton and Andersen 1997) near power-line corridors. The overall impact of power lines on wildlife populations may be influenced by surrounding environmental characteristics. For example, transmission lines may have a greater effect in open areas (e.g., shrublands or grasslands) relative to woodlands because of differences in flight behavior (Rollan et al. 2010), power-line visibility (Benitez-Lopez et al. 2010), or changes in local predator densities (Howe et al. 2014).

Placement of power lines within landscapes is typically not random because location of power lines is influenced by local topography and geology (Vajjhala and Fischbeck 2007). In the absence of conservation constraints, power-line corridors are typically placed along least-cost routes, which usually minimize

variation in slope and elevation (Bagli et al. 2011). This non-random distribution of power lines across a landscape results in covariance between proximity to, or density of, power lines and other environmental features (e.g., elevation, slope, hydrology) that may influence the structure of surrounding habitat, thereby complicating assessment of impacts of power lines themselves. For example, changes in demographic rates in proximity to a power line could result from a gradient in habitat quality that occurs along an elevational gradient, rather than an impact of the line itself.

Greater sage-grouse (*Centrocercus urophasianus*; hereafter sage-grouse) are of conservation concern and have been negatively influenced by anthropogenic disturbances, including energy development and its supporting infrastructure (Naugle et al. 2011b, Hovick et al. 2014). As such, it is important to understand the anthropogenic drivers of sage-grouse population change to make informed management decisions. Sage-grouse are endemic to sagebrush (*Artemisia* spp.) ecosystems of western North America (Connelly et al. 2011), which are characterized by large expanses of woody shrubs, with trees occurring in either low densities or localized patches. In these systems, anthropogenic structures including power lines can provide novel perches or nest sites for avian predators of sage-grouse that are otherwise unavailable in the local landscape (Steenhof et al. 1993, Howe et al. 2014, Coates et al. 2014b). Furthermore, an analysis conducted by Knick et al. (2011) found that power lines covered a minimum of 1,089 km² and had an ecological influence on almost 50% of sagebrush landscapes within the range of greater sage-grouse.

Power lines have the potential to directly (e.g., collisions) and indirectly (e.g., behavior, predator-prey dynamics) affect bird species (Smith and Dwyer 2016). Although sage-grouse, like other Galliformes, are susceptible to fatal collisions with power lines (Borell 1939, Bevanger 1998, Bevanger and Broseth 2004), numerous telemetry-based studies (Connelly et al. 2000, Beck et al. 2006, Blomberg et al. 2013a, Dinkins et al. 2014b) have reported low numbers of bird strikes by radio-marked individuals, which suggests this direct source of mortality is unlikely to be important at the population level, except in unusual circum-

stances. Site-specific mortality due to collisions may be appreciable, however, if elevated structures are placed perpendicular to a corridor of high periodic sage-grouse use (Stevens et al. 2011). Conversely, indirect effects of elevated structures, such as avoidance of habitat near lines (Doherty et al. 2008, Dinkins et al. 2014*b*), or lower vital rates due to increased predation (Ellis 1984, Bui et al. 2010), may be important at the population level. Sage-grouse and other grouse species appear to avoid habitat near elevated structures, which are primarily other types of energy infrastructure (Doherty et al. 2008, Silva et al. 2010, Hovick et al. 2014, LeBeau et al. 2014). Authors have speculated that the perceived threat of predation associated with power lines may explain this potential avoidance of otherwise suitable habitat (Braun 1998, Holloran et al. 2015).

Common ravens (*Corvus corax*; hereafter, ravens) are important predators of sage-grouse nests and chicks throughout the western portion of the species' range (Coates et al. 2008, Hagen 2011, Lockyer et al. 2013). Raven populations have steadily increased across western North America over the last 50 years, and are associated with increases in anthropogenic subsidies (Bui et al. 2010, Webb et al. 2011). Power poles and other elevated structures have increased availability of nesting substrate for ravens in shrublands and grasslands where nest sites are otherwise not typically abundant (Steenhof et al. 1993, Howe et al. 2014). Consequently, raven and other corvid densities are higher near elevated structures compared to the surrounding landscape (Knight and Kawashima 1993, Coates et al. 2014*b*, Cunningham et al. 2015, Harju et al. 2018). Ravens can have a substantial impact on prey population dynamics even at low densities (Brussee and Coates 2018). For example, Coates and Delehanty (2010) found that an increase of 1 raven per 10-km transect was associated with a 7.4% increase in the odds of sage-grouse nest failure. Therefore, we expect that effects of power lines on sage-grouse habitat use or reproductive success could depend on raven abundance associated with power lines.

Relatively few published studies have addressed the effects of power lines on sage-grouse (e.g., Johnson et al. 2011, Dinkins et al. 2014*a*) in contrast to the widely studied impacts of oil and gas development (e.g., Walker et al. 2007, Doherty et al. 2008, Holloran et al. 2010, Naugle et al. 2011*a*, Fedy et al. 2015, Holloran et al. 2015). Effects of oil and gas development cannot be extrapolated to those of power lines because the former is often associated with substantial human activity and noise (Blickley et al. 2012) and the scope of infrastructure differs between these forms of disturbance (Copeland et al. 2011). Although some studies have reported negative effects of elevated structures on individual vital rates (e.g., adult survival, nest success, brood survival; LeBeau et al. 2014, Dinkins et al. 2014*a*) or population connectivity (Shirk et al. 2015), these studies have not provided an inclusive evaluation of the complex linkages among power lines, predator abundance and behavior, and sage-grouse ecology (Hagen et al. 2011). Additionally, most studies are based on data over a relatively short time-series (<5 yr), which reduces the power to separate actual impacts from year-to-year fluctuations (McCain et al. 2016). Furthermore, large-scale patterns in population dynamics in relation to power lines are not consistent (Johnson et al. 2011, Wisdom et al. 2011), which may be related in part to regional variation in the quantity and quality of available sage-grouse habitat.

The relative lack of evidence for negative effects of power lines on vital rates may be related to reduced statistical power owing to low numbers of individuals using habitat near power lines (Kirol et al. 2015), given that avoidance is the most consistently reported effect. Thus, the absolute cost of power lines (i.e., functional habitat lost; Aldridge and Boyce 2007) is influenced in part by the extent of avoidance by sage-grouse. Interpreting previously reported patterns in habitat use or reproductive success related to power lines is further complicated by the fact that earlier studies did not control for potential confounding habitat effects. Therefore, we cannot be certain that negative effects of power lines are not an artifact of an association between location of power lines and other characteristics that affect habitat quality.

Our primary objective was to assess the influence of power lines on sage-grouse habitat selection and demographic rates during multiple life phases, and ultimately their population dynamics, after accounting for other sources of environmental heterogeneity. Our assessment of the impacts of power lines on sage-grouse behavior and demography builds on a series of published works focused on understanding the influence of the environment on sage-grouse life-history characteristics (e.g., Atamian et al. 2010; Blomberg et al. 2012, 2013*c*, 2014, 2017; Gibson et al. 2014, 2016, 2017). We used 10 years of data on sage-grouse behavior and population dynamics associated with construction of a 345-kV transmission line in central Nevada in our assessment. Our approach to determine the impacts of power lines by revisiting these previously published works improved the inferential strength of this manuscript because each dataset and analysis was independently peer-reviewed, allowing for substantial feedback from the greater scientific community. We could use peer-reviewed models of the relationships between demographic rates and environmental covariates to control for these effects when we assessed power-line effects. As a result, we developed a more complete picture of the background ecological processes in this system with respect to sage-grouse population ecology. Equipped with this information, we could better address the influence of power lines on sage-grouse populations in this dynamic and often complex system.

Recent studies have proposed that impacts of power lines on grouse may occur through the association of avian predators with such lines (Doherty et al. 2008, LeBeau et al. 2014, Fedy et al. 2015, Holloran et al. 2015); therefore, we also evaluated the hypothesis that variation in sage-grouse behavior and demography was related to changes in raven or raptor abundance. We predicted that spatial or numerical associations between ravens and power lines would result in reduced use of adjacent habitat, lower reproductive success, and ultimately reduced population growth, in areas near power lines as the raven population increased. Similarly, we hypothesized that variation in sage-grouse survival and population growth would be negatively correlated with raptor abundance, and spatial associations between raptors and power lines would result in reduced survival and population growth in areas near power lines.

STUDY AREA

The study site was located in east-central Nevada within Eureka County (Fig. 1). The study area encompassed approximately 7,000 km² of sagebrush steppe and mountain ranges supporting

pinyon-juniper woodlands. Within this system, sage-grouse occurred in habitat that varied in composition along an elevation gradient. At lower elevations (<2,000 m), the shrub community was dominated by Wyoming big sagebrush (*Artemisia tridentata wyomingensis*), with localized patches of black sagebrush (*A. nova*) and basin big sagebrush (*A. tridentata tridentata*). Rubber rabbitbrush (*Chrysothamnus nauseosus*), greasewood (*Sarcobatus vermiculatus*), and scattered Utah juniper (*Juniperus osteosperma*) also were relatively common. At higher elevations (>~2,000 m), the dominant shrub community was a mixture of mountain big sagebrush (*A. tridentata vaseyana*) and low sagebrush (*A. arbuscula*), with some intermixed common snowberry (*Symphoricarpos albus*), western serviceberry (*Aemilanchier alnifolia*), mountain mahogany (*Cercocarpus ledifolius*), and bitterbrush (*Purshia tridentata*). Large expanses of singleleaf pinyon (*Pinus monophylla*)-Utah juniper forest often occurred at mid-elevation sites between the low- and high-elevation sagebrush communities. Common annual and perennial forb taxa included phlox (*Phlox* spp.), lupine (*Lupinus* spp.), mustard

(*Descurainia* spp.), and milkvetch (*Astragalus* spp.). Common grasses consisted of blue grass (*Poa* spp.), cheatgrass (*Bromus tectorum*), crested wheatgrass (*Agropyron cristatum*), Indian rice grass (*Achnatherum hymenoides*), and squirreltail (*Elymus elymoides*).

We define transmission lines as any overhead structure that is capable of transmitting voltages >69 kV (Hamilton and Schwann 1995), whereas overhead structures transmitting <69 kV were considered distribution lines. We use the term power line to refer to all elevated energy transmission structures (i.e., transmission and distribution lines) regardless of voltage.

In fall 2003, Sierra Pacific Power Company (now NV Energy) began construction of a 345-kV transmission line (hereafter FG transmission line) between the Falcon and Gondor substations located in White Pine and Lander Counties, respectively, in Nevada, USA. Construction of the FG transmission line was completed in spring of 2004, and the line was energized in May of that year. The completed FG transmission line was approximately 299 km long and consisted of 734 towers that varied in

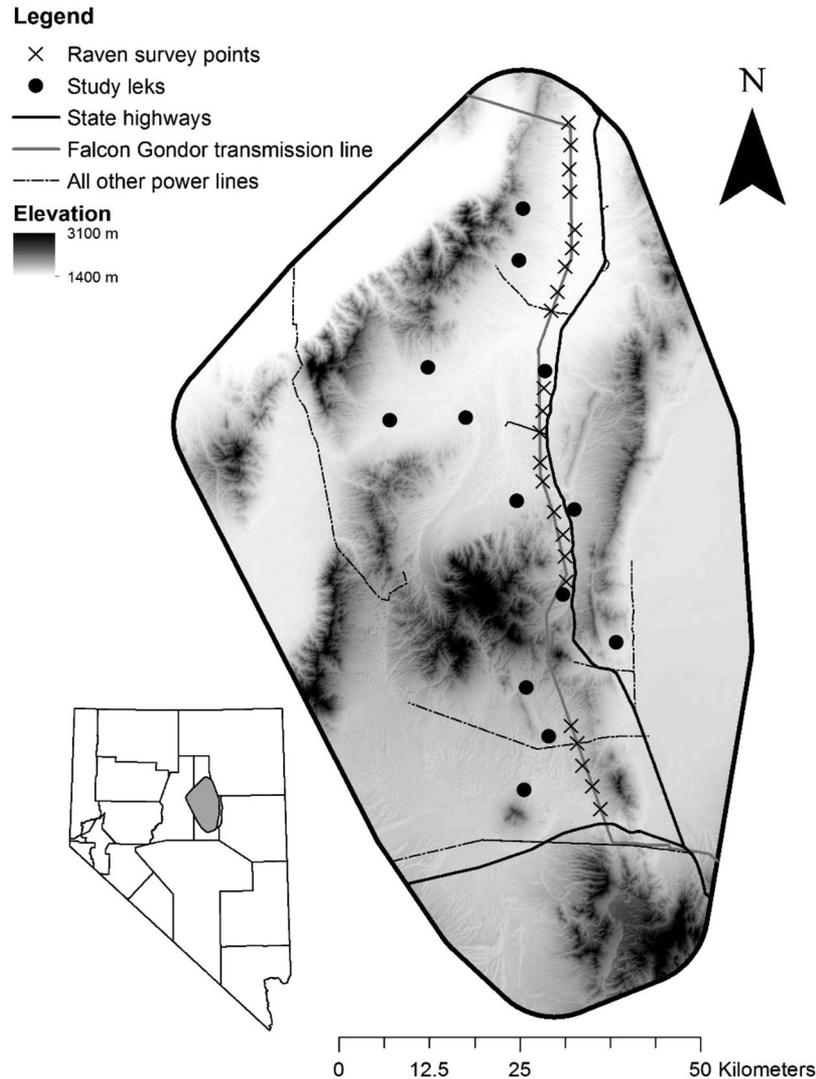


Figure 1. Map of the Falcon-Gondor (FG) transmission line (gray line), all other power lines (gray dashed lines), and state highways (black lines) occurring within the study system located primarily in Eureka County, Nevada, USA (see inset). Sage-grouse were primarily associated with one of 13 study leks (black circles). We monitored relative common raven and raptor abundance along a series of point transects (×) located along the FG transmission line corridor.

height (23–40 m), and design (2-pole H-frame or 3-pole guyed angle-transposition towers; Fig. 2), depending on topography and projection. Towers in areas of historical or active sage-grouse habitat, which included our study system, were fitted with experimental perch deterrents that were fixed on sections of towers where avian predators were most likely to perch. Deterrents consisted of 16-gauge steel in an inverted-Y design fit on horizontal tower arms, and steel plate deterrents fit on the tops of vertical tower arms and crossarms (Lammers and Collopy 2007).

We defined our study area as anything within a 10-km buffer surrounding the minimum convex-hull polygon that encompassed all female sage-grouse telemetry locations from 2003 to 2012 (Fig. 1). The study area included 134 km of the FG transmission line and focused primarily on individuals associated with 13 leks at various distances from the FG transmission line. Six study leks were within 5 km, 6 study leks were within 5–10 km, and 2 study leks were within 10–21 km of the FG transmission line. The most distant lek was 20.6 km from the FG transmission line.

The study area also included approximately 243 km of additional power lines, of which 42 km were associated with a second transmission line, and 201 km were either subtransmission or distribution lines. The other transmission line, which runs

east-west through the southern portion of the study system, was substantially older (circa 1980) but of similar design and structure to the FG transmission line. Subtransmission and distribution lines were similarly older, and were typically 1- or 2-pole structures that facilitated transmission to mines, ranches, and residences. Eight study leks were within 5 km of any power line.

The study area included 2 major paved roads, which were both 2-lane state or federal highways that intersected in the southeast portion of the study area, and were a combined 162 km in length. Four study leks were within 5 km of a highway. There were an additional 430 km of maintained gravel or dirt roads, and 3,500 km of unmaintained single-lane dirt access roads (2-tracks). All study leks were within 5 km of a maintained or unmaintained road. In this system, each transmission line corridor ran parallel (although not always immediately adjacent to) one of the 2 previously established highways, creating spatial correlation between highways and transmission lines.

Mineral extraction (primarily gold mining) is common throughout northern Nevada. Approximately 46,000 ha (~6.6%) of the study system was currently, or had recently been, within the physical footprint of mining activities (C. B. Van Dellen, Nevada Department of Wildlife, unpublished data). The level of disturbance associated with mining is spatially heterogeneous, and ranges from complete loss of functional habitat (e.g., creation of open pit mines) to minor disturbances (e.g., increased noise; Blickley et al. 2012). We did not quantify the percentage of the study area that was composed of actual surface disturbance versus less-intrusive activities such as prospecting, or previously mined areas with no current activity. Additionally, the area associated with mining was not completely additive to other potential disturbances because the acreage associated with mining typically included roads, power lines, or recent wildfire.

Wildfires disturbed approximately 85,000 ha (~12.1%) of our study system since 1999, with 90% of this disturbance occurring before the onset of this study. Burned areas were primarily colonized by exotic grasses, predominantly cheatgrass, but were also planted with crested wheatgrass. Exotic grasslands typically suppress establishment of native vegetation (Miller et al. 2011), and are negatively associated with sage-grouse population trajectories (Blomberg et al. 2012, Coates et al. 2016).

The majority (88%; ~619,000 ha) of the study system was under the jurisdiction and management of the Bureau of Land Management (BLM). Livestock grazing (primarily cattle and to a lesser extent sheep) was prevalent on BLM-managed lands. Of the ~82,500 ha of study system under private ownership, approximately 10,500 ha (1.5% of total study area) had been converted to cropland, primarily irrigated fields planted with alfalfa or non-native grass hay. These areas were generally located in the southeastern portion of the study area. Alfalfa fields that were bordered by sagebrush were used by sage-grouse as early brood-rearing habitat, but radio-marked sage-grouse were never observed in the interior of fields (D. Gibson, Virginia Tech, unpublished data). The remaining private land holdings were primarily rangelands in a checkboard pattern intermixed with BLM land localized in the northern portion of the study system, or were associated with mesic, lower-elevation sites scattered throughout the system, often containing grazing operations and maintained through flood irrigation.

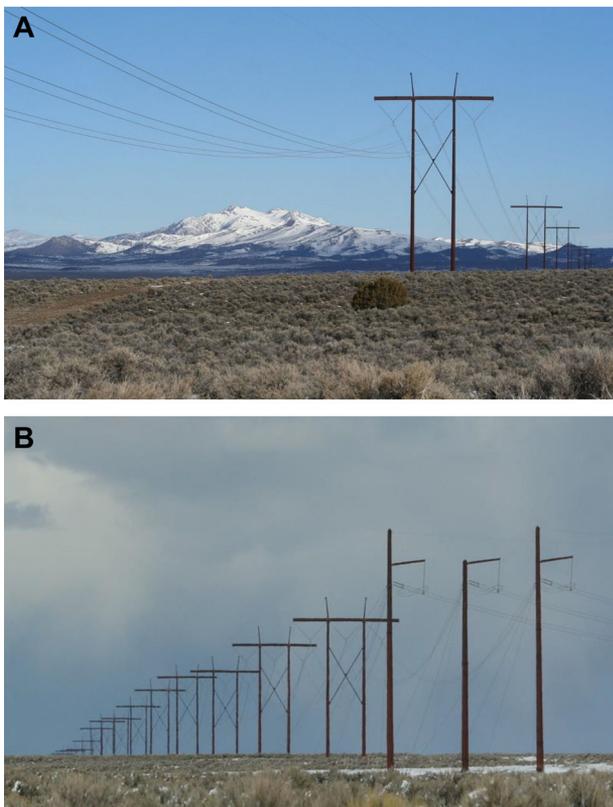


Figure 2. Representative images of towers within the Falcon-Gondor transmission line corridor depicting the A) 2-pole H-frame tower and B) 3-pole guyed angle-transposition tower design (foreground). The completed Falcon-Gondor transmission line was approximately 299 km long and consisted of 734 towers that varied in height (23–40 m), and design (2–3 pole) depending on topography and projection. Towers located in greater sage-grouse habitat in this system were fit with perch deterrents that were present but not easily visible in the figure above.

METHODS

Field Methods

We captured male and female sage-grouse at or near 10 to 13 leks during the mating season (Mar–May) from 2003 to 2012, and in seasonal high-elevation habitat during late summer and fall from 2005 to 2011. On average, we attempted to capture sage-grouse on or near each lek on 2 occasions per week throughout the mating season. Upon capture, birds were identified as male or female, classified as subadults (<1 yr) or adults (>1 yr) according to primary feather wear (Eng 1955), weighed, and measured (i.e., length of tenth primary, fifth primary, wing chord, tarsus, foot, and number of tail feathers). We banded each female with a size 14 aluminum band (National Band and Tag, Newport, KY, USA), and equipped most females with either a 22-g or 12-g radio with necklace-style attachment (A4060, A3950, Advanced Telemetry Systems, Isanti, MN, USA). Radios were equipped with a mortality sensor that doubled the signal pulse rate if the transmitter remained motionless for >8 hours. We banded each male with a size 16 aluminum band (National Band and Tag), and banded all adults and subadults that were large enough with a colored plastic tarsal band engraved with a unique 3-character alpha-numeric code for re-sighting during lek observations (described below). Individually marked male sage-grouse were re-encountered by recapture, re-sightings of tarsal bands during morning lek observations, or from images of tarsal bands recorded by trail cameras placed on leks (Gibson et al. 2013, 2014). Capture and handling of sage-grouse were approved by the University of Nevada Reno Institutional Animal Care and Use Committee (Protocol Numbers A02/03-22, A05/06-22, A07/08-22, A09/10-22).

We monitored 10 to 13 leks located within 20.6 km of the FG transmission line from 2003 to 2012. Lek activity began in late February and ceased in mid-May, with male lek attendance peaking during April, associated with high female attendance. We selected leks for study by evaluating previously collected data from the BLM and the Nevada Department of Wildlife (NDOW). Three leks were consistently monitored annually by NDOW and BLM for approximately 25 years before our study, which suggested that these populations have been declining since the early 1980s (population growth rate of 0.97; C. B. Van Dellen, Nevada Department of Wildlife, unpublished data), similar to population trends across the southern Great Basin (Garton et al. 2011, 2015).

We observed each study lek approximately once weekly during the mating season (Mar–May) from 2003 to 2012. Observers arrived on the leks a half hour before morning (nautical twilight), and remained until strutting activity ceased or birds dispersed. During these periods, observers monitored leks from trucks or mobile blinds with spotting scopes and binoculars. We occasionally included a mobile observation tower to facilitate band reading where terrain permitted and vegetation characteristics required it. Observers counted the number of males and females, marked and unmarked, on leks every 30 minutes during each observation period. Observers also recorded individual tarsal band codes (resights) and behavioral interactions with potential predators or ravens.

We located radio-marked females at least once but usually twice a week during the nesting season (end Mar–mid June) from 2003 to 2012 using a handheld receiver and Yagi antenna. Once we confirmed nesting, observers visited nests approximately twice a week until at least 1 egg hatched or the nest failed. Full nest monitoring protocols are described in Gibson et al. (2015). During 2005–2012, we continued to monitor females that successfully hatched a nest to assess brood status and habitat use. We assessed brood foraging habitat by locating brood-rearing females weekly during diurnal hours (i.e., 0700–1700), and recorded a global positioning system point near the brood's location (± 10 m). We monitored each female's current brood status through weekly brood flush counts. We performed weekly flush counts until 42 days after hatch (hereafter, pre-fledging period) or after 2 weeks of consecutive counts of zero chicks, whichever occurred first. Our complete brood monitoring protocols are described in Gibson et al. (2017). After all radio-collared females had fledged young or failed, we continued to monitor survival of radio-marked females approximately once a month using aerial telemetry from fixed-wing aircraft.

We measured vegetation at each nest site and weekly diurnal brood locations. We measured nest vegetation at all monitored nest sites within 3 days of either the predicted or actual date of hatch. We sampled nest-site vegetation along 10-m intersecting transects centered at the nest bowl (Gregg et al. 1994) using the line-intercept (Canfield 1941) and Daubenmire (1959) frame methods. We used the line-intercept method to estimate total shrub cover, sagebrush shrub cover, and non-sagebrush shrub cover. We used Daubenmire frames ($n = 5$) placed along each transect to classify ground cover of grass, forbs, and total cover (grass, forb, and shrub). See Gibson et al. (2015) for detailed nest vegetation protocols. We also measured vegetation at each weekly diurnal brood location approximately 1 week after obtaining the location; these vegetation points were centered approximately (± 5 m) where the brood had been located. Brood vegetation surveys followed the same protocols as nest vegetation surveys; however, from 2008 to 2012 we sampled brood vegetation surveys along 20-m intersecting transects (Gibson et al. 2017).

During March–May 2003–2012, we performed avian point counts that were spaced along 3 transects (hereafter referred to as south, central, and north) that paralleled the FG transmission line corridor (Fig. 1). The average distance between 2 points within a single transect was 3.36 km (SD = 0.70 km). The north and central transects had 9 points, and the south transect had 5 points. The nearest points in the central and north transects were 10.9 km apart, and the nearest points in the central and south transects were 20.2 km apart. Observers attempted to survey each transect once every 10 days from March to May. We alternated transect start times (between 1 hr after sunrise and at 1300), and survey start point (between northernmost and southernmost points of a transect). We did not conduct surveys if there was precipitation, fog, or if wind speeds exceeded 19 km/hr. Observers spent 10 minutes at each point, identified all observed raptor and corvid species, recorded number of individuals, and determined whether the observed individual was approximately within 400 m of the transmission line or beyond using a rangefinder to identify terrestrial landmarks.

Quantitative Methods

We estimated the following behavioral metrics or demographic rates from radio-telemetered female sage-grouse data: 1) nesting propensity; 2) re-nesting propensity; 3) nest-site selection; 4) nest survival; 5) brood-site selection; 6) pre-fledging chick survival; and 7) adult female survival. We estimated the following demographic rates from capture-mark-recapture data on male sage-grouse: 1) adult male survival; 2) male movements among leks; 3) *per capita* recruitment; and 4) lek-specific population growth rate. Lastly, we estimated whether ravens were spatially associated with the FG transmission line through occupancy models based on observed raven disturbance during lek surveys.

Approach to inference.—The underlying hypothesis for each analysis was that a particular behavior or demographic rate (e.g., nest-site selection, nest survival) was influenced by an individual's proximity to either the FG transmission line or any other power line. Environmental impact studies often employ a before-after control-impact (BACI; Green 1979) study design to account for potentially spurious correlations among various temporal or spatial variables and the potential disturbance (McNew et al. 2014, Winder et al. 2014). Although BACI study designs are ideal for disentangling variables that are spatially confounded (Green 1993), the pace at which disturbances occur, even those of anthropogenic origin, often precludes collecting sufficient data before development, thereby excluding BACI approaches. In such cases, collecting post-disturbance data sampled across sufficient spatial and temporal scales represent the only viable approach to assessing disturbance (Johnson et al. 2005). For our study, a BACI study design was not possible because the period between permitting and construction of the FG transmission line did not allow for adequate collection of pre-construction data. An additional design constraint was that other anthropogenic disturbances (e.g., highways, other transmission lines), and other natural environmental variation were associated with the location of power lines and were present before our study began. Therefore, our modeling approach had to account for potential correlations between an individual's distance from all power lines and other confounding sources of variation in behavior and demographic rates.

We developed a 2-stage approach for assessing impacts of power lines on sage-grouse habitat use and demography. First, we developed models that explained functional relationships among habitat characteristics (e.g., elevation, shrub cover), temporal processes (e.g., weather), and individual traits (e.g., age) with the response variable of interest (e.g., nest survival), which allowed us to account for variation in behavior or demography related to features of the environment that were not associated with power lines. We primarily used analysis-specific (e.g., nest survival) environmental variables based on analyses previously conducted in this study system (Blomberg et al. 2012, 2013c, 2017; Gibson et al. 2014, 2015, 2016, 2017; see Table SA1 in Appendix A for all covariates considered). However, we modified some analyses by considering additional variables that were not included in the original publications. We were unable to use a uniform suite of environmental variables across all analyses because of differences in levels of organization (e.g., individual- vs. lek-based analyses) and temporal resolution (e.g., daily vs. annual time-steps) for each analysis. Second, we developed a suite of explanatory variables (see below) that assessed the impact of power lines on

potential demographic rates, which we added to the best-supported model (see Tables SB1–9) from the first stage. Spatial correlation between anthropogenic features and habitat variables has the potential to render our approach conservative because inclusion of confounded variables in a single model generally results in a reduction in the effect sizes or an inflation of variances for each correlated variable.

Model covariates and selection.—We were primarily interested in assessing whether sage-grouse behavior or demography varied as a function of their distance from the FG transmission line. We also were interested in whether individuals responded to a new transmission line differently from previously existing power lines; thus, we considered 2 power-line covariates for each analysis: 1) distance from the FG transmission line and 2) distance from any power line. We digitized the FG transmission line corridor from Universal Transverse Mercator coordinates of all tower locations in our study system, and created a spatial surface that represented the Euclidian distance of each pixel from the FG transmission line using the spatial analyst toolbox in ArcMap 10.0 (Environmental Systems Research Institute, Redlands, CA, USA). We used this surface to assign individuals a distance from the FG transmission line, where assignment depended on temporal resolution of each analysis (see below). Similarly, we digitized locations of all known power lines using satellite imagery, and created a spatial surface of Euclidian distances from any power line for our study system, which we assigned to each individual in each analysis.

We tested for a distance-from-power-line threshold by comparing models containing both linear and quadratic effects of distance from power lines to models allowing for threshold effects on behavior or demographic rates associated with distance to a power line (Powell et al. 2017). We suspected a behavior or demographic rate would exhibit a more ramped response, in which a specific response would exhibit a linear pattern until an unknown distance threshold, and beyond this threshold we would not observe a response. Thus, for each analysis, we considered a suite of models that individually applied a variable threshold constraint that functionally allowed for a linear relationship until the threshold point, and constrained all points that exceeded the threshold to be assigned the value of the threshold point. For female-based analyses, we considered a range of *a priori* thresholds (i.e., 2.5, 5, 7.5, 10, 12.5 km from FG or any power line) where distance from each power line was an individual-level, continuous variable. However, distance from a transmission line was specified as a lek-level covariate in the male analyses ($n = 11$ or 13), and we considered only a threshold of 5 km, which effectively tested whether a linear association between distance from the FG or any power line was supported for the leks nearest to and most likely to be affected by a transmission line ($n = 5$ or 6 leks). We used the min function in Program MARK (White and Burnham 1999) to specify the threshold point for each demographic model, and altered the covariates to create similar threshold points manually for each habitat use analysis. For both male- and female-based analyses, we also tested a pseudo-threshold model (Franklin et al. 2000, Dugger et al. 2005, McNew et al. 2014), which constrained the non-standardized explanatory variable to be modeled on the natural log scale (plus an adjustment factor to push low values off

zero [i.e., $\ln(x + 0.001)$]). Comparisons among the threshold models allowed for inference regarding the spatial extent, and general shape of behavioral or demographic response to the FG transmission line or any power line.

An important hypothesis underlying the influence of power lines on sage-grouse demography is that power lines benefit sage-grouse predators, and thus indirectly affect prey such as sage-grouse. To assess support for this hypothesis, we evaluated relationships between annual abundances of ravens or raptors, and power-line effects. We used the mean number of ravens and raptors observed, not corrected for probability of detection, within 400 m of each survey point during each transect in each year as an annual index of common raven and general raptor abundance (hereafter, raven index, and raptor index, respectively). Because we observed ravens as singletons, pairs, and larger flocks of loafing individuals, the raven index represents a relative estimate of general raven abundance, and not an index of the local raven breeding population. We observed individual raptor species at relatively low rates; therefore, we combined observations of all raptor species that we determined could prey on adult sage-grouse. Species included ferruginous hawk (*Buteo regalis*), rough-legged hawk (*Buteo lagopus*), red-tailed hawk (*Buteo jamaicensis*), Swainson's hawk (*Buteo swainsoni*), Cooper's hawk (*Accipiter cooperii*), northern goshawk (*Accipiter gentilis*), sharp-shinned hawk (*Accipiter striatus*), northern harrier (*Circus cyaneus*), golden eagle (*Aquila chrysaetos*), and prairie falcon (*Falco mexicanus*). We used the raven index variable in models estimating metrics of sage-grouse reproductive behavior or success (e.g., nesting propensity, nest-site selection, nest survival, population growth) as an additive effect, and as an interaction with distance from the FG transmission line. We used the raptor index in models estimating adult sage-grouse survival or population growth. Additionally, we regressed the raven and raptor indices against year of the study to determine the general trend in common raven and raptor abundance throughout the study.

For more data-rich analyses (i.e., nest-site selection, nest survival), we considered models that allowed for full annual variation in the effects of distance from the FG transmission line (i.e., year-specific slopes) to estimate year-specific effects of distance from FG transmission line. For these models, we did not use an information-theoretic approach to compare relative explanatory power because these models were only used to test a specific hypothesis. *Post hoc*, we regressed these year-specific parameter estimates against the raven and raptor indices to assess whether annual patterns in female nesting behavior or nest survival were correlated with annual raven or raptor relative abundances. For analyses in which year-specific effects of distance from the FG transmission line were not estimable because of sparse data, we allowed the effect of the FG transmission line to vary as a function of a linear year trend to determine if the effect of distance from FG transmission lines increased or decreased in magnitude throughout the duration of the study. Lastly, we considered models that allowed nest-site selection and nest survival to vary as a function of 1) distance to highway and 2) distance to any maintained road, to determine whether sage-grouse nesting ecology was more influenced by power lines or roads. The distance that sage-grouse nests were from highways was highly correlated with distance from the FG

transmission line ($r=0.89$) or any power line ($r=0.91$), whereas distance from maintained roads and distance from the FG transmission line ($r=0.11$) or any power line ($r=0.08$) were substantially less correlated. We considered differential responses between roads and power lines in the nest-site selection and nest survival analyses because they were the datasets that had the highest spatial accuracy and largest sample sizes, in addition to relatively high precision on individual estimates. Furthermore, we believed that these vital rates were potentially most sensitive to road effects because of the potential role that common ravens play as a nest predator (Coates et al. 2008, 2014a) and their relationship with roads as a potential source of anthropogenic food subsidies (Howe et al. 2014, Dinkins et al. 2014b).

We used an information-theoretic approach to evaluate support for competitive models using maximum-likelihood (Burnham and Anderson 2002), which considered covariate effects to be meaningful if 85% confidence intervals of β coefficients did not overlap 0 (Arnold 2010). For models that considered interaction effects among covariates, we considered the combined interaction and covariate effects to be meaningful if the β coefficient that represented the interaction term was meaningful, and the model was more explanatory (lower Akaike's Information Criterion corrected for small sample-size [AIC_c]) than a similarly structured model that only considered additive effects of the relevant covariates. Although this approach could result in the linear components of an interaction not meeting our 85% confidence interval criteria, these components were not individually interpretable when constrained to interact with each other. We used an iterative process in model creation whereby we applied individual covariates to assess various potential sources of variation in each demographic rate. First, we added all covariates singly to the model that best accounted for temporal or spatial variation in the observation or state processes. Second, we added covariates into a more complex model 1 covariate at a time, in which we combined the covariate(s) that were most supported with the least supported covariate that had yet not been considered. We retained covariates that improved model fit in the model structure. We did not include covariates that were correlated with each other (Pearson's $r > 0.50$) simultaneously in models; however, if both covariates were explanatory, we retained the more explanatory ($<AIC_c$) covariate. During the explanatory model stage, we were primarily concerned with developing a covariate model that explained the most information possible with the fewest parameters; therefore, we retained the covariate model with the lowest AIC_c for the power-line model stage. During the power-line model stage, we were interested in determining support for various hypotheses regarding the mechanism(s) by which power lines influenced sage-grouse and the spatial extent of these relationships. Because these hypotheses were not mutually exclusive, we considered models to be competitive that were more explanatory ($<AIC_c$) than the relevant covariate model (Covar) regardless of the models overall model rank (ΔAIC) relative to other hypotheses considered. All covariates in all analyses were z-standardized ($\bar{x}=0.0$, $SD=1.0$; White and Burnham 1999), unless specifically mentioned otherwise.

Specific Quantitative Analyses

Nesting and brood-rearing habitat metrics.—We used spring (1 Apr–31 May) locations from radio-marked female sage-grouse from 2003 to 2012 in a multi-state framework in Program MARK to assess the influence of power lines on probabilities of nest initiation. We formatted encounter histories and model state specifications following methods outlined in Blomberg et al. (2017), which used the recorded nesting state from each check of a radio-marked female to generate an encounter history for each female in each study year. In this analysis, we defined occasion-specific nesting states as a female not yet observed on a nest, a female observed on her first nest in that year, a female observed not on a nest following failure of a first nest, and a female observed on a second nest in that year. We were primarily interested in estimating the probabilities of transitioning (ψ /Nest) among nesting states, which we used to derive an overall probability of nest initiation and second nest initiation conditioned on failure of a first nest. Our assessment of other environmental variables that influenced nesting and re-nesting propensity was based on previous work in this system (Blomberg et al. 2017; Table SB1 in Appendix B).

We used nest and brood location data during 2004–2012 to assess the influence of power lines on habitat selection during the nesting and brood-rearing periods using resource-selection functions as described by Boyce and McDonald (1999) and Hebblewhite and Merrill (2008). We performed resource selection function (RSF) analyses in a use versus available framework for both the nesting and brood-rearing periods, in which used points represented nest or brood locations, and available points were randomly selected from throughout the study system (Fig. 1). Thus, our approach reflects resource selection that approximates Johnson's (1980) second order for population-level selection. We randomly selected 2,200 points for each RSF analysis, which was approximately 5 times the number of available nest or brood locations. We assigned each nest, brood, and random point a value for a suite of spatial habitat characteristics. We performed each RSF analysis in a generalized linear mixed model framework (Zuur et al. 2009) using the lme4 package (Bates and Maechler 2010) in R (R Core Team 2012). For both analyses, we included year and individual as a random effect, where we randomly assigned each random point a year value that occurred during our study, and randomly paired each point with an individual female. Our assessment of other environmental variables that influenced habitat selection was based on previous work in this system (Gibson et al. 2016; Table SB2–3 in Appendix B).

We used the nest survival module in Program MARK to model the influence of power lines on daily nest survival probabilities based on nest visit and vegetation data collected from nests monitored during 2004–2012. We estimated overall nest survival rates (i.e., nest initiation to hatch) based on a 37-day exposure period that incorporated laying and exposure periods (Blomberg et al. 2015). We did not censor research-related abandonments for this analysis, which biased our estimates of overall nest survival low (~ 0.07 ; Gibson et al. 2015); however, this bias should not substantially influence estimated covariate effects on nest survival. Our assessment of other environmental variables that influenced nest survival was

based on previous work in this system (Gibson et al. 2016; Table SB4 in Appendix B).

For the power-line analysis, we calculated the average distance during each spring to the closest power line or the FG transmission line for all unique locations for each female: nest, brood, or random location. We used these values as covariates for nesting propensity, re-nesting propensity, nest-site selection, nest survival, and brood-site selection parameters. For each analysis, we considered both linear and quadratic effects of distance from either the FG transmission line or any power line. We did not assess the influence of the FG transmission line on any parameter before its construction (i.e., before 2004). For each analysis, we used the raven index as an explanatory covariate, and in an interaction with distance from the FG transmission line to assess whether the impact of the transmission line varied as a function of common raven abundance. *Post hoc*, for the nest-site selection and nest-survival analyses, we allowed the distance-to-FG-transmission-line variable to be estimated for each year of the study (i.e., year-specific slopes) to assess how patterns in nest-site selection (random effect of year) and nest survival (fixed effect of year) varied over time. Additionally, for the brood-rearing habitat-selection models, we allowed the effect of distance from either power line covariate to vary as a function of weekly brood age to assess whether habitat selection varied as chicks aged.

Survival rates.—We used the Lukacs young survival of marked adults module (Lukacs-survival; Lukacs et al. 2004) in Program MARK to assess the influence of power lines on pre-fledging chick survival based on brood flush count and brood-site vegetation survey data collected from 2005 to 2012. The Lukacs young survival of marked adults model uses repeated counts of unmarked individuals (i.e., chicks) that are completely associated with a marked individual (i.e., radio-marked female), who is available for detection, to estimate apparent offspring survival (ϕ) while accounting for imperfect detection (p) of offspring. We did not estimate pre-fledging chick survival during 2003–2004 because broods were not monitored after hatch during those years. Our assessment of other environmental variables that influenced ϕ was based on previous work in this system (Gibson et al. 2017; Table SB5 in Appendix B).

We used the nest survival module in Program MARK to assess the influence of proximity to power lines on monthly female survival probabilities (S) based on year-round telemetry data collected from radio-marked females during 2003–2012. We used nest survival models as they more appropriately assign timing of mortality when telemetry data are collected at irregular intervals (Dinsmore et al. 2002, Mong and Sandercock 2007, Blomberg et al. 2014). Individual encounter histories included 12 intervals (months), beginning 1 March and terminating 28–29 February the following calendar year. We defined each year ($n_{\text{years}} = 10$) as a group; females that were monitored across multiple years had a unique 12-occasion encounter history for each year we monitored them. We acknowledge that including females monitored across multiple years may result in pseudo-replication; however, we monitored 61% of nesting females for only a single year. Thus, more sophisticated modeling approaches to account for repeated observations of individuals would not converge. We right censored encounter histories from individuals that we were unable to monitor because of radio failure or

unrecorded dispersal. Our assessment of other environmental variables that influenced S was based on previous work in this system (Blomberg et al. 2013c; Table SB6 in Appendix B).

We used the multistate robust design model in Program MARK to assess the influence of proximity to power lines on annual male survival (φ_{male}) and male lek-lek movement rates (ψ_{movement}) based on mark-recapture data collected from 2003 to 2012 during trapping events on leks (captures and recaptures) and lek observations (resights). We generated encounter histories from physical recaptures and band resights, and used them in a multistate ($n_{\text{states}}=2$) robust design framework, where we grouped males together by lek of capture ($n_{\text{leks}}=13$). As in Gibson et al. (2014), state transition probabilities represented the annual probability of a male moving to a lek different from its lek of previous encounter. To fit criteria necessary for robust design analyses, we defined primary occasions as an annual breeding season, and subdivided each breeding season into 2 35-day secondary occasions. Our assessment of other environmental variables that influenced φ_{male} and ψ_{movement} was based on previous work in this system (Gibson et al. 2013; Table SB7 in Appendix B).

We considered linear and quadratic effects of distance from either the FG transmission line or any power line on survival of chicks, adult females, and adult males. For the pre-fledging chick survival analysis, we calculated the distance a female and her brood was located from either the nearest power line or FG transmission line at the beginning of each week, and used each of these values as a weekly time-varying covariate for the power-line analysis. For the analysis of adult female survival, we calculated the average distance a female was located from either the nearest power line or FG transmission line using all ground-based telemetry locations collected for each female during a given month (Mar–Aug), and we used each of these values as a monthly time-varying covariate for the power-line analysis. We did not assess the influence of distance from a power line or the FG transmission line from the beginning of September to the end of February because we lacked precise location data for these months. For the analysis of adult male survival and movement, we assigned each male annual time-varying covariates that represented the distance between the lek he attended in year t and the nearest power line or FG transmission line to assess the influence of power lines on either φ_{male} or ψ_{movement} from year t to year $t+1$. For each analysis, we did not assign the time-varying FG transmission line covariate to individuals in 2003 because this year preceded completion of the FG transmission line.

We used the raven index as an annual covariate for the pre-fledging chick survival analysis. Additionally, we considered an interaction between distance from the FG transmission line and the raven index to assess temporal variation in the influence of distance from the FG transmission line as a function of the number of common ravens observed near the transmission line during a given year. We did not use the raven index to model female survival, male survival, or male movement because ravens are not known predators of adult sage-grouse (Hagen 2011). However, we considered an interaction between distance from the FG transmission line and the raptor index to assess the influence of distance from the FG transmission line on female and male survival as a function of the number of raptors observed

near the FG transmission line. Lastly, for each analysis, we allowed the effect of the FG transmission line to vary as function of a linear year trend (FG \times trend) to determine if the potential impacts of the FG transmission line on pre-fledging chick, adult female, or adult male survival increased or decreased during the study.

Recruitment and population growth.—We used robust design Pradel models in Program MARK to assess the influence of proximity to power lines on lek-specific population growth (λ) and recruitment rates (f) based on male encounters during trapping events on leks during 2003–2012. We generated encounter histories only from physical captures of males at leks that were monitored during the entire length of the study ($n_{\text{leks}}=11$). We did not use tarsal band re-sights during lek observations in this analysis because Pradel models assume equal detection probabilities for newly marked and previously marked individuals (Sandercock 2006), and unmarked individuals are unavailable for encounter when band re-sights are used (Blomberg et al. 2013b). Similar to the multistate robust design analysis, we defined primary occasions as an annual breeding season, and subdivided each breeding season into 2 35-day secondary occasions. Our assessment of other environmental variables that influenced λ and f were based on previous work in this system (Blomberg et al. 2013b; Table SB8–9 in Appendix B).

We assigned each male annual time-varying covariates that represented the distance between the lek he attended in year t and the nearest power line or FG transmission line to assess the influence of power lines on λ or f between years t and $t+1$. We did not assign the time-varying FG transmission line covariate to individuals in 2003 because this year preceded completion of the FG transmission line. We also used the raven and raptor indices as annual covariates. Additionally, we considered interactions between distance from the FG transmission line and the raven index to assess temporal variation of FG transmission line effects on population growth and *per capita* recruitment, as a function of the number of common ravens observed near the transmission line during a given year. Lastly, we allowed the effect of the FG transmission line to vary as function of a linear year trend (FG \times trend) to determine if the potential impacts of the FG transmission line on population growth or *per capita* recruitment increased or decreased during the study.

Spatial association between common ravens and Falcon–Gondor transmission line.—We used a robust design occupancy model in Program MARK based on raven observation data collected during morning sage-grouse lek observations during 2003–2012 to estimate the following: 1) probability of a lek being visited (i.e., disturbed) by a raven (ψ_{Dis}) in year i ; 2) probability that a lek not visited by a raven in year t would be visited in year $t+1$ (γ_{Dis}); and 3) probability of detecting a raven visit to a lek (p_{Dis}). We modeled raven visitations recorded during lek observations as a Bernoulli (presence or absence) response variable describing whether a lek was disturbed at least once by a raven during a morning lek observation. We considered each study lek to be independent ($n_{\text{leks}}=13$), and assigned each lek observation to a 20-day secondary occasion based on the ordinal date (OD) of the survey (OD: 61–140; number of secondary occasions = 4) within each year, and a primary occasion based on year (number of primary occasions = 10). We used lengths of 20 days for

secondary periods to increase the probability that at least 1 full survey per lek was completed per occasion (some scheduled observations were cancelled because of weather) and to decrease the absolute variation in length of survey observations. Although this model assumes population closure among secondary occasions, we believe this analysis is relatively insensitive to violations of this assumption because it was highly likely that each lek was available to be visited by at least 1 raven during each secondary occasion. We allowed detection probabilities to vary among secondary occasions but constrained them to be constant among years because of data limitations.

Although we were primarily interested in determining the associations between disturbance rates and the FG transmission line, we also fit linear and quadratic trends on γ_{Dis} to allow for annual variation in colonization of disturbance events. We assessed whether raven disturbance rates were spatially associated with the FG transmission line by comparing models that constrained ψ_{Dis} during 2004–2012 to vary as linear, quadratic, or natural log functions of the distance from the FG transmission line. Additionally, we tested a series of distance-threshold models (i.e., 5, 7.5, and 10 km from the FG transmission line). We also considered models that constrained γ_{Dis} to vary as a function of a linear trend across years to assess whether the rate of raven occupancy increased throughout the study. Lastly, we ran an identical suite of models that constrained ψ_{Dis} during 2003–2012 to vary as a function of distance to the nearest highway. For this analysis, we did not consider interactions between time and distance from the FG transmission line because of data sparseness.

RESULTS

We captured and radio-marked 361 (153, 192, and 16 captured as adults, subadults, or unclassified, respectively) female sage-grouse

and captured and banded 988 (529, 380, and 79 captured as adults, subadults, or unclassified, respectively) male sage-grouse during the study (Table 1). Over the 10-year period, we attributed 0 mortalities of radio-marked individuals to a collision with a power line or pole. We discovered and monitored 427 nests by 249 unique females from 2003 to 2012, of which 138 nests from 116 unique females were successful. We classified 355 of the nests as first nests, 66 as second nests, and 6 as third nest attempts. Adults initiated 312 of the nests, subadults initiated 96, and 19 nests were from unknown-age females. We monitored 120 broods from 99 unique females after hatch, and observed 862 chicks at hatch, of which 163 chicks were associated with their mothers at approximately 6 weeks after hatch. We completed 875 vegetation surveys associated with breeding females, of which 423 were associated with nests, and 452 were associated with brood locations. We completed 1,067 lek observations at our 13 study leks (\bar{x} = 8.73 observations per lek per year). We observed a decline in the number of breeding male sage-grouse (-1.51 sage-grouse per lek per year (95% CI = -0.25 to -2.76) based on the mean maximum lek counts (Fig. 3A), whereas ravens increased by 0.09 ravens (95% CI = 0.05 – 0.14) per survey point per year and raptors exhibited no trend (Fig. 3B) in the years after construction of the FG transmission line.

Results from the first stage of model selection (i.e., functional relationships with environmental variables) can be found within the supporting information and previous publications from this system (Blomberg et al. 2012, 2013c, 2017; Gibson et al. 2014, 2015, 2016, 2017). For the remainder of the results section, we restrict comparisons of the top environmental covariate models (Tables SB1–SB9) to those containing model-supported covariates plus the explanatory variables associated with power lines (e.g., distance to FG, raven index) or roads.

Table 1. Summary of year-specific greater sage-grouse monitoring data during 2003–2012 in Eureka County, Nevada, USA.

Year	Number of radio-marked females ^a	Unique females that nested ^b	Unique females that re-nested ^c	Number of hatched nests ^d	Number of active broods at 6 weeks ^e	Number of new males captured ^f	Number of males recaptured (unique) ^g	Number of males resighted (unique) ^h
2003	15	11	1	5	NA	146	26 (20)	12 (11)
2004	21	16	3	7	NA	106	43 (36)	41 (26)
2005	35	28	8	12	9	104	55 (48)	37 (25)
2006	62	41	1	20	11	134	37 (35)	56 (35)
2007	50	25	1	10	3	113	37 (30)	34 (12)
2008	41	31	6	7	5	62	30 (26)	91 (45)
2009	54	46	17	20	9	46	50 (34)	59 (23)
2010	68	59	18	20	10	50	35 (31)	109 (33)
2011	63	48	8	18	10	63	44 (30)	107 (42)
2012	63	49	5	19	6	68	13 (12)	135 (40)
Total	472	354	68	138	63	892	370	681

^a Number of female sage-grouse recorded alive with an active radio-collar during the spring of a given year.

^b Number of nests assigned to a unique female in a given year.

^c Number of nests assigned to a unique female that was known to have previously nested in a given year.

^d Number of monitored nests that hatched in a given year.

^e Number of broods that hatched from a monitored nest that had at least 1 chick at 6 weeks after hatch. Broods were not monitored during 2003–2004.

^f Number of males captured for the first time on a lek during the spring on a given year. These values do not sum to the total number of males captured across the 10-year study because we also captured male sage-grouse during the fall in seasonal habitat.

^g Total number of previously captured males recaptured during the spring lek-centric capture events; values in parentheses represent the unique number of individual's recaptured.

^h Total number of previously captured males reencountered through visual observation of their plastic tarsal band during the spring morning lek observations; values in parentheses represent the unique number of individual's reencountered.

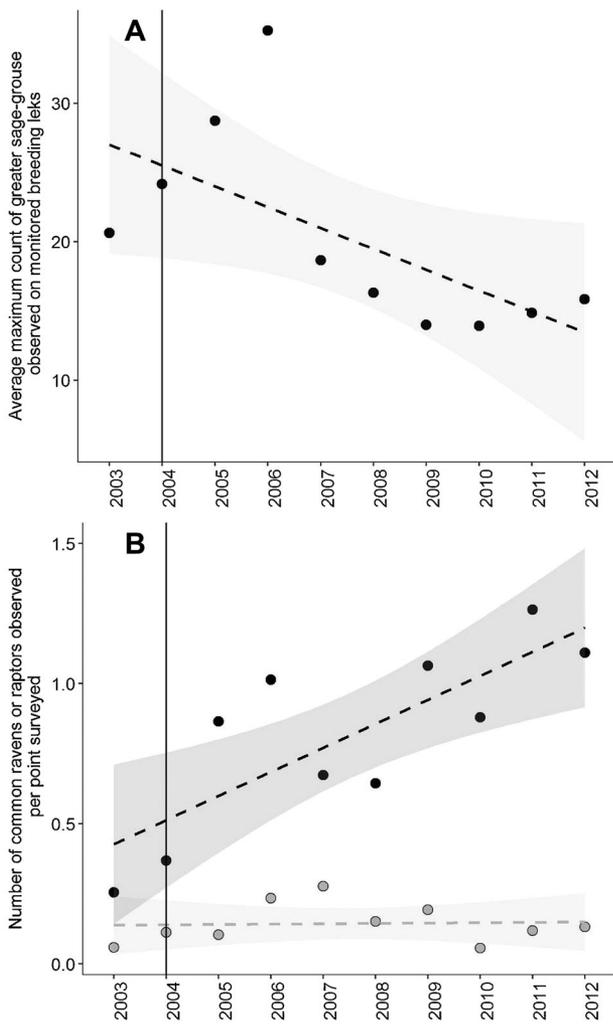


Figure 3. The average A) of the maximum male sage-grouse lek count from all monitored leks during the spring for each year, and B) the average number of common ravens (black circles) and raptor species thought to prey on adult sage-grouse (gray circles) observed within 400 m of survey points associated with the Falcon-Gondor transmission line in Eureka County, Nevada from 2003–2012, regressed against year (dashed line). Construction for the Falcon-Gondor transmission line began in the fall of 2003 and was completed in spring of 2004 (solid line). Error bands represent 95% confidence intervals.

Nesting and Brood-Rearing Metrics

We did not find support for an increase in nesting propensity for individuals located farther from either the FG transmission line or any power line (Table 2). Annual relative raven abundance was negatively associated with re-nesting propensity (re-nest: $\beta_{RavenIndex} = -0.63$; 85% CI = -0.98 to -0.29 ; Fig. 4A) but not nesting propensity (nest: $\beta_{RavenIndex} = 0.02$; 85% CI = -0.09 – 0.14 ; Table 2). Unlike nesting propensity, we found that probabilities of re-nesting (conditioned on initial failure) were highest in areas closer to the FG transmission line ($\beta_{FG} = -0.44$; 85% CI = -0.71 to -0.17 , $\beta_{FG^2} = 0.23$; 85% CI = 0.07 – 0.39 ; Fig. 4B). The negative effect of distance to the FG transmission line and re-nesting propensity was supported to a threshold of 10–12.5 km ($\beta_{FG10} = -0.66$; 85% CI = -1.12 to -0.19 ; $\beta_{FG12.5} = -0.53$; 85% CI = -0.91 to -0.15) from the line (Table 3). We found no model or parameter support for the hypothesis that nesting or re-nesting propensity was

associated with distance from any power line at any of our thresholds.

We found support for a quadratic effect of distance from any road on nest-site selection ($\beta_{Road} = -0.47$; 85% CI = -0.61 to -0.34 ; $\beta_{Road^2} = 0.30$; 85% CI = 0.22 – 0.38 ; Table 4), which suggested selection of areas near maintained roads. For non-road models, we found support for an interaction ($\beta_{All \times RavenIndex} = 0.19$; 85% CI = 0.07 – 0.32) between the raven index ($\beta_{RavenIndex} = 0.36$; 85% CI = 0.18 – 0.54) and distance to any power line ($\beta_{All} = 0.18$; 85% CI = 0.07 – 0.29), which suggested that the magnitude of avoidance of any power line increased when raven abundance was higher (Fig. 5A). The pseudo-threshold model ($\beta_{log(FG)} = 0.17$; 85% CI = 0.07 – 0.26 ; Fig. 6; Table 5) was the best-supported description of avoidance behavior associated with the FG transmission line, which suggested high avoidance of areas within 3 km of the FG transmission line.

Annual raven abundance, by itself, did not influence nest survival; however, we found support for an interaction ($\beta_{FG^2 \times RavenIndex} = 0.21$; 85% CI = 0.08 – 0.33) between a quadratic effect of distance to the FG transmission line ($\beta_{FG} = 0.09$; 85% CI = -0.04 – 0.22 ; $\beta_{FG^2} = -0.10$; 85% CI = -0.16 to -0.08) and the raven index ($\beta_{RavenIndex} = 0.08$; 85% CI = -0.02 – 0.20), which suggested nest survival near the FG transmission line was reduced when raven abundance was higher (Table 6 and Fig. 5B). This pattern resulted in a 2-fold increase in benefits of nesting farther from any power line during years of high raven abundance as overall nest survival probability increased by approximately 0.014 per km from the FG transmission line, compared to a 0.006 per km increase during years of average raven abundance. In models lacking a raven effect, we found model support for a quadratic effect of distance from the FG transmission line on nest survival ($\beta_{FG} = 0.15$; 85% CI = 0.03 – 0.28 , $\beta_{FG^2} = -0.08$; 85% CI = -0.15 – 0.02 ; Table 6). We found the most support for the effect of FG transmission line on nest survival extending to 12.5 km from the line ($\beta_{FG12.5} = 0.23$; 85% CI = 0.06 – 0.40 ; Table 7), which indicated the effect of the line on nest survival extended substantially farther than female avoidance behavior (Fig. 7). Although a 7.5-km threshold from any power line had more support than the full linear model (Table 7), the 85% confidence interval for the distance effect crossed zero and was not considered supported ($\beta_{All7.5} = 0.19$; 85% CI = -0.01 – 0.39). We did not find support for an effect of distance to road or highway on nest survival, which suggests that the observed impacts of power lines were most likely associated with elevated structures, rather than the roads with which they were partially spatially confounded.

Year-specific slopes for the effect of distance from the FG transmission line on nest-site selection covaried positively with estimated raven abundance (Fig. 6C), indicating that females were more likely to nest farther from the line in years when greater numbers of ravens were present in the study landscape. Similarly, we found that year-specific slopes for the effect of distance from the FG transmission line on nest survival positively covaried with relative raven abundance (Fig. 5C). The degree to and the distance at which nest survival was reduced at a given distance from the FG transmission line were both positively correlated with annual raven abundance. Therefore, in years of greater raven abundance, the transmission line had a stronger

Table 2. Performance of multistate models to assess the influence of power lines and common raven abundance on greater sage-grouse nesting and re-nesting propensities in Eureka County, Nevada, from 2003–2012. We considered variables in models that outperformed (lower ΔAIC_c) the Nesting: (NP:covar) Re-nesting: (RNP:covar) model and had 85% confidence intervals that did not overlap 0 to be explanatory.

Model ^a	ΔAIC_c^b	w_i^c	K^d	Deviance
Nesting: (NP:covar) Re-nesting: (RNP:covar + raven)	0.00	0.64	28	47,414.95
Nesting: (NP:covar) Re-nesting: (RNP:covar + FG ²)	3.05	0.14	29	47,415.97
Nesting: (NP:covar) Re-nesting: (RNP:covar + FG)	4.83	0.06	28	47,419.78
Nesting: (NP:covar) Re-nesting: (RNP:covar)	5.07	0.05	27	47,422.05
Nesting: (NP:covar + FG) Re-nesting: (RNP:covar)	7.02	0.02	28	47,421.98
Nesting: (NP:covar + raven) Re-nesting: (RNP:covar)	7.02	0.02	28	47,421.98
Nesting: (NP:covar + power) Re-nesting: (RNP:covar)	7.03	0.02	28	47,421.98
Nesting: (NP:covar) Re-nesting: (RNP:covar + power)	7.06	0.02	28	47,422.02
Nesting: (NP:covar + FG ²) Re-nesting: (RNP:covar)	7.70	0.01	29	47,420.63
Nesting: (NP:covar + power ²) Re-nesting: (RNP:covar)	8.08	0.01	29	47,421.00
Nesting: (NP:covar) Re-nesting: (RNP:covar + power ²)	9.00	0.01	29	47,421.92
Nesting: (NP:covar + FG × raven) Re-nesting: (RNP:covar)	10.46	0.00	30	47,421.35

^a All models constrained site fidelity, nest failure, and re-nest failure to be constant among and within years ($K=3$). Detection was allowed to vary by breeding stage ($K=3$), year ($K=10$), and fit with a quadratic trend across occasions within years ($K=2$). NP:covar represents the environmental characteristics ($K=3$) that influenced nesting propensity (male population size [-]; female age [+]; female age² [-]; Table SB1 in Appendix B). RNP:covar represents the environmental characteristics ($K=2$) that influenced re-nesting propensity (population size [-]; spring precipitation [+]; Table SB1 in Appendix B). Power and FG represent the average distance a female sage-grouse was from any power line or the Falcon–Gondor transmission line during a given spring (1 Apr–31 May), respectively. Raven represents the mean number of common ravens observed per point surveyed during spring point count surveys. We denote a quadratic relationship with a square notation (²), and it includes the linear component. Models with interactions consider both the variables and interaction terms.

^b The difference in Akaike’s Information Criterion between the top ranked and selected model.

^c The relative likelihood of a model (i.e., Akaike weights).

^d The number of estimated parameters in a given model.

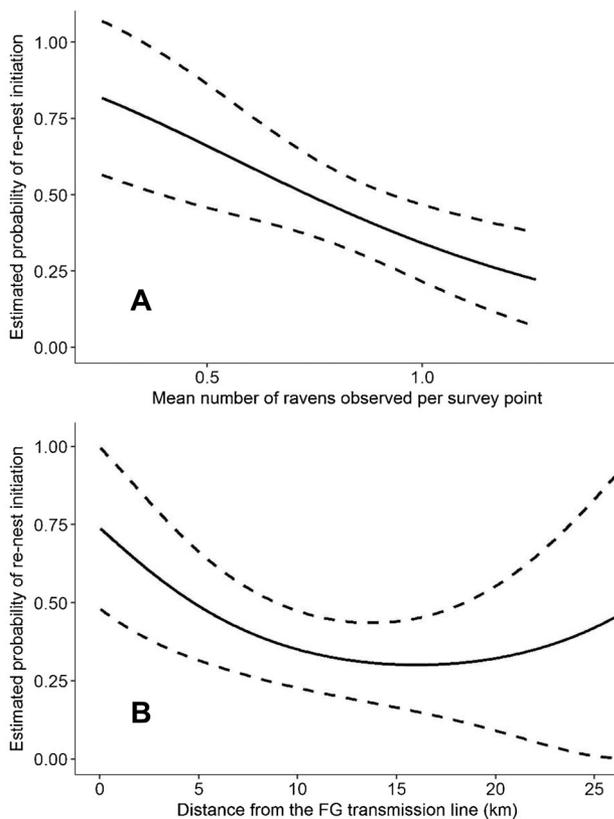


Figure 4. The influence of A) the average number of common ravens observed within 400 m of a point count survey associated the Falcon–Gondor (FG) transmission line, and B) the average distance a female greater sage-grouse was from the FG transmission line during the breeding (Apr–May) season on re-nesting propensities in Eureka County, Nevada from 2003–2012. Error lines (dashed lines) represent 95% confidence intervals.

negative effect that persisted for a greater distance away from the line itself. We found no support for a similar relationship between relative raptor abundance and year-specific slopes for the effect of distance from the FG transmission line on nest-site selection or nest survival (Fig. 5D).

We found support for a positive linear effect of distance to any power line on brood-site selection ($\beta_{All} = 0.29$; 85% CI = 0.20–0.38; Table 8), indicative of overall avoidance. *Post hoc*, we found additional support for a power-line effect on brood-site selection to 7.5 km for any power line ($\beta_{All7.5} = 0.90$; 85% CI = 0.62–1.19), and to 5 km for the FG transmission line ($\beta_{FG5} = 1.02$; 85% CI = 0.56–1.47; Table 9; Fig. 8).

Survival Rates

We found that pre-fledging chick survival was explained in part by an interaction ($\beta_{Raven \times FG} = 0.36$; 85% CI = 0.19–0.53) between the raven index ($\beta_{RavenIndex} = -0.25$; 85% CI = -0.44 to -0.07) and distance from the FG transmission line ($\beta_{FG} = -0.27$; 85% CI = -0.39 to -0.14; Fig. 9; Table 10), which suggested that chick survival near the FG transmission line decreased as raven abundance increased. During years of low and average raven abundance, pre-fledging chick survival was lower in areas farther from the FG transmission line; however, in years of high raven abundance pre-fledging chick survival was greater in areas farther from the FG transmission line. We also found support for an interaction ($\beta_{FG \times Trend} = 0.06$; 85% CI = 0.02–0.10) between distance from the FG transmission line ($\beta_{FG} = -0.37$; 85% CI = -0.59 to -0.15) and a yearly-trend variable ($\beta_{Trend} = -0.05$; 85% CI = -0.09–0.00), which suggested that pre-fledging chick survival for broods near the FG transmission line has generally declined over the course of the study (Fig. 10). We found no support for an influence of relative raptor abundance on pre-fledging chick survival, regardless of the distance a brood was found from FG. In the absence of more complex interactions, however, we found that pre-fledging chick

Table 3. Performance of multistate models assessing support of distance-threshold effects of distance from the Falcon–Gondor or any transmission line on greater sage-grouse nesting and re-nesting propensities in Eureka County, Nevada, from 2003–2012. We considered variables in models that outperformed (lower ΔAIC) the Nesting: (NP:covar) Re-nesting: (RNP:covar) model and had 85% confidence intervals that did not overlap 0 to be explanatory.

Model ^a	ΔAIC_c^b	w_i^c	K^d	Deviance
Nesting: (NP:covar) Re-nesting: (RNP:covar + FG ₁₀)	0.00	0.13	28	47,418.05
Nesting: (NP:covar) Re-nesting: (RNP:covar + FG _{12.5})	0.09	0.12	28	47,418.14
Nesting: (NP:covar) Re-nesting: (RNP:covar + FG _{7.5})	0.41	0.11	28	47,418.46
Nesting: (NP:covar) Re-nesting: (RNP:covar + FG ₅)	0.76	0.09	28	47,418.81
Nesting: (NP:covar) Re-nesting: (RNP:covar + FG _{log})	0.76	0.09	28	47,418.81
Nesting: (NP:covar) Re-nesting: (RNP:covar + FG)	1.73	0.05	28	47,419.78
Nesting: (NP:covar) Re-nesting: (RNP:covar)	1.97	0.05	27	47,422.05
Nesting: (NP:covar) Re-nesting: (RNP:covar + FG _{2.5})	3.38	0.02	28	47,421.43
Nesting: (NP:covar + FG _{2.5}) Re-nesting: (RNP:covar)	3.71	0.02	28	47,421.76
Nesting: (NP:covar) Re-nesting: (RNP:covar + power _{7.5})	3.76	0.02	28	47,421.82
Nesting: (NP:covar + FG _{12.5}) Re-nesting: (RNP:covar)	3.83	0.02	28	47,421.88
Nesting: (NP:covar + FG _{7.5}) Re-nesting: (RNP:covar)	3.83	0.02	28	47,421.89
Nesting: (NP:covar) Re-nesting: (RNP:covar + power _{2.5})	3.85	0.02	28	47,421.91
Nesting: (NP:covar) Re-nesting: (RNP:covar + power ₁₀)	3.91	0.02	28	47,421.96
Nesting: (NP:covar + FG) Re-nesting: (RNP:covar)	3.92	0.02	28	47,421.98
Nesting: (NP:covar + power) Re-nesting: (RNP:covar)	3.93	0.02	28	47,421.98
Nesting: (NP:covar + power ₅) Re-nesting: (RNP:covar)	3.97	0.02	28	47,422.03
Nesting: (NP:covar + power _{12.5}) Re-nesting: (RNP:covar)	3.98	0.02	28	47,422.04
Nesting: (NP:covar + FG _{log}) Re-nesting: (RNP:covar)	3.99	0.02	28	47,422.04
Nesting: (NP:covar + power _{7.5}) Re-nesting: (RNP:covar)	3.99	0.02	28	47,422.04
Nesting: (NP:covar + power _{2.5}) Re-nesting: (RNP:covar)	4.00	0.02	28	47,422.05
Nesting: (NP:covar + FG ₅) Re-nesting: (RNP:covar)	4.00	0.02	28	47,422.05
Nesting: (NP:covar) Re-nesting: (RNP:covar + power _{log})	4.00	0.02	28	47,422.05
Nesting: (NP:covar) Re-nesting: (RNP:covar + power ₅)	4.00	0.02	28	47,422.05
Nesting: (NP:covar + power ₁₀) Re-nesting: (RNP:covar)	4.00	0.02	28	47,422.05
Nesting: (NP:covar) Re-nesting: (RNP:covar + power _{12.5})	4.00	0.02	28	47,422.05
Nesting: (NP:covar + FG ₁₀) Re-nesting: (RNP:covar)	7.81	0.00	30	47,421.80
Nesting: (NP:covar) Re-nesting: (RNP:covar + power)	8.02	0.00	30	47,422.02
Nesting: (NP:covar + power _{log}) Re-nesting: (RNP:covar)	10.08	0.00	31	47,422.04

^a All models constrained site fidelity, nest failure, and re-nest failure to be constant among and within years ($K=3$). Detection was allowed to vary by breeding stage ($K=3$), year ($K=10$), and fit with a quadratic trend across occasions but within years ($K=2$). NP:covar represents the environmental characteristics ($K=3$) that influenced nesting propensity (male population size [-]; female age [+]; female age² [-]; Table SB1 in Appendix B). RNP:covar represents the environmental characteristics ($K=2$) that influenced re-nesting propensity (population size [-]; spring precipitation [+]; Table SB1 in Appendix B). Power and FG represent the average distance a female sage-grouse was from any power line or the Falcon–Gondor transmission line during a given spring (April 1st–May 31st), respectively. Raven represents the mean number of common ravens observed per point surveyed during spring point count surveys. Subscripts represent the maximum extent (in km) to which the linear distance from the FG transmission or any power line was applied to the decision to initiate a nest. The log represents a model that used the natural log of the normalized distance from FG or all transmission line covariate + 0.001, which estimates a pseudo-threshold. All models included individual and year as random effects.

^b The difference in Akaike’s Information Criterion between the top ranked and selected model.

^c The relative likelihood of a model (i.e., Akaike weights).

^d The number of estimated parameters in a given model.

survival was higher for broods near any power line relative to broods located farther from power lines. Benefits associated with being near power lines extended to 10 km from the FG transmission line ($\beta_{FG10} = -0.22$; 85% CI = -0.03 to -0.41) and 5 km from any power line ($\beta_{All5} = -0.59$; 85% CI = -0.19 to -0.98 ; Table 11; Fig. 11A).

We did not find support for effect of an interaction between a linear year trend and distance from the FG transmission line (Table 12) on adult female survival. We also did not find support that female survival was influenced by relative raptor abundance. *Post hoc*, we found support for a power-line effect on female survival to 2.5 km for any power line ($\beta_{All2.5} = 0.45$; 85% CI = 0.03 – 0.88), and to 7.5 km for the FG transmission line ($\beta_{FG7.5} = 0.42$; 85% CI = 0.04 – 0.81 ; Table 13; Fig. 11B), but model support and the resulting effect were weak.

Similar to results from the pre-fledging chick survival analysis, we found support for an interaction ($\beta_{FG \times Trend} = 0.06$; 85% CI = 0.01 – 0.11) between distance from the FG transmission line ($\beta_{FG} = -0.28$; 85% CI = -0.65 to -0.08) and an annual trend ($\beta_{YearTrend} = -0.13$; 85% CI = -0.19 to -0.08) in survival of

adult males, which suggested that annual survival of males associated with leks closer to the FG transmission line declined throughout the study, whereas male survival at more distant leks was more stable (Fig. 10 and Table 14). However, this effect was not explained by relative raptor abundance. *Post hoc*, we found support for the hypothesis that male survival for individuals associated with leks within 5 km of any power line was positively associated with distance from any power line ($\beta_{All5} = 0.53$; 85% CI = 0.00 – 1.07 ; Fig. 11C). We did not include any covariates on the lek $\psi_{movement}$ parameter because the data were too sparse to reliably assess model structures more complicated than single-variable models. We did not find that the distance from a lek to the FG transmission line or any power line influenced male inter-lek movement rates (Table 14).

Lek-Specific Recruitment and Population Growth Rates

We found the most support for an interaction effect ($\beta_{FG \times Trend} = 0.05$; 85% CI = 0.04 – 0.06) between distance from the FG transmission line ($\beta_{FG} = -0.25$; 85% CI = -0.30 to -0.19) and an annual trend ($\beta_{YearTrend} = -0.07$; 85% CI = -0.11 to

Table 4. Performance of resource selection functions based on generalized linear mixed effects models used to assess the influence of distance from power lines on greater sage-grouse nest-site use in Eureka County, Nevada, from 2004–2012. We considered variables in models that outperformed (lower ΔAIC) the Covar model and had 85% confidence intervals that did not overlap 0 to be explanatory.

Model ^a	ΔAIC_c^b	w_i^c	K^d	Deviance
Covar + road ²	0.00	0.98	13	1,695.75
Covar + power × raven	7.47	0.02	14	1,701.22
Covar + power	14.83	0.00	12	1,712.58
Covar + power ²	16.80	0.00	13	1,712.55
Covar + road	25.25	0.00	12	1,723.01
Covar + FG × raven	25.47	0.00	14	1,719.23
Covar + FG	30.04	0.00	12	1,727.79
Covar	30.54	0.00	11	1,730.29
Covar + FG ²	30.69	0.00	13	1,726.44
Covar + highway ²	31.31	0.00	13	1,727.06
Covar + highway	32.22	0.00	12	1,729.97

^a Power and FG represent the distance a female sage-grouse nest or random point was located from any power line or the Falcon–Gondor transmission line, respectively. Highway and road represent the distance a female sage-grouse nest or random point was located from the nearest state highway or managed road, respectively. Covar represents the environmental characteristics ($K=8$) that influenced nest-site selection at the landscape scale: (distance from lek [-]; sagebrush cover classification [+]; sagebrush cover classification × distance from lek [-]; slope [-]; elevation [+]; slope × elevation [-]; distance from water [-]; and distance from water² [-]; Table SB2 in Appendix B). We denote a quadratic relationship with a square notation (²). Raven represents the mean number of common ravens observed per point surveyed during spring point count surveys. All models included individual and year as random effects. Models with interactions included the terms for the individual effects and interactions.

^b The difference in Akaike’s Information Criterion between the top ranked and selected model.

^c The relative likelihood of a model (i.e., Akaike weights).

^d The number of estimated parameters in a given model.

–0.04) in population growth rate, which suggested abundance of males at leks closer to the FG transmission line was initially greater, then declined at a greater rate than those farther from the FG line during the study (Fig. 12 and Table 15). We also found support for an interaction ($\beta_{FG \times Raven} = 0.12$; 85% CI = 0.08–0.16) between distance from the FG transmission line ($\beta_{FG} = 0.01$; 85% CI = –0.01–0.03) and relative raven abundance ($\beta_{Raven} = -0.20$; 85% CI = –0.03–0.33; Fig. 13A), which suggested that population growth for leks near the FG transmission line was more reduced during years of greater relative raven abundance. Likewise, we found support for an interaction ($\beta_{FG \times Raptor} = 0.11$; 85% CI = 0.07–0.15) between distance from the FG transmission line ($\beta_{FG} = -0.03$; 85% CI = –0.01–0.05) and relative raptor abundance ($\beta_{Raptor} = -0.01$; 85% CI = –0.18–0.19; Fig. 13B), which suggested that population growth for leks near the FG transmission line was also reduced during years of higher relative raptor abundance. In the absence of more complicated interactions, however, relative raptor abundance was not supported to explain a substantial amount of variation in population growth (Table 15). *Post hoc*, we found that male population growth at leks within 5 km of the FG (Fig. 14A) transmission line was positively associated with distance from the line ($\beta_{FG5} = 0.12$; 85% CI = 0.03–0.2; Table 15).

Similar to population growth, we found support for an interaction ($\beta_{FG \times Trend} = 0.05$; 85% CI = 0.04–0.06) between distance from the FG transmission line ($\beta_{FG} = -0.25$; 85% CI = –0.30 to –0.19) and an annual trend ($\beta_{YearTrend} = -0.07$;

85% CI = –0.11 to –0.04) in *per capita* recruitment, which suggested a greater decline in *per capita* recruitment throughout the study at leks that were closer to the FG transmission line than more distant leks (Fig. 12 and Table 16). We also found support for an interaction ($\beta_{FG \times Raven} = 0.23$; 85% CI = 0.12–0.34) between effects on *per capita* recruitment of distance from the FG transmission line ($\beta_{FG} = -0.05$; 85% CI = –0.14–0.03) and relative raven abundance ($\beta_{Raven} = -0.08$; 85% CI = –0.18–0.33; Fig. 13C), but not raptor abundance (Table 16). *Post hoc*, we found support that *per capita* recruitment at leks within 5 km of any power line was positively associated with distance from the line ($\beta_{All5} = 0.12$; 85% CI = 0.00–0.25; Fig. 14B; Table 16).

Raven Occupancy Rates

We found that probability of a raven occupying a location near a monitored sage-grouse lek was higher for leks near the FG transmission line relative to leks more distant from the transmission line (Table 17; $\beta_{log(FG)} = -1.02$; 85% CI = –0.23 to –1.82). Furthermore, the pseudo-threshold model was supported over other linear or threshold models, which indicated that raven occupancy rates were greater, but decreased more rapidly with increasing distance, near the FG transmission line (within 5 km); however, occupancy rates continued to decline past this threshold (Fig. 15). A similar response was supported between distance from the nearest highway and raven occupancy ($\beta_{log(Highway)} = -1.07$; 85% CI = –0.13 to –2.02). Although this relationship was less well-supported than the top model, both models similarly described the observed spatial distribution of ravens on the landscape. We found probability of raven colonizing, or disturbing, a lek unoccupied the previous year (γ_{Dis}) increased throughout the duration of the study ($\beta_{Trend} = 2.22$; 85% CI = 0.46–3.99). These results, in conjunction with raven observations from the transect surveys, indicated that raven activity near the line generally increased throughout this study.

DISCUSSION

We found support for avoidance of power lines, for demographic suppression by those lines, and ultimately, for negative effects on sage-grouse population growth (Table 18). Additionally, we found that the magnitude of the avoidance of power lines and the extent to which vital rates were suppressed interacted with common raven abundance, which, in turn, was also positively associated with power lines. The geographical extent to which power lines could negatively influence sage-grouse demographic processes may therefore not be completely generalizable because it is likely contingent on local raven abundance and behavior. Although relationships between demographic processes or behaviors and raven abundance or other temporal processes complicated the spatial extent or magnitude of power-line effects, patterns indicative of habitat avoidance were supported up to 10 km from any power line, and we observed reductions in individual reproductive processes up to 12.5 km from the FG transmission line. Together, these resulted in a negative association between the FG transmission line and population growth, which was supported to at least 5 km from this line. Similarly, we observed a substantial increase

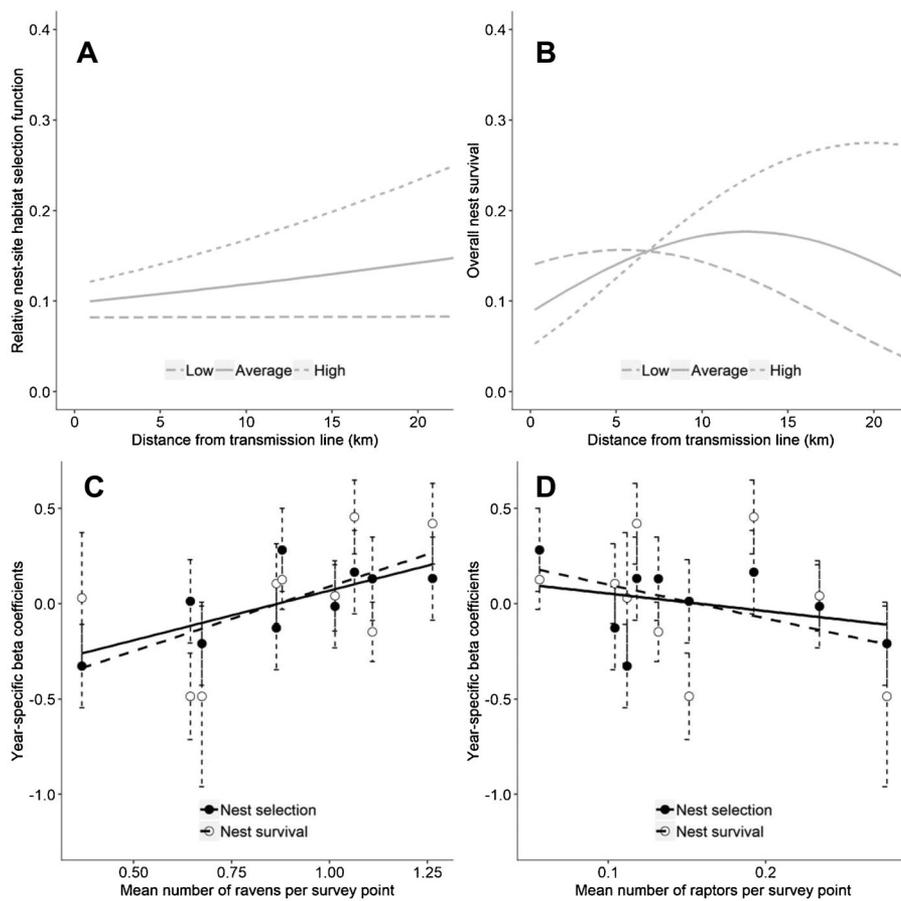


Figure 5. Associations between distance from the Falcon–Gondor transmission line and A) sage-grouse relative nest-site selection or B) overall nest survival as a function of common raven abundance (low [−1 SD from mean raven abundance, long-dash], average [solid], and high [+1 SD from mean raven abundance, short-dash]). Year-specific beta parameter estimates assessing the relationships between distance from the Falcon–Gondor transmission line and nest-site selection (filled circles, solid regression line) and nest survival (open circles, dashed regression line) were regressed on C) mean number of common ravens and D) mean number of raptors observed on the surveyed portion of the Falcon–Gondor transmission line in Eureka County, Nevada from 2004–2012. Error bars represent standard errors.

in raven populations near the FG transmission line since construction (Fig. 3), as well as higher raven occupancy rates for leks within at least 5 km from the FG transmission line (Fig. 15).

We did not attribute any sage-grouse mortalities to direct collisions with a power line, pole, or guy wire during the 10-year study period. Collisions between Galliformes and power lines have been suggested to be disproportionately high relative to those of other birds (Bevanger 1998, Bevanger and Broseth 2004); however, the observed lack of direct mortality in this system was consistent with other long-term studies that have recorded low numbers of mortalities associated with power lines, relative to other mortality, of radio-marked sage-grouse (Connelly et al. 2000, Beck et al. 2006, Dinkins et al. 2014b) or other North American Galliformes (Pruett et al. 2009). Thus, the effect of power lines on sage-grouse population dynamics during our study was associated with indirect mechanisms, such as avoidance of habitat near power lines or suppressed vital rates, mediated by predators that were subsidized by power lines (Boarman 2003, Kristan and Boarman 2007, Strickland and Janzen 2010). The exploitation of anthropogenic structures by predators can substantially alter the demographic processes, abundance, and ultimately, distribution

of their prey (Liebezeit et al. 2009, Russell et al. 2014, Peebles and Conover, 2017, Schakner et al. 2017). Likewise, our results suggested that the effect of associations between ravens and power lines on sage-grouse behavior and demographic rates were sufficiently large to cause populations to decline, which reinforces recent calls for future studies to better consider the indirect effects of energy infrastructure (Loss 2016, Smith and Dwyer 2016).

The observed impact of power lines on certain demographic rates were small (e.g., female survival), which highlights the importance of long-term data collection on impact assessment. Determining mechanisms of population change from year-to-year variation cannot be achieved with short time-series (<5 years), especially in highly variable systems, and may lead to spurious conclusions (Gerber et al. 1999, McCain et al. 2016). Although the discussion regarding the minimum time-series required to detect population trend is ongoing (Gerber et al. 1999, Nichols and Williams 2006, White 2017), 10–20 years of continuous monitoring data may be required to have confidence in a given prediction. However, we speculate that this duration can be reduced to some extent through spatial replication and study design (e.g., independent assessment of multiple species, sexes, age classes, demographic processes).

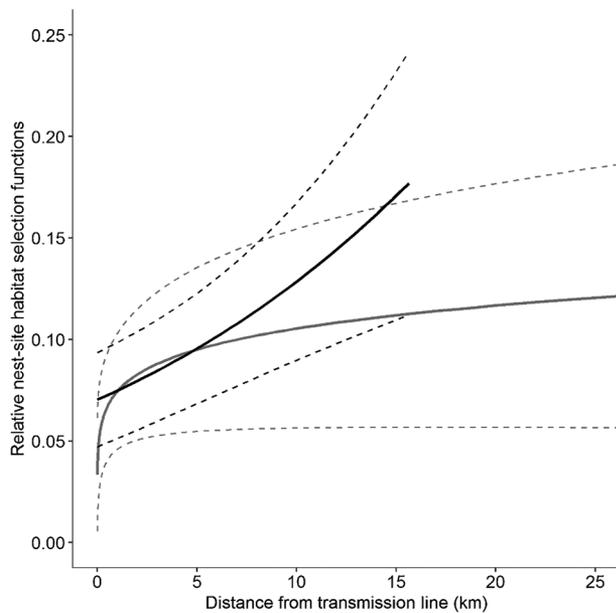


Figure 6. Relationship between distance from the Falcon–Gondor (solid gray line) or any power line (solid black line) and the relative probability of selection of a point as a sage-grouse nesting site in Eureka County, Nevada from 2004–2012. The most competitive models supported a pseudo-threshold constraint on the Falcon–Gondor effect, and a linear effect of any power line on relative nest-site selection probabilities. Error lines (dashed lines) represent 95% confidence intervals.

Avoidance of Power Lines

We found consistent support for the hypothesis that female sage-grouse avoided areas near any power line. Areas proximate to either the FG transmission line or any power line, which we otherwise predicted to be appropriate habitat for either nesting or brood rearing, were less likely to be used by female sage-grouse. Most notably, we found that the degree of avoidance during the nesting period was positively associated with raven abundance (Fig. 5). This novel result suggests that changes in predator density may be one mechanism driving the avoidance of potential nesting habitat near power lines. Raven populations have been positively associated with power lines (Knight and Kawashima 1993, Knight et al. 1995, Howe et al. 2014, Coates et al. 2014a), and sage-grouse avoid nesting in areas with high densities of avian nest predators (Dinkins et al. 2012). However, to our knowledge, we uniquely demonstrate that sage-grouse avoid nesting near power lines when faced with increased abundance of nest predators.

We also found that females avoided power lines during the brood-rearing period, and there are at least 2 possible explanations for this result. First, it is possible the effect carried over from avoidance behavior during nesting (Fig. 6) and lower nest survival near power lines (Fig. 7). Consequently, nesting habitat and early brood habitat were causally linked and fewer broods hatching near versus farther from power lines would have resulted in fewer broods using habitats near power lines during early brood rearing. Second, it is possible that females tending broods actively avoided areas near power lines. We cannot, however, distinguish between these 2 possibilities. Regardless of the mechanism, the combined effects of avoidance during nesting, reduced reproductive success, and lower likelihood of brood use near power lines resulted in a reduction in the

Table 5. Performance of resource selection functions based on generalized linear mixed effects models assessing support for distance-threshold effects of distance from the Falcon–Gondor or any transmission line on greater sage-grouse nest-site use in Eureka County, Nevada, from 2004–2012. We considered variables in models that outperformed (lower ΔAIC) the Covar model and had 85% confidence intervals that did not overlap 0 to be explanatory.

Model ^a	ΔAIC_{ϵ}^b	w_i^c	K^d	Deviance
Covar + power	0.00	0.32	12	1,712.58
Covar + power ₁₀	0.31	0.28	12	1,712.89
Covar + power _{7.5}	1.21	0.18	12	1,713.79
Covar + power _{12.5}	1.74	0.14	12	1,714.32
Covar + power _{log}	2.97	0.07	12	1,715.55
Covar + power ₅	8.18	0.01	12	1,720.76
Covar + FG _{log}	11.27	0.00	12	1,723.85
Covar + FG ₁₀	12.84	0.00	12	1,725.42
Covar + FG _{7.5}	12.90	0.00	12	1,725.48
Covar + power _{2.5}	13.14	0.00	12	1,725.72
Covar + FG _{12.5}	14.61	0.00	12	1,727.19
Covar + FG ₅	14.72	0.00	12	1,727.30
Covar + FG _{2.5}	15.21	0.00	12	1,727.79
Covar + FG	15.21	0.00	12	1,727.79
Covar	15.71	0.00	11	1,730.29

^a Power and FG represent the distance a female sage-grouse nest or random point was located from any power line or the Falcon–Gondor transmission line, respectively. Covar represents the environmental characteristics ($K=8$) that influenced nest-site selection at the landscape scale: (distance from lek [–]; sagebrush cover classification [+]; sagebrush cover classification \times distance from lek [–]; slope [–]; elevation [+]; slope \times elevation [–]; distance from water [–]; and distance from water² [–]; Table SB2 in Appendix B). Subscripts represent the maximum extent (in km) to which the linear distance from the FG transmission or any power line was applied to nest-site selection. The log represents a model that used the natural log of the normalized distance from FG or any power line covariate + 0.001, which estimates a pseudo-threshold. All models included individual and year as random effects.

^b The difference in Akaike’s Information Criterion between the top ranked and selected model.

^c The relative likelihood of a model (i.e., Akaike weights).

^d The number of estimated parameters in a given model.

effective quality of brood-rearing habitat in those areas, as such habitat is only functional if it is physically accessible (i.e., near successful nests) to broods (Aldridge and Boyce 2007, Gibson et al. 2017).

Suppression of Individual Vital Rates

We found variable support for reductions of vital rates as a function of proximity to power lines. Nesting propensity was not influenced by an individual’s proximity to either the FG transmission line or any power line. However, we found support for greater re-nesting rates near the FG transmission line. This relationship was not directly related to reductions in nest survival near the FG transmission line, as our estimates of re-nesting propensity were conditional on nest failure, and did not directly increase as a function of increased nest failure. However, increased levels of nest predation may result in more nests failing earlier in the nesting season, which could indirectly increase re-nesting propensity by giving unsuccessful females more time to attempt a second nest, or leaving them in better body condition for such an attempt (Gregg et al. 2008). Sage-grouse nesting propensity has been negatively influenced by other anthropogenic disturbances (e.g., oil development; Lyon and Anderson 2003); however, these estimates were reported as apparent nesting propensity and are not directly comparable to our results (Blomberg et al. 2017).

Table 6. Performance of nest survival models assessing influence of power lines and common raven abundance on greater sage-grouse nest survival in Eureka County, NV, from 2004–2012. We considered variables in models that outperformed (lower ΔAIC) the Covar model and had 85% confidence intervals that did not overlap 0 to be explanatory.

Model ^a	ΔAIC_c^b	w_i^c	K^d	Deviance
Covar + $\text{FG}^2 \times \text{raven}$	0.00	0.25	8	1,502.42
Covar + $\text{FG} \times \text{raven}$	1.38	0.13	7	1,505.81
Covar + FG^2	2.06	0.09	6	1,508.49
Covar	2.32	0.08	4	1,512.76
Covar + power^2	2.46	0.07	6	1,508.89
Covar + FG_{year}	2.48	0.07	13	1,494.85
Covar + FG	3.19	0.05	5	1,511.62
Covar + highway	3.63	0.04	5	1,512.06
Covar + raven	3.64	0.04	5	1,512.07
Covar + $\text{FG}^2 + \text{raven}$	3.71	0.04	7	1,508.14
Covar + power	3.86	0.04	5	1,512.29
Covar + road	4.01	0.03	5	1,512.44
Covar + highway^2	4.30	0.03	6	1,512.72
Covar + $\text{FG} + \text{raven}$	4.73	0.02	6	1,511.16
Covar + road^2	5.62	0.02	6	1,512.05

^a FG and power represent the distance a female greater sage-grouse nest was located from the Falcon–Gondor transmission line or any power line, respectively. Highway and road represent the distance a female sage-grouse nest was located from one of the 2 state highways or any road, respectively. The covariate FG_{year} allowed the parameter estimate for distance from Falcon–Gondor to vary (fixed effect) among years. Covar represents the environmental characteristics ($K=3$) that influenced nest survival (non-sagebrush shrub cover [+]; forb cover [+]; and population the female was associated with (i.e., Roberts Creek Mountain [+]; or Cortez Mountains [–]; Table SB4 in Appendix B). Raven represents annual average number of common ravens observed along the survey transect along the Falcon–Gondor transmission line. We denote a quadratic relationship with a square notation (²). Models with interactions include both the variables and their interaction.

^b The difference in Akaike’s Information Criterion between the top ranked and selected model.

^c The relative likelihood of a model (i.e., Akaike weights).

^d The number of estimated parameters in a given model.

Reductions in re-nesting propensity and the amount of habitat avoided were correlated with greater raven abundance, which suggests that power-line effects on reproductive decision-making by female sage-grouse was associated with nest predator densities. Nest survival was similarly reduced near the FG transmission line and negatively covaried with annual raven abundance. Together these results suggest that females may perceive increased risk of nest failure near power lines as a function of raven density, and respond by avoiding those areas or reducing their reproductive investment—or both—near power lines during years of high raven abundance. Together, these results are in agreement with the general ecological literature indicating that breeding individuals reduce fitness consequences associated with predation risk through habitat selection or reproductive flexibility (Lima 2009). For example, Eurasian skylarks (*Alauda arvensis*) shifted the distribution of their nests in response to shifts in kestrel (*Falco tinnunculus*) densities, and brant (*Branta bernicla bernicla*) had lower nest initiation rates when arctic foxes (*Vulpes lagopus*), a common nest predator, were present (Suhonen et al. 1994, Spaans et al. 1998). Likewise, female sage-grouse have also exhibited avoidance of brood-rearing habitat associated with greater raven densities (Dinkins et al. 2012), which suggests behavioral mechanisms exist in sage-grouse to reduce predation risk. Given the generally low rates

Table 7. Performance of nest survival models assessing support of distance-threshold effects of distance from the Falcon–Gondor transmission line on greater sage-grouse nest success in Eureka County, Nevada, from 2004–2012. We considered variables in models that outperformed (lower ΔAIC) the Covar model and had 85% confidence intervals that did not overlap 0 to be explanatory.

Model ^a	ΔAIC_c^b	w_i^c	K^d	Deviance
Covar + $\text{FG}_{12.5}$	0.00	0.19	5	1,509.04
Covar + FG_{10}	0.85	0.13	5	1,509.90
Covar	1.71	0.08	4	1,512.76
Covar + $\text{power}_{7.5}$	1.90	0.08	5	1,510.94
Covar + power_{10}	1.97	0.07	5	1,511.01
Covar + $\text{FG}_{7.5}$	2.18	0.07	5	1,511.22
Covar + $\text{power}_{12.5}$	2.52	0.06	5	1,511.56
Covar + FG	2.58	0.05	5	1,511.62
Covar + FG_{\log}	2.60	0.05	5	1,511.64
Covar + power_5	2.68	0.05	5	1,511.72
Covar + power	3.25	0.04	5	1,512.29
Covar + power_{\log}	3.35	0.04	5	1,512.39
Covar + $\text{power}_{2.5}$	3.46	0.03	5	1,512.50
Covar + FG_5	3.58	0.03	5	1,512.62
Covar + $\text{FG}_{2.5}$	3.71	0.03	5	1,512.75

^a Covar represents the environmental characteristics ($K=3$) that influenced nest survival (non-sagebrush shrub cover [+]; forb cover [+]; and population the female was associated with (i.e., Roberts Creek Mountain [+]; or Cortez Mountain [–]; Table SB4 in Appendix B). FG and power represent the distance a female greater sage-grouse nest was located from the Falcon–Gondor transmission line or any power line, respectively. Subscripts represent the maximum extent (in km) to which the linear distance from the FG transmission or any power line was applied to the nest survival model and log represents a model that used the natural log of the normalized distance from FG or all power line covariate + 0.001, which estimates a pseudo-threshold.

^b The difference in Akaike’s Information Criterion between the top ranked and selected model.

^c The relative likelihood of a model (i.e., Akaike weights).

^d The number of estimated parameters in a given model.

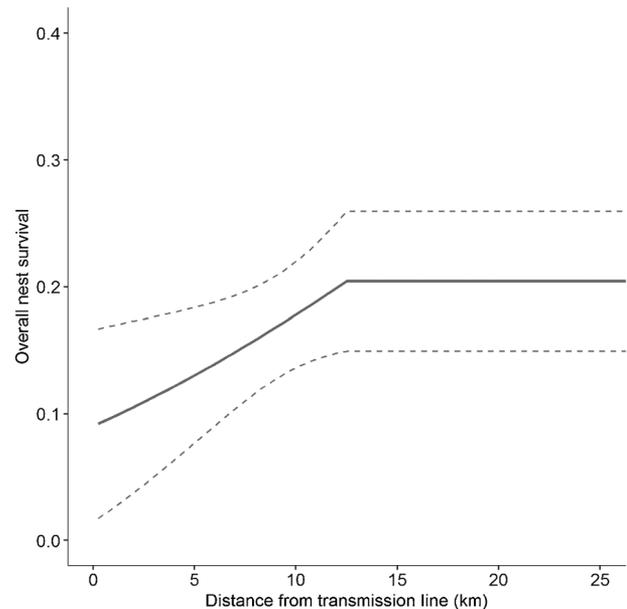


Figure 7. Relationship between the distance of a sage-grouse nest from the Falcon–Gondor (FG) line and its probability of surviving to hatch (to 37 days) in Eureka County, Nevada from 2004–2012. The threshold model that constrained the linear distance effect to end at 12.5 km (gray line) from the FG transmission line was most supported. Error lines (dashed lines) represent 95% confidence intervals.

Table 8. Performance of resource selection functions (based on generalized linear mixed effects models) to assess the influence of a distance from power lines on greater sage-grouse brood-site use in Eureka County, Nevada, from 2005–2012. We considered variables in models that outperformed (lower ΔAIC) the Covar model and had 85% confidence intervals that did not overlap 0 to be explanatory.

Model ^a	ΔAIC_c^b	w_i^c	K^d	Deviance
Covar + age + power	0.00	0.55	7	2,030.18
Covar + age \times power	1.64	0.24	8	2,029.82
Covar + age	2.78	0.14	6	2,034.96
Covar + age + FG	4.78	0.05	7	2,034.96
Covar + age \times FG	5.88	0.03	8	2,034.05
Covar + power	26.95	0.00	6	2,059.13
Covar + power ²	28.43	0.00	7	2,058.60
Covar	29.57	0.00	5	2,063.75
Covar + FG	31.57	0.00	6	2,063.75
Covar + FG ²	31.75	0.00	7	2,061.93

^a FG and power represent the average distance a female sage-grouse brood or random point was located from the Falcon–Gondor transmission line or any power line, respectively. Covar represents the environmental characteristics ($K=2$) that influenced brood-site selection (slope [-]; elevation [+]; see Table S3 in Appendix B). Age represented the age (in weeks) since the brood hatched. We denote a quadratic relationship with a square notation (²). Models with interactions include both the variables and their interaction. All models included individual and year as random effects.

^b The difference in Akaike’s Information Criterion between the top ranked and selected model.

^c The relative likelihood of a model (i.e., Akaike weights).

^d The number of estimated parameters in a given model.

Table 9. Performance of resource selection functions based on generalized linear mixed effects models assessing support for distance-threshold effects in distance from the Falcon–Gondor transmission line on greater sage-grouse brood-site use in Eureka County, Nevada, from 2004–2012. We considered variables in models that outperformed (lower ΔAIC) the Covar model and had 85% confidence intervals that did not overlap 0 to be explanatory.

Model ^a	ΔAIC_c^b	w_i^c	K^d	Deviance
Covar + power _{7.5}	0.00	0.99	6	2,042.12
Covar + power _{log}	9.88	0.01	6	2,052.00
Covar + FG ₅	11.65	0.00	6	2,053.77
Covar + power ₅	15.32	0.00	6	2,057.44
Covar + FG _{2.5}	16.23	0.00	6	2,058.35
Covar + FG _{7.5}	16.68	0.00	6	2,058.80
Covar + power	17.01	0.00	6	2,059.13
Covar + power ₁₀	17.12	0.00	6	2,059.24
Covar + FG _{log}	19.10	0.00	6	2,061.22
Covar + power _{12.5}	19.61	0.00	6	2,061.73
Covar	19.63	0.00	5	2,063.75
Covar + power _{2.5}	20.49	0.00	6	2,062.62
Covar + FG ₁₀	20.54	0.00	6	2,062.66
Covar + FG _{12.5}	21.62	0.00	6	2,063.74
Covar + FG	21.63	0.00	6	2,063.75

^a Covar represents the environmental characteristics ($K=2$) that influenced brood-site selection at the landscape scale (slope [-]; elevation [+]; see Table S3 in Appendix B). Age represented the age (in weeks) since the brood hatched. FG and power represent the average distance a female sage-grouse brood or random point was located from the Falcon–Gondor transmission line or any power line, respectively. Subscripts represent the maximum extent (in km) to which the linear distance from the FG transmission or any power line was applied to the brood-site selection function model and log represents a model that used the natural log of the normalized distance from FG or any power-line covariate + 0.001, which estimates a pseudo-threshold.

^b The difference in Akaike’s Information Criterion between the top ranked and selected model.

^c The relative likelihood of a model (i.e., Akaike weights).

^d The number of estimated parameters in a given model.

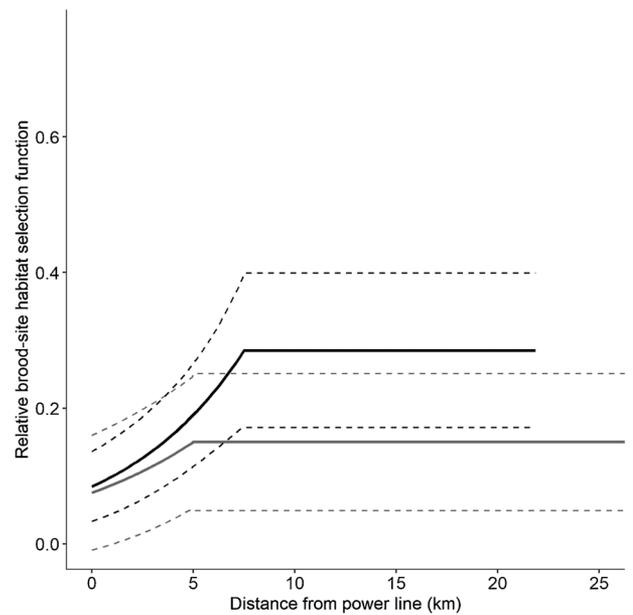


Figure 8. Relationships between distance from the Falcon–Gondor (FG; solid gray line) or any power line (solid black line) and the relative probability of selection of a point by sage-grouse as brood-rearing habitat in Eureka County, Nevada from 2005–2012. Models that applied the threshold constraint at 5 km from the FG transmission line, or 7.5 km from any power line were the most supported. Error lines (dashed lines) represent 95% confidence intervals.

of nest success in many sage-grouse populations (Connelly et al. 2011), lower rates of nesting combined with even lower nest survival associated with power lines is biologically significant.

We found more support for distance-threshold effects of any power line on sage-grouse behavior or demography than for simple linear models that considered the full range of observed

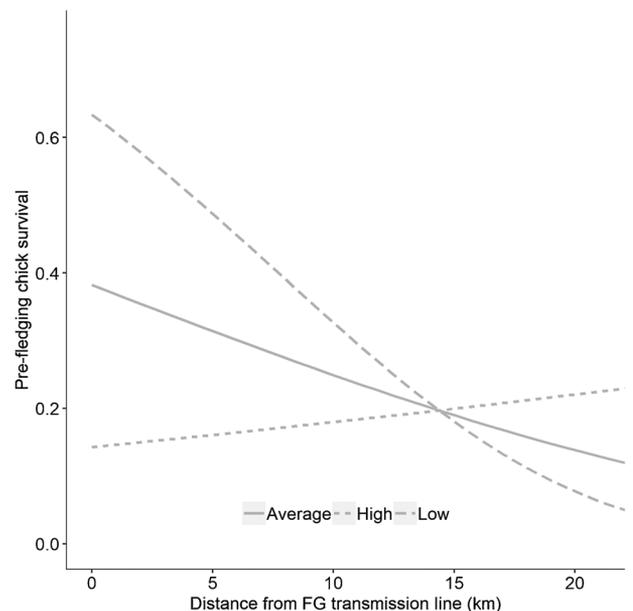


Figure 9. The association between the distance sage-grouse broods were from the Falcon–Gondor (FG) transmission line and 42-day pre-fledging chick survival varied as a function of common raven abundance (low: long-dash; average: solid; and high: short-dash) in Eureka County, Nevada from 2005–2012.

Table 10. Performance of Lukacs young of marked adults survival models assessing influence of power lines and common raven abundance on pre-fledging survival of greater sage-grouse chicks in Eureka County, Nevada, from 2005–2012. We considered variables in models that outperformed (lower ΔAIC_c) the Covar model and had 85% confidence intervals that did not overlap 0 to be explanatory.

Model ^a	ΔAIC_c^b	w_i^c	K^d	Deviance
Covar + FG × raven	0.00	0.68	24	2,037.77
Covar + power ²	4.81	0.06	23	2,044.82
Covar + FG × trend	5.11	0.05	24	2,042.87
Covar + raptor	5.38	0.05	22	2,047.63
Covar	6.43	0.03	21	2,050.91
Covar + raven	6.46	0.03	22	2,048.71
Covar + FG + raptor	6.63	0.02	23	2,046.65
Covar + FG	7.29	0.02	22	2,049.54
Covar + FG ²	7.56	0.02	23	2,047.57
Covar + FG + raven	7.68	0.01	23	2,047.69
Covar + FG + trend	7.74	0.01	23	2,047.76
Covar + power	8.55	0.01	22	2,050.80
Covar + FG × raptor	8.80	0.01	24	2,046.56

^a All models allowed detection probability to vary among years ($K=8$) and weeks ($K=4$) in an additive manner. FG and power were weekly time-varying covariates that represented the mean distance a female sage-grouse and her brood was from the Falcon–Gondor transmission line or any power line, respectively, in a given week. We denote a quadratic relationship with a square notation (²). Models with interactions included both the variables and their interactions. Covar represents the environmental characteristics ($K=8$) that influenced pre-fledging chick survival (drought severity index [+]; total vegetation cover [+]; distance brood moved in previous week [–]; average grass height [–]; distance from nearest water source [+]; nest-site quality [+]; female age [+]; female age² [–]; Table SB5 in Appendix B). Trend represents an annual trend. Raven represents annual average number of common ravens observed on the survey transect along the Falcon–Gondor transmission line. The final 2 weekly detection parameters were constrained to be the same, which resulted in the 6-occasion history having 4 estimated parameters for detection.

^b The difference in Akaike’s Information Criterion between the top ranked and selected model.

^c The relative likelihood of a model (i.e., Akaike weights).

^d The number of estimated parameters in a given model.

distances, suggesting that the indirect effects of the FG transmission line were geographically limited to areas within 12.5 km of the FG transmission line. We found that the most spatially expansive impact of the FG transmission line was on nest survival, which occurred out to 12.5 km from the transmission line.

We observed that multiple vital rates (i.e., pre-fledging chick survival, male survival, *per capita* recruitment, and population growth) trended downwards since the construction of the FG transmission line. We also found that the strength of the effect of the FG transmission line was influenced by the number of ravens in the transmission line corridor, which exhibited an increasing trend in relative abundance during our study. Having only 1 year of pre-construction data limits our ability to draw inferences about raven responses to the presence of power lines versus a general numeric response of ravens due to other factors (e.g., general population growth). Nevertheless, the annual rate of increase of ravens along the FG line (9% increase/year) was about 3 times greater than the annual rate of increase for North America (2.7% increase/year) as a whole (BirdLife International 2017).

The mechanism(s) driving the declines in adult male survival for individuals near the FG transmission line are not completely clear. Although ravens are known to be predators of sage-grouse nests and young chicks, they are not known to kill adults (Hagen

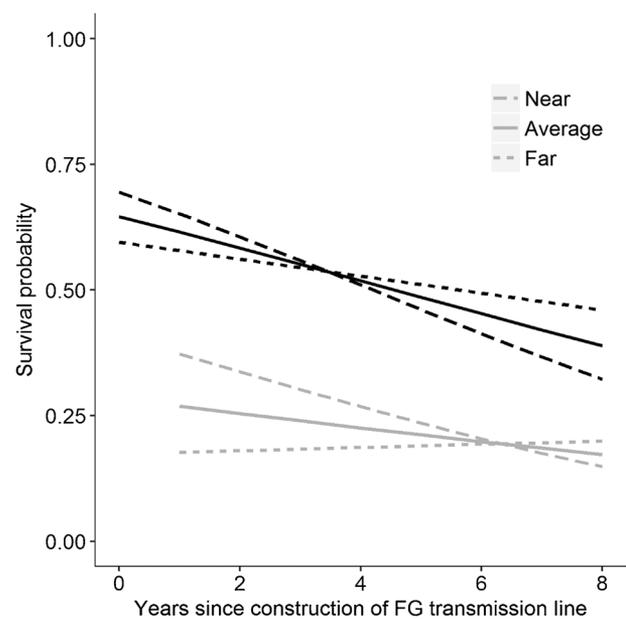


Figure 10. Sage-grouse 42-day pre-fledging chick survival (gray lines) and annual male survival (black lines) were supported to be both spatially (i.e., distance from the Falcon–Gondor [FG] transmission line [near: –1 SD from mean distance; average: mean distance; far: +1 SD from mean distance]) and temporally variable in Eureka County, Nevada from 2003–2012. Chick survival declined near and at average distance from the line over the duration of the study, whereas there was no trend far from the line. Survival of adult males declined at slower rates as distance from the line increased. Error lines represent 95% confidence intervals. Pre-fledging chick survival was not estimated prior to 2005.

2011). We did not have sufficient data to estimate variation in the abundances of mammalian predators of adult sage-grouse (e.g., coyotes [*Canis latrans*], American badgers [*Taxidea taxus*]) within this system; therefore, we could not design more targeted models related to adult male survival. Raptor abundances, however, were generally low and did not increase following the construction of the FG transmission line (Lammers and Collopy 2007; Fig. 3). Additionally, our index of relative raptor abundance explained little variation in adult female and male survival, or *per capita* recruitment. Nevertheless, the patterns we observed are consistent with hypothesized responses of ravens to elevated structures or other anthropogenic features (Knight et al. 1995, Kristan and Boarman 2003, Howe et al. 2014) and the effects of ravens on sage-grouse reproductive success (Coates and Delehanty 2004, Dinkins 2013) and recruitment.

We also found chick survival near the FG transmission line was reduced in years of high raven numbers. However, on average, areas near the FG transmission line were associated with the highest levels of chick survival in our system, which suggests this habitat remained the best option for brood-rearing (Kane et al. 2017) despite high mortality during years of greater predator abundance. Raven densities have been reported to be greater near sage-grouse brood-rearing areas (Bui et al. 2010), indicative of response (either numerical or functional) by ravens to increased food abundance.

Do Power Lines Lead to Population-Level Effects?

Although increased raven density has been associated with reduced nest survival across many taxa (Andren 1992, Kurki et al.

Table 11. Performance of Lukacs young of marked adults survival models assessing support of distance-threshold effects of distance from the Falcon–Gondor transmission line on pre-fledging survival of greater sage-grouse chicks in Eureka County, Nevada, from 2005–2012. We considered variables in models that outperformed (lower ΔAIC) the Covar model and had 85% confidence intervals that did not overlap 0 to be explanatory.

Model ^a	ΔAIC_c^b	w_i^c	K^d	Deviance
Covar + power ₅	0.00	0.22	22	2,046.08
Covar + power _{7.5}	0.24	0.19	22	2,046.32
Covar + FG ₁₀	1.88	0.09	22	2,047.95
Covar + FG ₅	1.97	0.08	22	2,048.05
Covar + FG _{7.5}	2.54	0.06	22	2,048.62
Covar + power ₁₀	2.58	0.06	22	2,048.66
Covar	2.61	0.06	21	2,050.91
Covar + FG _{log}	3.33	0.04	22	2,049.40
Covar + FG	3.47	0.04	22	2,049.54
Covar + FG _{12.5}	3.50	0.04	22	2,049.57
Covar + FG _{2.5}	4.01	0.03	22	2,050.09
Covar + power _{12.5}	4.10	0.03	22	2,050.17
Covar + power _{log}	4.28	0.03	22	2,050.36
Covar + power	4.72	0.02	22	2,050.80
Covar + power _{2.5}	4.82	0.02	22	2,050.89

^a Covar represents the environmental characteristics ($K=8$) that influenced pre-fledging chick survival (drought severity index [+]; total vegetation cover [+]; distance brood moved in previous week [-]; average grass height [-]; distance from nearest water source [+]; nest-site quality [+]; female age [+]; female age² [-]; Table SB5 in Appendix B). FG and power were weekly time-varying covariates that represented the mean distance a female sage-grouse and her brood were from the Falcon–Gondor transmission line or any power line, respectively, in a given week. Subscripts represent the maximum extent (in km) to which the linear distance from the FG transmission or any power line was applied to pre-fledging chick survival and log represents a model that used the natural log of the normalized distance from FG, or any power-line covariate + 0.001, which estimates a pseudo-threshold.

^b The difference in Akaike's Information Criterion between the top ranked and selected model.

^c The relative likelihood of a model (i.e., Akaike weights).

^d The number of estimated parameters in a given model.

1997, Klausen et al. 2010), support is lacking for population-level effects of ravens on avian populations in general (Madden et al. 2015). In our study, habitat use (e.g., nest- and brood-site selection) and reproductive success (e.g., nest survival, chick survival) were reduced for female sage-grouse near power lines, and this effect was linked to raven abundance. Most importantly, we found that 1) reductions in components of recruitment resulted in population-level effects; 2) recruitment of new males to breeding leks and rates of population growth were both reduced near the FG transmission line during years of high raven abundance; and 3) negative impacts on survival, recruitment, and population growth associated with any power line was observed at leks within 5 km of power lines regardless of raven abundance. Our observation of lowest recruitment into leks nearest the line is consistent with our finding of negative effects of proximity to the line on key components of the recruitment process: nest-site selection, nest success, and chick survival.

In summary, we found that multiple behaviors and vital rates estimated from a variety of data sources showed the same general pattern: vital rates were reduced, or individuals avoided habitat near power lines, generally when raven abundance was higher. Together, these analyses suggest power lines indirectly influenced various sage-grouse vital rates, and ultimately population growth, through the positive association of ravens with power lines. We posit that power lines created a subsidized

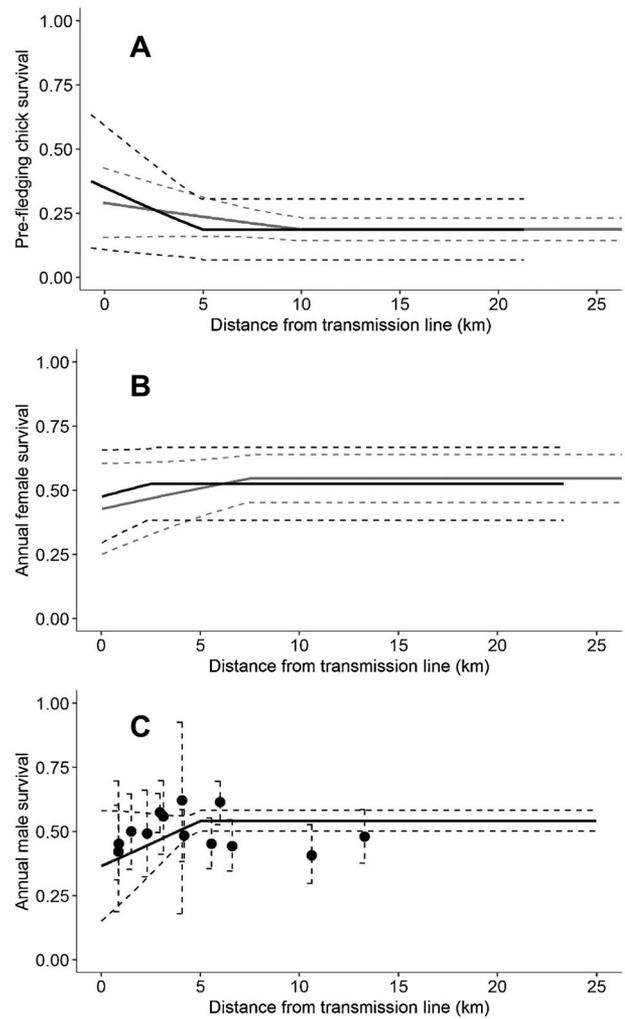


Figure 11. Sage-grouse 42-day pre-fledging chick survival (A), annual female survival (B), and annual male survival (C) were affected by an individual's association with the Falcon–Gondor (FG) transmission (gray lines) or any power line (black lines). The negative effect of distance from FG transmission line or any power line pre-fledging chick survival (A) extended out to 10 km and 5 km, respectively, which suggested that chick survival was greater near power lines relative to areas more distant. The positive effects of distance from FG transmission line or any power line on female survival (B) were weakly supported but extended out to 7.5 km and 2.5 km, respectively, which suggested female survival was slightly reduced near power lines. Lastly, for males associated with leks within 5 km of any power line, male survival (C) increased as a function of the lek's distance from any power line. Lek specific estimates of male survival are represented by circles. Error bars and lines represent 95% confidence intervals.

resource for ravens resulting in increased raven densities near power lines. This increase led to habitat avoidance, lower vital rates, and population decline for sage-grouse near any power line in our study area.

MANAGEMENT IMPLICATIONS

Our finding that negative impacts of the transmission line were primarily associated with raven abundance suggested that mitigation of line effects might be accomplished by reducing raven abundance near power lines. Ravens, like other corvids, have experienced a substantial increase in distribution and abundance that has been linked with increased energy

Table 12. Performance of nest survival models used to assess the influence of power lines on female greater sage-grouse survival in Eureka County, Nevada, from 2003–2012. We considered variables in models that outperformed (lower ΔAIC) the Covar model and had 85% confidence intervals that did not overlap 0 to be explanatory.

Model ^a	ΔAIC_c^b	w_i^c	K^d	Deviance
Covar	0.00	0.34	8	386.46
Covar + raptor	1.45	0.17	9	386.29
Covar + power	1.87	0.13	9	386.29
Covar + FG	1.92	0.13	9	386.34
Covar + FG + raptor	3.34	0.06	10	385.77
Covar + power ²	3.83	0.05	10	386.22
Covar + FG ²	3.86	0.05	10	386.25
Covar × FG(trend)	4.75	0.03	11	385.10
Covar + FG × raptor	4.90	0.03	11	385.25

^a FG and power were monthly time-varying covariates that represented the average distance a female sage-grouse was located from the Falcon–Gondor transmission line or any power line, respectively, in a given month. We denote a quadratic relationship with a square notation (²). Covar represents the environmental characteristics ($K=7$) that influenced female survival (minimum age [+]; nest success in given year [-]; brood success in given year [-]; seasonal differences: spring [-], summer [+], fall [-]; Table SB6 in Appendix B). Raptor represents annual average number of raptors observed along the survey transect along the Falcon–Gondor transmission line. Trend represents an annual linear trend. The covariate model was modified from Blomberg et al. (2013a).

^b The difference in Akaike’s Information Criterion between the top ranked and selected model.

^c The relative likelihood of a model (i.e., Akaike weights).

^d The number of estimated parameters in a given model.

Table 13. Performance of nest survival models used to assess support for distance-threshold effects of distance from transmission lines on adult female greater sage-grouse annual survival in Eureka County, Nevada, from 2003–2012. We considered variables in models that outperformed (lower ΔAIC) the Covar model and had 85% confidence intervals that did not overlap 0 to be explanatory.

Model ^a	ΔAIC_c^b	w_i^c	K^d	Deviance
Covar + power _{2.5}	0.00	0.11	9	1,511.41
Covar + FG _{7.5}	0.14	0.10	9	1,511.55
Covar + FG ₅	0.28	0.10	9	1,511.69
Covar + FG _{12.5}	0.36	0.09	9	1,511.78
Covar + FG ₁₀	0.43	0.09	9	1,511.84
Covar	0.53	0.09	8	1,513.96
Covar + power _{12.5}	1.08	0.06	9	1,512.49
Covar + power ₁₀	1.13	0.06	9	1,512.55
Covar + power ₅	1.35	0.06	9	1,512.76
Covar + power	1.80	0.05	9	1,513.21
Covar + power _{7.5}	1.82	0.04	9	1,513.23
Covar + FG	1.90	0.04	9	1,513.31
Covar + power _{log}	2.04	0.04	9	1,513.45
Covar + FG _{2.5}	2.54	0.03	9	1,513.95
Covar + FG _{log}	2.54	0.03	9	1,513.95

^a Covar represents the environmental characteristics ($K=7$) that influenced female survival (minimum age [+]; nest success in given year [-]; brood success in given year [-]; seasonal differences: spring [-], summer [+], fall [-]; Table SB6 in Appendix B). FG and power were monthly time-varying covariates that represented the average distance a female sage-grouse was located from the Falcon–Gondor transmission line or any power line, respectively, in a given month. Subscripts represent the maximum extent (in km) to which the linear distance from the FG transmission or any power line was applied to female survival and log represents a model that used the natural log of the normalized distance from FG, or any power-line covariate + 0.001, which estimates a pseudo-threshold.

^b The difference in Akaike’s Information Criterion between the top ranked and selected model.

^c The relative likelihood of a model (i.e., Akaike weights).

^d The number of estimated parameters in a given model.

Table 14. Performance of multistate robust design models assessing the influence of transmission lines on male greater sage-grouse survival (φ) and among-lek movement rates (ψ) in Eureka County, Nevada, from 2003–2012. We considered variables in models that outperformed (lower ΔAIC) the $\varphi(\text{covar})\psi(\cdot)$ model and had 85% confidence intervals that did not overlap 0 to be explanatory.

Model ^a	ΔAIC_c^b	w_i^c	K^d	Deviance
$\varphi(\text{covar} + \text{FG} \times \text{trend})\psi(\cdot)$	0.00	0.52	33	4,352.86
$\varphi(\text{covar} + \text{FG} + \text{trend})\psi(\cdot)$	0.75	0.36	32	4,355.70
$\varphi(\text{covar})\psi(\cdot)$	7.49	0.01	30	4,366.62
$\varphi(\text{covar} + \text{power}_5)\psi(\cdot)$	7.80	0.01	31	4,364.85
$\varphi(\text{covar} + \text{FG}_5)\psi(\cdot)$	7.84	0.01	31	4,364.88
$\varphi(\text{covar})\psi(\text{FG}_{\log})$	8.75	0.01	31	4,365.78
$\varphi(\text{covar})\psi(\text{power}_5)$	8.89	0.01	31	4,365.93
$\varphi(\text{covar})\psi(\text{FG}_5)$	8.96	0.01	31	4,366.01
$\varphi(\text{covar} + \text{power}_{\log})\psi(\cdot)$	9.11	0.01	31	4,366.16
$\varphi(\text{covar})\psi(\text{power}_{\log})$	9.28	0.01	31	4,366.32
$\varphi(\text{covar} + \text{power})\psi(\cdot)$	9.33	0.00	31	4,366.38
$\varphi(\text{covar} + \text{FG})\psi(\cdot)$	9.42	0.00	31	4,366.47
$\varphi(\text{covar} + \text{raptor})\psi(\cdot)$	9.47	0.00	31	4,366.51
$\varphi(\text{covar})\psi(\text{power})$	9.51	0.00	31	4,366.56
$\varphi(\text{covar})\psi(\text{FG})$	9.52	0.00	31	4,366.57
$\varphi(\text{covar} + \text{FG}_{\log})\psi(\cdot)$	9.54	0.00	31	4,366.59
$\varphi(\text{covar})\psi(\text{FG}^2)$	9.80	0.00	32	4,364.75
$\varphi(\text{covar} + \text{FG}^2)\psi(\cdot)$	10.73	0.00	32	4,365.68
$\varphi(\text{covar} + \text{power}^2)\psi(\cdot)$	10.77	0.00	32	4,365.72
$\varphi(\text{covar})\psi(\text{power}^2)$	11.38	0.00	32	4,366.33
$\varphi(\text{covar} + \text{FG} + \text{raptor})\psi(\cdot)$	11.54	0.00	32	4,366.50
$\varphi(\text{covar} + \text{FG} \times \text{raptor})\psi(\cdot)$	13.40	0.00	33	4,366.25
$\varphi(\text{covar})\psi(\text{FG} \times \text{trend})$	13.56	0.00	33	4,366.41

^a All models allowed detection to vary among years (i.e., primary occasion; $K=10$), months (i.e., secondary occasion; $K=2$), and lek of capture ($K=12$).

Covar represents the environmental characteristics supported to influence male survival (lek elevation [+]; population the lek was associated with (Roberts [+]; Cortez [-]; the total precipitation recorded for the year prior [+]; Table SB7 in Appendix B). FG and power represent the distance from the lek with which a male was associated to Falcon–Gondor transmission line or any power line, respectively. Trend represents an annual trend. We denote a quadratic relationship with a square notation (²). We modeled annual apparent survival (φ) and the annual probability of a male moving to a new breeding lek between years (ψ). Raptor represents annual average number of raptors observed on the survey transect along the Falcon–Gondor transmission line and (.) denotes the intercept-only model. Subscripts represent the maximum extent (in km) to which the linear distance from the FG transmission or any power line was applied to male survival and log represents a model that used the natural log of the normalized distance from FG, or any power-line covariate + 0.001, which estimates a pseudo-threshold.

^b The difference in Akaike’s Information Criterion between the top ranked and selected model.

^c The relative likelihood of a model (i.e., Akaike weights).

^d The number of estimated parameters in a given model.

infrastructure in some areas (Cunningham et al. 2015). Active removal of ravens in the area affected by power lines is one potential approach to mitigation. Across all avian taxa, predator control regimes, on average, have successfully improved individual reproductive parameters (Smith et al. 2010), and tend to be more effective if all predator taxa are removed because reductions in predation risk from the removed species may be compensated by increased risk from another predator (Ellis-Felege et al. 2012). Meta-analyses on the effectiveness of predator control, however, have not found that predator removal leads to observable growth in prey populations (Côté and Sutherland 1997, Smith et al. 2010), which may suggest that 1) predator removal was not effective in reducing predation by the target species; 2) reduced predation by the removed predator was

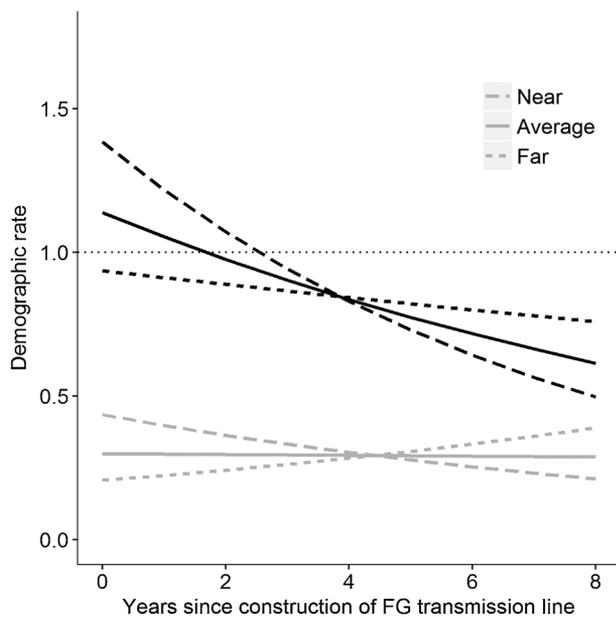


Figure 12. Sage-grouse *per capita* recruitment (gray lines) and population growth (λ , black lines) were both spatially (i.e., distance a lek was from the Falcon–Gondor [FG] transmission line [near: -1 SD from mean distance; average: mean distance; far: $+1$ SD from mean distance]) and temporally variable in Eureka County, Nevada from 2003–2012. Recruitment declined near the line, was stable at average distances, and slightly increased far from the line as the study progressed. Population growth declined at all distances from the line during the study; λ was >1 near and at average distances from the line early in the study, indicating a stable or increasing population in these areas, but declined to <1 , indicating a declining population, by the second year of the study. Population growth was never >1 in habitats far from the line. Trend lines were generated from models that constrained each demographic parameter to vary as function of an interaction between a lek’s distance from the transmission line and a yearly trend. Dotted line represents a λ value of 1.0, or stable population growth.

compensated by increased predation by other predators; or 3) reductions in reproductive success and survival due to predation were compensated through density-dependent mechanisms that regulate population growth, or latent individual heterogeneity (Pettorelli et al. 2011, Lindberg et al. 2013).

The effectiveness of raven removal, primarily achieved through deployment of poisoned eggs or meat, for improving sage-grouse demographic rates is inconclusive (Hagen 2011). Control measures (i.e., poison baits) can effectively reduce raven populations; however, numbers of ravens removed may be overestimated (Coates et al. 2007). Also, it is not clear whether territorial ravens, which may disproportionately contribute to both population growth of ravens and reproductive failure in sage-grouse, are as susceptible to control measures as migratory or subadult ravens (Bui et al. 2010, Dinkins 2013, Harju et al. 2018). Additionally, support for a positive impact of raven removal on individual sage-grouse reproductive rates has been inconsistent (Coates and Delehanty 2004, Dinkins 2013, Orning 2013). Peebles et al. (2017) reported an increase in counts of male sage-grouse attending leks associated with a decline in local raven abundance; however, the demographic mechanism(s) that accounted for these changes in breeding male abundance could not be determined (e.g., shifts in reproductive success, lek attendance, or lek fidelity). Thus, more studies are needed to understand the effect of raven removal on population growth

Table 15. Performance of robust design Pradel models used to assess the influence of distance from power lines and annual common raven abundance on lek-specific population growth of greater sage-grouse in Eureka County, Nevada, from 2003–2012. We considered variables in models that outperformed (lower Δ AIC) the Covar model and had 85% confidence intervals that did not overlap 0 to be explanatory.

Model ^{a,b}	Δ AIC _c	ω_i^d	K^e	Deviance
Covar + FG \times trend	0.00	1.00	36	6,419.53
Covar + FG \times raven	20.65	0.00	36	6,440.19
Covar + FG \times raptor	26.04	0.00	36	6,445.57
Covar + FG + trend	34.27	0.00	35	6,455.95
Covar + FG ₅	34.34	0.00	34	6,458.16
Covar + raven	34.92	0.00	34	6,458.74
Covar	36.00	0.00	33	6,461.96
Covar + power _{log}	36.68	0.00	34	6,460.50
Covar + FG + raven	36.81	0.00	35	6,458.49
Covar + power + raven	36.83	0.00	35	6,458.51
Covar + power ₅	37.16	0.00	34	6,460.98
Covar + FG _{log}	37.40	0.00	34	6,561.22
Covar + FG ²	37.63	0.00	35	6,459.31
Covar + power ²	37.64	0.00	35	6,459.32
Covar + power	37.80	0.00	34	6,461.63
Covar + FG	37.96	0.00	34	6,461.78
Covar + raptor	38.12	0.00	34	6,461.94
Covar + FG + raptor	40.08	0.00	35	6,461.76

^a Apparent survival was allowed to vary among years ($K=9$), as was detection probability ($K=10$) and lek ($K=11$). Covar represents the suite of explanatory variables supported to influence lek-specific population growth rates (i.e., lek elevation [+]; annual precipitation [+]; Table SB9 in Appendix B). The suite of explanatory variables considered for this analysis was modified from Blomberg et al. (2013b). FG and power represent the distance from the lek with which a male was associated to Falcon–Gondor transmission line or any power line, respectively. Raven represents annual average number of common ravens observed on the survey transect along the Falcon–Gondor transmission line. Raptor represents annual average number of raptors observed on the survey transect along the Falcon–Gondor transmission line. Trend represents a year trend. We denote a quadratic relationship with a square notation (²). Models with interactions consider both the variables and interaction terms. Subscripts represent the maximum extent (in km) to which the linear distance from the FG transmission or any power line was applied to lek-specific male population growth and log represents a model that used the natural log of the normalized distance from FG, or any power-line covariate $+0.001$, which estimates a pseudo-threshold.

^b See supplemental material (Table SB9 in Appendix B) for full model results.

^c The difference in Akaike’s Information Criterion between the top ranked and selected model.

^d The relative likelihood of a model (i.e., Akaike weights).

^e The number of estimated parameters in a given model.

(Hagen 2011). Additionally, the extent that roads, and more importantly roadkill, influence raven foraging behavior, raven fitness, and the attractiveness of power lines as nesting territories for ravens remains unclear (Kristan et al. 2004). Thus, efficacy of raven management or removal measures requires well-designed studies to assess impacts of such management actions on raven populations and sage-grouse (Hagen 2011).

Installation of deterrents to perching and nesting offers another approach to reducing raven populations associated with power lines. Perch deterrents have been used extensively to reduce damage caused by perching birds on power-line towers or surrounding structures, to reduce electrocutions for species of conservation concern, and to reduce perching by avian predators on elevated structures (Lammers and Collopy 2007, Seamans et al. 2007, Lopez-Lopez et al. 2011, Dwyer and Leiker 2012). Typically, perch deterrents only inhibit the

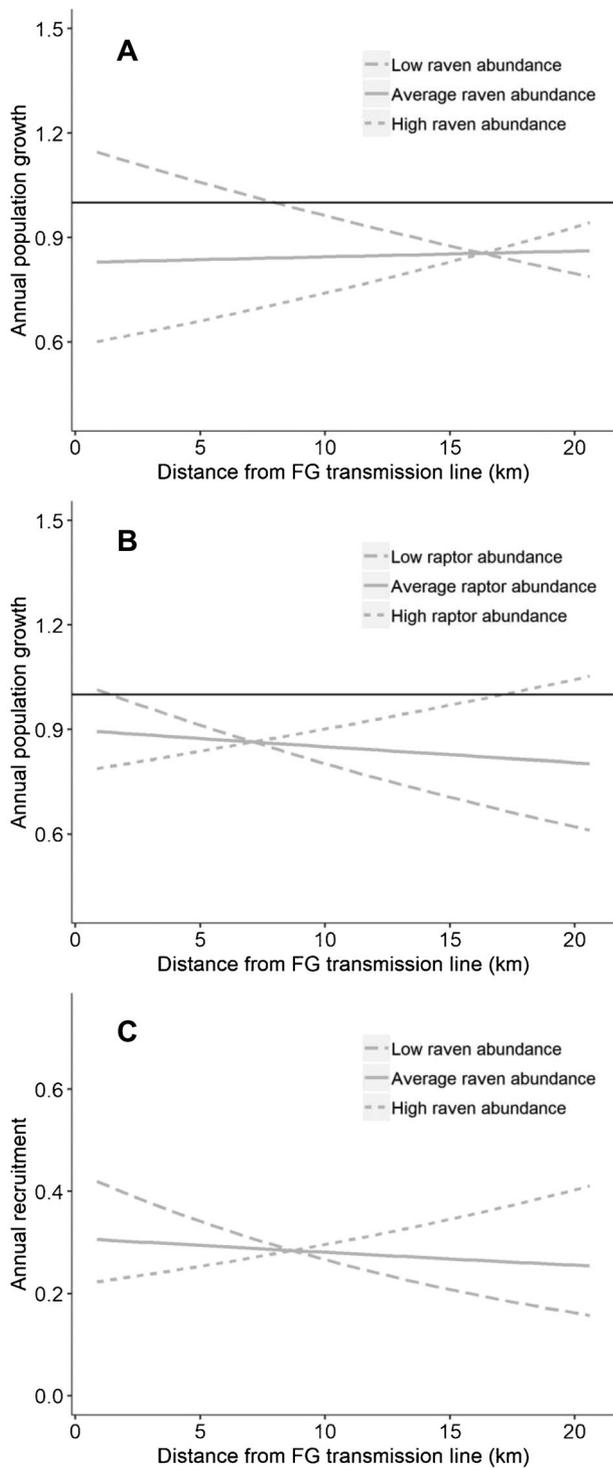


Figure 13. The relationships of sage-grouse population growth (A, B) and annual recruitment (C) as a function of the distance a lek was from the Falcon-Gondor (FG) transmission line were associated with relative common raven abundance (A, C) or relative raptor abundance (B) in Eureka County, Nevada from 2004–2012 (low: -1 SD from mean abundance; average: mean abundance; high: $+1$ SD from mean abundance). Population growth declined farther from the transmission line under both low raven and raptor abundance (long dashes) but increased with distance from the line under high raven and raptor abundance (short dashed). Recruitment also declined with increasing distance from the line under low raven abundance but increased with increasing distance from the line under high raven abundance. Under average weather conditions, only leks near the Falcon-Gondor line in years of low common raven abundance (i.e., before and shortly after construction) experienced positive population growth. Solid black line represents stable population growth.

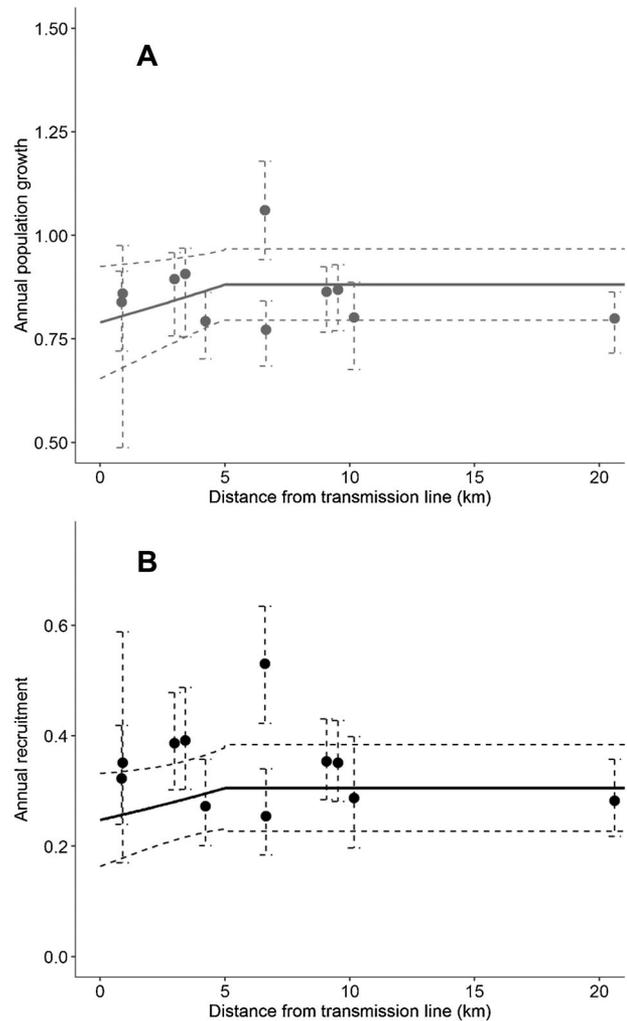


Figure 14. Greater sage-grouse population growth (A) for leks within 5 km of the Falcon-Gondor transmission line and greater sage-grouse annual recruitment (B) for leks within 5 km of any power line were negatively affected by the lek's proximity to a power line in Eureka County, Nevada from 2004–2012.

duration of perching bouts, meaning they are not perch inhibitors (Lammers and Collopy 2007). The overall effectiveness of perch deterrents on raven habitat use or foraging efficiency is questionable as some studies have reported short-term reductions in perching or habitat use related to perch deterrents (e.g., Slater and Smith 2010, Dwyer and Leiker 2012), whereas others failed to detect reductions in perching or nesting behavior (e.g., Lammers and Collopy 2007, Prather and Messmer 2010). Furthermore, we observed reductions in vital rates of sage-grouse that were associated with a transmission line (i.e., FG transmission line) although it was outfitted with perch deterrents within suitable sage-grouse habitat. We conclude that the use of currently available perch deterrents as a mitigation strategy for power-line impacts to sage-grouse is not singularly effective.

Alternative mitigation strategies could involve burying existing power lines within sage-grouse habitat (Fedy et al. 2015, Kirol et al. 2015) or routing new lines through non-habitat or areas less critical to local populations (Bagli et al. 2011). The effectiveness of these 2 approaches is conditioned on accurate delineations of

Table 16. Performance of robust design Pradel models used to assess the influence of distance from power lines and common ravens on lek-specific *per capita* recruitment rates of greater sage-grouse in Eureka County, Nevada, from 2003–2012. We considered variables in models that outperformed (lower ΔAIC) the Covar model and had 85% confidence intervals that did not overlap 0 to be explanatory.

Model ^{a,b}	ΔAIC_c^c	w_i^d	K^e	Deviance
Covar + FG × trend	0.00	0.93	39	6,388.40
Covar + FG ²	6.76	0.03	38	6,397.33
Covar + FG × raven	7.45	0.02	39	6,395.85
Covar + power ²	8.55	0.01	38	6,399.11
Covar + power ₅	12.70	0.00	37	6,405.41
Covar	12.70	0.00	36	6,407.56
Covar + power _{log}	13.46	0.00	37	6,406.17
Covar + FG ₅	13.64	0.00	37	6,406.35
Covar + raptor	13.82	0.00	37	6,406.54
Covar + power	14.11	0.00	37	6,406.83
Covar + FG	14.13	0.00	37	6,406.85
Covar + raven	14.63	0.00	37	6,407.34
Covar + FG _{log}	14.67	0.00	37	6,407.39
Covar + FG + raptor	15.21	0.00	38	6,405.76
Covar + power + raven	16.02	0.00	38	6,406.58
Covar + FG + raven	16.16	0.00	38	6,406.73
Covar + FG + trend	16.18	0.00	38	6,406.74
Covar + FG × raptor	17.34	0.00	39	6,405.74

^a Apparent survival was allowed to vary by year ($K=10$). Detection was allowed to vary by year ($K=10$) and lek ($K=10$). Covar represents the suite of explanatory variables supported to influence lek-specific *per capita* recruitment (i.e., lek elevation [+]; annual precipitation [+]; total vegetation cover [+]; habitat converted to exotic grassland [-]; annual precipitation × habitat converted to exotic grassland [-]; Table SB8 in Appendix B). The suite of explanatory variables considered for this analysis was modified from Blomberg et al. (2013b). FG and power represent the distance from the lek with which a male was associated to Falcon–Gondor transmission line or any power line, respectively. Raptor represents annual average number of raptors observed on the survey transect along the Falcon–Gondor transmission line. Raven represents annual average number of common ravens observed along the survey transect along the Falcon–Gondor transmission line. Trend represents a year trend. We denote a quadratic relationship with a square notation (²). Models with interactions include both the variables and interaction. Subscripts represent the maximum extent (in km) to which the linear distance from the FG transmission or any power line was applied to lek-specific male recruitment and log represents a model that used the natural log of the normalized distance from FG, or any power-line covariate + 0.001, which estimates a pseudo-threshold.

^b See supplemental material (Table SB8 in Appendix B) for model results.

^c The difference in Akaike’s Information Criterion between the top ranked and selected model.

^d The relative likelihood of a model (i.e., Akaike weights).

^e The number of estimated parameters in a given model.

critical habitat, defined in the United States as the “geographic area occupied by the species” (U.S. Department of the Interior 2014: 27069), which is widespread for sage-grouse (Aldridge and Boyce 2007, Doherty et al. 2008, Kaczor et al. 2011, Fedy et al. 2014). Both of these measures result in increased cost to developers (Fenrick and Getachew 2012). However, some of these costs may be recouped because underground lines are often more reliable, less susceptible to environmental damage, and require less maintenance (Hall 2009). Furthermore, cost-benefit analyses suggest that realized cost differentials, after accounting for other costs (e.g., aesthetics, wildlife interactions, maintenance) between underground and overhead transmission lines, may be less than previously thought (Navrud et al. 2008), and many countries in Europe have adopted this strategy (Lehman et al. 2007). Sage-grouse have positively responded (e.g., reduced

Table 17. Performance of robust design occupancy models used to assess the influence of proximity to the Falcon–transmission line or nearest highway on common raven disturbance rates at greater sage-grouse leks in Eureka County, Nevada, from 2003–2012.

Model ^a	ΔAIC_c^b	w_i^c	K^d	Deviance
$\psi(FG_{log}) \gamma(\text{trend}) p(s)$	0.00	0.74	8	441.15
$\psi(FG_{log}) \gamma(\text{trend} + FG_{log}) p(s)$	2.33	0.23	9	441.12
$\psi(FG_{log}) \gamma(.) p(s)$	8.26	0.01	7	451.72
$\psi(FG_{10}) \gamma(.) p(s)$	10.49	0.00	7	453.95
$\psi(\text{highway}_{log}) \gamma(.) p(s)$	11.27	0.00	7	454.73
$\psi(FG_{7.5}) \gamma(.) p(s)$	11.62	0.00	7	455.08
$\psi(\text{highway}_{10}) \gamma(.) p(s)$	11.82	0.00	7	455.28
$\psi(\text{highway}_{10}) \gamma(.) p(s)$	12.13	0.00	7	455.59
$\psi(FG) \gamma(.) p(s)$	12.49	0.00	7	455.95
$\psi(\text{highway}_5) \gamma(.) p(s)$	12.55	0.00	7	456.01
$\psi(FG^2) \gamma(.) p(s)$	12.57	0.00	8	453.73
$\psi(\text{highway}_{7.5}) \gamma(.) p(s)$	12.72	0.00	7	456.18
$\psi(.) \gamma(.) p(s)$	12.80	0.00	6	458.53
$\psi(\text{highway}^2) \gamma(.) p(s)$	13.52	0.00	8	454.67
$\psi(FG_5) \gamma(.) p(s)$	14.86	0.00	7	458.32

^a Annual occupancy denoted by (ψ). Local colonization denoted by (γ). Detection (p) was allowed to vary by secondary occasion ($n=4$). Highway and FG represent each lek’s distance from any state highway or the Falcon–Gondor transmission line, respectively. Trend represents a year trend. Subscripts represent the maximum extent (in km) to which the linear distance from the FG transmission or any highway was applied to raven occupancy of sage-grouse leks and log represents a model that used the natural log of the normalized distance from FG transmission line or any highway covariate + 0.001, which estimates a pseudo-threshold.

^b The difference in Akaike’s Information Criterion between the top ranked and selected model.

^c The relative likelihood of a model (i.e., Akaike weights).

^d The number of estimated parameters in a given model.

avoidance behavior, increased nest survival rates) to mitigation treatments, which included burying power lines and other reductions in surface disturbance (Fedy et al. 2015, Kirolo et al. 2015). However, the response of individual vital rates to removal of transmission towers is unclear, and these studies could not

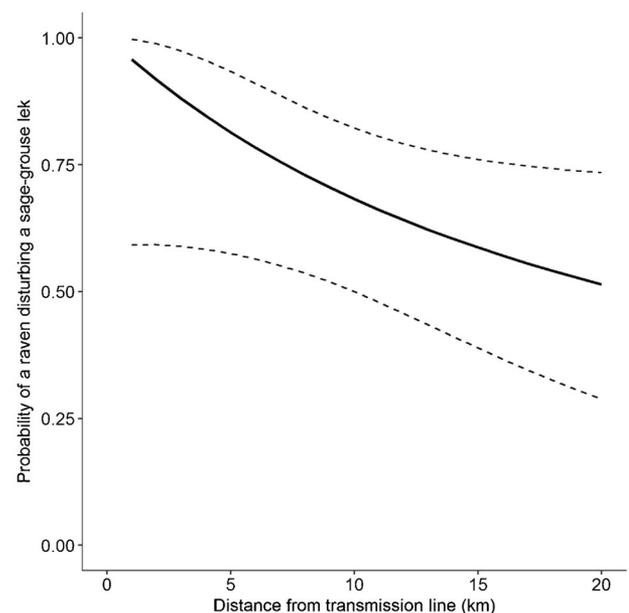


Figure 15. The association between the probability of common raven occupancy of an area surrounding a greater sage-grouse lek and the lek’s distance from the Falcon–Gondor transmission line in Eureka County, Nevada from 2004–2012.

Table 18. Summary of the overall impacts of the Falcon–Gondor transmission line (FG) and all power lines on greater sage-grouse demography or behavior. The spatial extent, direction, and associations with nest predators, such as common ravens were variable among analyses.

Demographic rate or behavior	Linear power-line effect ^a	Trend since FG construction	FG threshold	Any power-line threshold	Negatively associated with common raven abundance
Nesting propensity	No	Not determined	No	No	No
Re-nesting propensity	(+)	Not determined	10–12.5 km (+)	No	Yes
Nest-site selection	(–)	Not determined	<3 km (–)	>10 km (–)	Yes
Nest survival	(–)	Not determined	10–12.5 km (–)	No	Yes
Brood-rearing habitat selection	(–)	Not determined	5 km (–)	7.5 km (–)	Not determined
Pre-fledging chick survival	(+)	Negative	10 km (+)	5 km (+)	Yes
Adult female survival	No	No	No	No	Not determined
Adult male survival	(–)	Negative	No	5 km (–)	Not determined
Male population growth	(–)	Negative	5 km (–)	5 km (–)	Yes
Per capita recruitment	(–)	Negative	No	5 km (–)	Yes
Raven occupancy or abundance	(+)	Positive	5 km (–)	Not determined	Not determined

^a (+) power-line effect means that the demographic rate was greater closer to the line relative to more distant, whereas a (–) effect indicates that demographic rates were greater farther from the line relative to closer.

quantify the overall impact of mitigation efforts on population growth. Additionally, surface disturbance associated with a buried line may still result in landscape-level changes, such as introduction of exotic grasses or reduction of shrub cover, which elicit a response by ravens through the creation of edge habitat (Howe et al. 2014). Additional research is required to determine if burying power lines is an effective strategy for reducing local raven abundance or their effectiveness as predators, and results in improved probabilities of sage-grouse population persistence.

Other possible mitigation strategies include constructing new transmission lines in currently existing power-line rights-of-way (i.e., co-locating). Although we doubt this approach, singularly, would reduce the influence of existing corridors on sage-grouse demographic rates, it would reduce the cumulative impact of power lines on sage-grouse through time by reducing the cumulative development footprint relative to plans that proposed multiple spatially independent power-line corridors (Hansen et al. 2016). Future work, however, is needed to assess whether avian predator use of these super-corridors scales linearly with total number of perching sites, or if other mechanisms influence their attractiveness as habitat. Mitigation plans also should consider alternative designs of power lines or poles. Although the design of power lines can influence electrocution rates of large-bodied birds (Janss 2000), studies are lacking that demonstrate power lines with reduced surface area of potential nesting substrate (e.g., no horizontal crossbeams) are used less by avian predators relative to standard power-pole line designs.

Gaps remain in our knowledge of the efficacy of various power-line mitigation strategies for management of sage-grouse populations. Until the necessary research has been completed, we recommend that management agencies throughout the sage-grouse range assume at least a 10-km radius of disturbance when planning the placement of new power-line corridors, and provide preferential treatment to mitigation strategies that reduce the number of elevated structures placed within 10 km of critical sage-grouse habitat.

SUMMARY

1. Power lines can alter wildlife population dynamics by influencing survival, reproduction, habitat selection, and movements of individuals through increased presence of

electromagnetic fields, avoidance of elevated structures, or increased harassment by predators associated with elevated structures.

- In 2004, a 345-kV transmission line (i.e., Falcon–Gondor transmission line) was completed in central Nevada, USA. The completed transmission line was approximately 299-km long and located partially in habitats of greater sage-grouse.
- Relative abundance of common ravens near the Falcon–Gondor transmission line increased throughout the 9 years of post-construction monitoring more rapidly than ravens in the Great Basin as a whole, suggesting a numerical response by ravens to the Falcon–Gondor line.
- Nest-site selection and nest survival of greater sage-grouse were lower in areas closer to the Falcon–Gondor transmission line. Additionally, the magnitude of the effect of the transmission line on nest-site selection and nest survival interacted with an abundance index of common ravens. Together, these results suggest that changes in predator distribution across the landscape may be influencing the avoidance behavior of individuals nesting in suitable habitat near power lines.
- Relative abundance of ravens or the association between raven abundance and an individual’s distance from the Falcon–Gondor transmission also was associated with reductions in greater sage-grouse re-nesting propensity, pre-fledging chick survival, *per capita* recruitment, and population growth. Thus, shifts in individual reproductive potentials related to changes in predator communities resulted in population-level impacts.
- We found that habitats near the footprint of the FG transmission line were more productive (e.g., greater reproductive success and population growth) than areas farther from the transmission line before and immediately after construction. However, demographic rates in habitats near the transmission line have generally declined in the years following construction, associated with the increase in common ravens.
- We found that leks located within 5 km of power lines were negatively influenced by their proximity to power lines. Males associated with close leks had lower survival than males associated with leks more distant from power lines. *Per capita* recruitment and population growth at these leks were similarly affected.

8. The geographical extent to which power lines negatively influence greater sage-grouse demographic processes is not completely generalizable because it was contingent on local raven abundance or behavior. In this system, we found that effects of power lines exceeded current maximum recommendations for placement of tall structures relative to active sage-grouse leks (8 km; Manier et al. 2014), and extended to at least 10 km from transmission lines and up to 7.5 km from any power line.

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APPENDIX A. EXPLANATORY COVARIATES

Table SA1. List of all covariates considered to account for background environmental variation (Tables SB1–SB9), how the data were collected, and a publication that describes data collection for each analysis that estimated a particular demographic rate or behavior of greater sage-grouse in Eureka County, Nevada, USA, from 2003–2012.

Variable	Data type	Additional information	Nesting (and re-nesting) propensity	Nest-site selection	Nest survival	Brood-site selection	Pre-fledging chick survival	Adult female survival	Adult male survival	Recruitment	Population growth
Percent non-sagebrush shrub cover	Line intercept surveys	Gibson et al. (2016)			x		x			x	x
Percent forb cover	Daubenmire frame surveys	Gibson et al. (2016)			x		x			x	x
Percent total shrub cover	Line intercept surveys	Gibson et al. (2016)			x		x			x	x
Average shrub height	Daubenmire frame surveys	Gibson et al. (2016)			x		x			x	x
Total percent vegetation cover	Daubenmire frame surveys	Gibson et al. (2016)			x		x			x	x
Percent grass cover	Daubenmire frame surveys	Gibson et al. (2016)			x		x			x	x
Percent sagebrush shrub cover	Line intercept surveys	Gibson et al. (2016)			x		x			x	x
Forb taxa richness	Daubenmire frame surveys	Gibson et al. (2016)			x		x			x	x
Average live grass height	Daubenmire frame surveys	Gibson et al. (2016)			x		x			x	x
Average residual grass height	Daubenmire frame surveys	Gibson et al. (2016)			x		x			x	x
Average forb height	Daubenmire frame surveys	Gibson et al. (2016)			x		x			x	x
Proportion of surrounding area classified as exotic grasslands	Bureau Of Land Management wildfire data layer For Nevada (NV Fire History; BLM)	Gibson et al. (2016)		x	x	x	x	x		x	x
Distance from nearest road	Roads data layer For Eureka County, NV	Gibson et al. (2016)		x	x	x	x	x	x	x	x
Proportion of surrounding area classified as Pinyon-Juniper woodlands	Southwest Regional Gap (SWREGAP; USGS National Gap Analysis Program 2004)	Gibson et al. (2016)		x	x	x	x	x			
Proportion of surrounding area classified as sagebrush	Southwest Regional Gap (SWREGAP; USGS National Gap Analysis Program 2004)	Gibson et al. (2016)		x	x	x	x	x			
Elevation	National Elevation Dataset Digital Elevation Model (Ned Dem; USGS)	Gibson et al. (2016)		x	x	x	x	x	x	x	x
Distance to nearest active lek	Nevada Department Of Wildlife (NDOW) lek data layer	Gibson et al. (2016)		x	x	x	x				
Distance to nearest spring or water source	Water source data layer	Gibson et al. (2016)		x	x	x	x		x	x	x

(Continued)

Table SA1. (Continued)

Variable	Data type	Additional information	Nesting (and re-nesting) propensity	Nest-site selection	Nest survival	Brood-site selection	Pre-fledging chick survival	Adult female survival	Adult male survival	Recruitment	Population growth
Slope	National Elevation Dataset Digital Elevation Model (Ned Dem; USGS)	Gibson et al. (2016)		x	x	x	x				
Northness: cosine(aspect)	National Elevation Dataset Digital Elevation Model (Ned Dem; USGS)	Gibson et al. (2016)		x	x	x	x				
Eastness: sine(aspect)	National Elevation Dataset Digital Elevation Model (Ned Dem; USGS)	Gibson et al. (2016)		x	x	x	x				
Minimum age	Monitoring	Blomberg et al. (2013)	x				x	x			
Estimated male population size	Model estimate	Gibson et al. (2014)	x								
Precipitation/ Drought severity	Model estimate	Gibson et al. (2017)	x				x		x	x	x
Summer temperature	PRISM climate data explorer http://www.prism.oregonstate.edu/	Gibson et al. (2017)	x				x		x		
Nest hatch date	Monitoring	Gibson et al. (2015)			x		x				
Nesting success	Monitoring	Blomberg et al. (2013)						x			
Fledging success	Monitoring	Blomberg et al. (2013)						x			
Nest quality	Model estimate	Gibson et al. (2016)					x				
Distance brood moved	Monitoring	Gibson et al. (2017)					x				
Population (Roberts versus Cortez)	Monitoring or model estimate	Jahner et al. (2016)	x		x		x	x	x	x	x

APPENDIX B. ENVIRONMENTAL ANALYSES

Table SB1. Performance of all multistate models used to assess the influence of environmental conditions on female greater sage-grouse nesting and re-nesting propensity Eureka County, Nevada, 2003–2012. Model design, structure, and results are based on analyses previously published in Blomberg et al. (2017).

Model ^a	ΔAIC_c^b	w_i^c	K^d	Deviance
$\varphi(.) p(\text{stage} + \text{year} + \text{quad}) \text{Nesting}(N + \text{age}^2 + \text{quad}) \text{Fail}(\cdot) \text{ReNesting}(N + \text{prec})$	0.00	0.74	27	47,422.05
$\varphi(.) p(\text{stage} + \text{year} + \text{quad}) \text{Nesting}(N + \text{age}^2 + \text{quad}) \text{Fail}(\cdot) \text{ReNesting}(N + \text{prec} + \text{age}^2)$	2.35	0.23	29	47,420.34
$\varphi(.) p(\text{stage} + \text{year} + \text{quad}) \text{Nesting}(N + \text{quad}) \text{Fail}(\cdot) \text{ReNesting}(\text{year})$	8.32	0.01	32	47,420.22
$\varphi(.) p(\text{stage} + \text{year} + \text{quad}) \text{Nesting}(N + \text{quad}) \text{Fail}(\cdot) \text{ReNesting}(N + \text{prec})$	9.77	0.01	25	47,435.88
$\varphi(.) p(\text{stage} + \text{year} + \text{quad}) \text{Nesting}(N + \text{quad}) \text{Fail}(\cdot) \text{ReNesting}(N)$	9.88	0.01	24	47,438.02
$\varphi(.) p(\text{stage} + \text{year} + \text{quad}) \text{Nesting}(N + \text{prec} + \text{quad}) \text{Fail}(\cdot) \text{ReNesting}(\text{year})$	10.23	0.00	33	47,420.10
$\varphi(.) p(\text{stage} + \text{year} + \text{quad}) \text{Nesting}(N \times \text{prec} + \text{quad}) \text{Fail}(\cdot) \text{ReNesting}(\text{year})$	11.39	0.00	34	47,419.22
$\varphi(.) p(\text{stage} + \text{year} + \text{quad}) \text{Nesting}(N + \text{season} + \text{quad}) \text{Fail}(\cdot) \text{ReNesting}(N + \text{prec} + \text{season})$	12.58	0.00	27	47,434.63
$\varphi(.) p(\text{stage} + \text{year} + \text{quad}) \text{Nesting}(\text{year} + \text{quad}) \text{Fail}(\cdot) \text{ReNesting}(\text{year})$	16.72	0.00	40	47,412.32
$\varphi(.) p(\text{stage} + \text{year} + \text{quad}) \text{Nesting}(\text{year} + \text{quad}) \text{Fail}(\cdot) \text{ReNesting}(N + \text{prec})$	18.10	0.00	33	47,427.96
$\varphi(.) p(\text{stage} + \text{year} + \text{quad}) \text{Nesting}(\text{year} + \text{quad}) \text{Fail}(\cdot) \text{ReNesting}(N)$	18.19	0.00	32	47,430.09
$\varphi(.) p(\text{stage} + \text{year} + \text{quad}) \text{Nesting}(\text{year} + \text{quad}) \text{Fail}(\cdot) \text{ReNesting}(N \times \text{prec})$	19.69	0.00	34	47,427.52
$\varphi(.) p(\text{stage} + \text{year} + \text{quad}) \text{Nesting}(\text{year} + \text{quad}) \text{Fail}(\cdot) \text{ReNesting}(\cdot)$	20.06	0.00	31	47,434.00
$\varphi(.) p(\text{stage} + \text{year} + \text{quad}) \text{Nesting}(\text{quad}) \text{Fail}(\cdot) \text{ReNesting}(\text{year})$	49.03	0.00	31	47,462.96
$\varphi(.) p(\text{stage} + \text{year} + \text{quad}) \text{Nesting}(\text{year}) \text{Fail}(\cdot) \text{ReNesting}(\text{year})$	187.47	0.00	38	47,587.15
$\varphi(.) p(\text{stage} + \text{year} + \text{quad}) \text{Nesting}(\text{age}^2) \text{Fail}(\cdot) \text{ReNesting}(N + \text{prec})$	197.99	0.00	24	47,626.12
$\varphi(.) p(\text{stage} + \text{year} + \text{quad}) \text{Nesting}(\cdot) \text{Fail}(\cdot) \text{ReNesting}(\cdot)$	206.29	0.00	20	47,642.51

^a Parameters estimated are apparent survival (φ), detection (p), and transition probabilities (ψ) from not nesting to nesting (Nesting), from not nesting to a second nest (ReNesting), and from nesting to not nesting (Fail). We denote the intercept-only model as (\cdot). Year = full annual variation. Quad = quadratic constraint applied across within-year interval transition probabilities. N = estimated male population size (Gibson et al. 2014). Age² = quadratic relationship of minimum hen age. Prec = sum of total monthly precipitation recorded for the year prior (Aug–July). Season = season of capture (spring or fall). All covariates were z-standardized prior to analysis. See Blomberg et al. (2017) for analytical procedures. We retained the highest ranked model (lowest ΔAIC) and considered it as the baseline covariate model for the power-line impact analysis.

^b The difference in Akaike’s Information Criterion between the top ranked and selected model.

^c The relative likelihood of a model (i.e., Akaike weights).

^d The number of estimated parameters in a given model.

Table SB2. Performance of all landscape-scale nest-site selection species distribution models (GLMM) used to assess the influence of habitat features on nest-site selection in Eureka County, Nevada, 2004–2012. Models based on analyses previously published in Gibson et al. (2016).

Model ^a	ΔAIC_c^b	w_i^c	K^d	Deviance
Topography				
DLeK + elevation + DSpring ²	0.00	0.42	7	2,037.24
DLeK + elevation × slope + DSpring ²	0.55	0.32	9	2,033.79
DLeK + elevation	2.69	0.11	5	2,043.92
DLeK + elevation + slope	2.88	0.10	6	2,042.12
DLeK + elevation × slope	4.32	0.05	7	2,041.55
DLeK + DSpring ²	57.42	0.00	6	2,096.66
DLeK	63.72	0.00	4	2,106.95
DSpring ²	183.05	0.00	5	2,224.29
Slope + elevation	190.04	0.00	5	2,231.27
Slope × elevation	190.72	0.00	6	2,229.96
Elevation	191.86	0.00	4	2,235.10
Intercepts-only	200.83	0.00	3	2,246.07
Northing	201.94	0.00	4	2,245.17
DSpring	202.42	0.00	4	2,245.66
Easting	202.61	0.00	4	2,245.85
Slope	202.64	0.00	4	2,245.88
Vegetation classifications				
Sagebrush ₁₀₀₀	0.00	0.69	4	2,011.45
Sagebrush ₁₀₀₀ ²	1.66	0.30	5	2,011.11
Sagebrush ₂₀₀₀ ²	11.56	0.00	5	2,021.01
Sagebrush ₂₀₀₀	14.35	0.00	4	2,025.80
Sagebrush ₅₀₀	17.45	0.00	4	2,028.90
Sagebrush ₅₀₀ ²	18.85	0.00	5	2,028.30
PJ ₅₀₀ ²	185.88	0.00	5	2,195.32
PJ ₁₀₀₀ ²	186.09	0.00	5	2,195.54
PJ ₅₀₀	190.92	0.00	4	2,202.37
PJ ₁₀₀₀	194.48	0.00	4	2,205.92
PJ ₂₀₀₀ ²	199.46	0.00	5	2,208.91
PJ ₂₀₀₀	213.05	0.00	4	2,224.49
Intercepts-only	232.62	0.00	3	2,246.07

(Continued)

Table SB2. (Continued)

Model ^a	ΔAIC_c^b	w_i^c	K^d	Deviance
Environmental disturbance				
WF ₅₀₀ + DRoad	0.00	0.98	5	2,217.62
WF ₅₀₀	8.34	0.02	4	2,227.96
WF ₁₀₀₀	10.69	0.00	4	2,230.31
DRoad	12.08	0.00	4	2,231.70
WF ₂₀₀₀	19.55	0.00	4	2,239.18
Intercepts-only	24.45	0.00	3	2,246.07
Overall model				
DLek × sagebrush ₁₀₀₀ + elevation × slope + DSpring ²	0.00	1.00	11	1,730.29
DLek + elevation × slope + DSpring ² + sagebrush ₁₀₀₀	37.24	0.00	10	1,769.54
DLek + elevation × slope + DSpring ² + sagebrush ₁₀₀₀ + WF ₅₀₀	37.43	0.00	11	1,767.72
DLek + elevation × slope + DSpring ² + sagebrush ₁₀₀₀ + WF ₅₀₀ + DRoad	37.54	0.00	12	1,765.84
DLek + elevation + slope + DSpring ² + sagebrush ₁₀₀₀	57.44	0.00	9	1,791.74
DLek + elevation + DSpring ² + sagebrush ₁₀₀₀	59.59	0.00	8	1,795.89
DLek + elevation × slope + DSpring ² + PJ ₅₀₀ ² + WF ₅₀₀ + DRoad	223.26	0.00	13	1,949.55

^a Subscripts denote the scale of the variable (i.e., within a radius of 500 m, 1,000 m, or 2,000 m of a point). DLek, DRoad, and DSpring represent distance (in m) from nearest active lek, nearest road, and nearest spring or water source, respectively. Sagebrush represent the proportion of habitat classified as sagebrush at a specified scale; WF represented the proportion of habitat converted to exotic grasslands by wildfire at a specified scale; PJ represented the proportion of habitat classified as pinyon-juniper woodlands at a specified scale. Elevation represented the elevation (in m) of a point; slope represented the slope (in degrees) of a point. North is the cosine of aspect; east is the sin of aspect. Intercepts-only denotes intercept-only model. We denote a quadratic relationship with a square notation (²). Models with interactions contain the linear parameter components. Model weights (w_i) and differences in corrected Akaike's Information Criterion (ΔAIC_c) are relative only to the subset of models within each group. All covariates were z-standardized prior to analysis. See Gibson et al. (2016) for analytical procedures. We retained the highest ranked model (lowest ΔAIC) in the overall model category and considered it as the baseline covariate model for the power-line impact analysis.

^b The difference in Akaike's Information Criterion between the top ranked and selected model.

^c The relative likelihood of a model (i.e., Akaike weights).

^d The number of estimated parameters in a given model.

Table SB3. Performance of all landscape-scale brood-site selection species distribution models (GLMM) used to assess the influence of habitat features on greater sage-grouse brood-site selection in Eureka County, Nevada, 2005–2012.

Model ^a	ΔAIC_c^b	w_i^c	K^d	Deviance
Elevation + slope	0.00	0.37	5	2,063.75
Elevation × slope	0.21	0.34	6	2,061.96
Elevation ² + slope	0.50	0.29	6	2,062.25
Elevation ²	21.00	0.00	5	2,084.75
Elevation	21.99	0.00	4	2,087.74
Sagebrush ₅₀₀	73.83	0.00	4	2,139.58
Sagebrush ₁₀₀₀	75.42	0.00	4	2,141.17
PJ ₅₀₀	78.89	0.00	4	2,144.64
Sagebrush ₂₀₀₀	88.29	0.00	4	2,154.04
PJ ₁₀₀₀	93.19	0.00	4	2,158.94
PJ ₂₀₀₀	136.71	0.00	4	2,202.46
Slope	163.51	0.00	4	2,229.26
WF ₁₀₀₀	179.60	0.00	4	2,245.35
WF ₅₀₀	179.95	0.00	4	2,245.70
Intercepts-only	180.08	0.00	3	2,247.83
WF ₂₀₀₀	180.50	0.00	4	2,246.25
DSpring ²	180.77	0.00	5	2,244.52
DSpring	181.88	0.00	4	2,247.63

^a All models include random intercepts for year and individual. Subscripts denote the scale of the variable (i.e., radius of 500 m, 1,000 m, or 2,000 m from a point), superscripts denote quadratic relationships. DLek, DRoad, and DSpring represent distance (in m) from nearest active lek, nearest road, and nearest spring or water source, respectively. All sagebrush represented the proportion of area classified as sagebrush at a specified scale; WF represented the proportion of area converted to exotic grasslands by wildfire at a specified scale; PJ represented the proportion of area classified as pinyon-juniper woodlands at a specified scale. Elevation represented the elevation (in m) of a point; slope represented the slope (in degrees) of a point. Intercepts-only denotes intercept-only model. All variables were z-standardized prior to analysis. Analytical framework based on nest-site selection analyses presented in Gibson et al. (2016). We retained the highest ranked model (lowest ΔAIC) and considered it as the baseline covariate model for the power-line impact analysis.

^b The difference in Akaike's Information Criterion between the top ranked and selected model.

^c The relative likelihood of a model (i.e., Akaike weights).

^d The number of estimated parameters in a given model.

Table SB4. Performance of all nest survival models used to assess the influence of nest-site features greater sage-grouse nest survival in Eureka County, Nevada, 2004–2012. Tables are organized by individual heterogeneity, disturbance, landscape-scale habitat features, temporal characteristics, local-scale vegetation features, and multivariable models. Models based on analyses previously published in Gibson et al. (2016).

Model ^a	ΔAIC_c^b	w_i^c	K^d	Deviance
Individual heterogeneity models				
Base + pop	0.00	0.84	5	1,268.21
Base	6.19	0.04	4	1,276.40
Base + ID ²	6.71	0.03	6	1,272.91
Base + season	6.88	0.03	5	1,275.08
Base + age class	7.46	0.02	5	1,275.67
Base + min age	8.09	0.01	5	1,276.30
Base + ID	8.11	0.01	5	1,276.32
Base + nest attempt	8.18	0.01	5	1,276.39
Disturbance models				
Base + WF ₂₀₀₀	0.00	0.31	5	1,274.06
Base	0.33	0.26	4	1,276.40
Base + WF ₁₀₀₀	1.26	0.17	5	1,275.32
Base + WF ₅₀₀	1.68	0.14	5	1,275.75
Base + DRoad	2.01	0.12	5	1,276.07
Spatial models				
Base + PJ ₂₀₀₀	0.00	0.71	5	1,265.60
Base + elev	4.20	0.09	5	1,269.80
Base + PJ ₁₀₀₀	4.22	0.09	5	1,269.81
Base + Dlek	5.62	0.04	5	1,271.21
Base + DLek ²	7.51	0.02	6	1,271.11
Base + all ₂₀₀₀	8.11	0.01	5	1,273.71
Base + PJ ₅₀₀	8.13	0.01	5	1,273.72
Base	8.80	0.01	4	1,276.40
Base + DSprng	8.82	0.01	5	1,274.42
Base + north	8.83	0.01	5	1,274.43
Base + slope	8.96	0.01	5	1,274.56
Base + sagebrush ₁₀₀₀	9.76	0.01	5	1,275.36
Base + sagebrush ₅₀₀	10.56	0.00	5	1,276.16
Base + east	10.61	0.00	5	1,276.20
Base + DSprng ²	10.82	0.00	6	1,274.42
Base + north × east	11.78	0.00	7	1,273.37
Temporal models				
Stage + incubation trend (base)	0.00	0.23	4	1,276.40
(.)	0.64	0.17	1	1,283.04
Stage	0.64	0.16	3	1,279.05
Snowpack	1.54	0.11	2	1,281.95
Weekly trend	2.50	0.07	2	1,282.90
Daily trend	2.60	0.06	2	1,283.00
Precipitation	2.60	0.06	2	1,283.00
Week quadratic trend	4.50	0.02	3	1,282.90
Day quadratic trend	4.56	0.02	3	1,282.96
Week	5.65	0.01	6	1,278.04
Year + stage + incubation trend	9.18	0.00	12	1,269.53
Year	10.24	0.00	9	1,276.61
Local vegetation models				
Base + NSC ₅	0.00	0.79	5	1,264.68
Base + FC ₅	4.88	0.07	5	1,269.56
Base + TC _{0.5}	6.54	0.03	5	1,271.22
Base + TSC ₅	6.64	0.03	5	1,271.32
Base + SH ₅	6.95	0.02	5	1,271.63
Base + TC ₅	8.39	0.01	5	1,273.07
Base + FH ₅	8.67	0.01	5	1,273.34
Base + SH _{0.5}	9.53	0.01	5	1,274.21
Base	9.72	0.01	4	1,276.40
Base + GH _{0.5}	10.87	0.00	5	1,275.55
Base + GH ₅	11.24	0.00	5	1,275.92
Base + GC ₅	11.32	0.00	5	1,276.00
Base + SC ₅	11.57	0.00	5	1,276.24
Base + FRich ₅	11.71	0.00	5	1,276.39
Base + RGH ₅	11.72	0.00	5	1,276.39
Base + FH _{0.5}	11.72	0.00	5	1,276.40
Multivariable models				
Base + NSC ₅ + FC ₅ + pop	0.00	0.29	7	1,253.92
Base + NSC ₅ + FC ₅ + pop + PJ ₂₀₀₀	0.56	0.22	8	1,252.47
+ NSC ₅ + FC ₅ + PJ ₂₀₀₀	1.29	0.15	7	1,255.20
Base + NSC ₅ + FC ₅	3.29	0.06	6	1,259.21
Base + NSC ₅ + FC ₅ + SH ₅	3.96	0.04	7	1,257.88
Base + NSC ₅ + PJ ₂₀₀₀	4.19	0.04	6	1,260.12
Base + NSC ₅ + FC ₅ + Dlek	4.29	0.03	7	1,258.21
Base + NSC ₅ + FC ₅ + elev	4.88	0.03	7	1,258.80

(Continued)

Table SB4. (Continued)

Model ^a	ΔAIC_c^b	w_i^c	K^d	Deviance
Base + NSC ₅ + FC ₅ + TC _{0.5}	4.93	0.02	7	1,258.85
Base + NSC ₅ + pop	5.13	0.02	6	1,261.05
Base + NSC ₅ + TC _{0.5}	6.50	0.01	6	1,262.42
Base + NSC ₅ + Dlek	6.50	0.01	6	1,262.42
Base + NSC ₅ + SH ₅	6.58	0.01	6	1,262.50
Base + NSC ₅ + elev	6.63	0.01	6	1,262.56
Base + NSC ₅	6.75	0.01	5	1,264.68
Base + NSC ₅ + DSprng	7.05	0.01	6	1,262.97
Base + NSC ₅ + TC ₅	7.13	0.01	6	1,263.05
Base + NSC ₅ + WF ₂₀₀₀	7.66	0.01	6	1,263.59
Base + PJ ₂₀₀₀	7.67	0.01	5	1,265.60
Base + NSC ₅ + TSC	8.08	0.01	6	1,264.00
Base + NSC ₅ + SH _{0.5}	8.46	0.00	6	1,264.38
Base + NSC ₅ + FH _{0.5}	8.72	0.00	6	1,264.65
Base + pop	10.28	0.00	5	1,268.21
Base + FC ₅	11.63	0.00	5	1,269.56
Base + elev	11.87	0.00	5	1,269.80
Base + Dlek	13.28	0.00	5	1,271.21
Base + TC _{0.5}	13.29	0.00	5	1,271.22
Base + TSC ₅	13.39	0.00	5	1,271.32
Base + SH ₅	13.70	0.00	5	1,271.63
Base + TC ₅	15.14	0.00	5	1,273.07
Base + WF ₂₀₀₀	16.13	0.00	5	1,274.06
Base + SH _{0.5}	16.28	0.00	5	1,274.21
Base + DSprng	16.49	0.00	5	1,274.42
Base + FH _{0.5}	18.47	0.00	5	1,276.40

^a Base represents a competitive 4 parameter design to account for variation in nest survival related to nest age; we allowed the laying period for the average nest (occasions 1–10), early incubation/late laying period (occasions 11–15), and the primary incubation period (occasions 16–44) to estimate independently from each other, with the linear trend (daily) on the primary incubation period. Subscripts denote the scale of the variable (i.e., within 0.5 m, 5 m or within a radius of 500 m, 1,000 m, or 2,000 m of a point). Horizontal cover variables included non-sagebrush shrub cover of all size classes (NSC), sagebrush shrub cover at all size classes (SC), total shrub cover (TSC), forb cover (FC), grass cover (GC), and total vegetation cover (TC). Vertical cover variables included average shrub height (SH), average forb height (FH), average live grass height (GH), and average residual grass height (RGH). FRich represented forb taxa richness within a given plot. Dlek, DRoad, and DSprng represent distance (in m) from nearest active lek, nearest road, and nearest spring or water source, respectively. Sagebrush represent the proportion of habitat classified as sagebrush at a specified scale; WF represented the proportion of habitat converted to exotic grasslands by wildfire at a specified scale; PJ represented the proportion of habitat classified as pinyon-juniper woodlands at a specified scale. Elev represented the elevation (in m) of a point; slope represented the slope (in degrees) of a point. North is the cosine of aspect; east is the sin of aspect. Pop was a binomial covariate delineating nests from females associated from the Cortez Mountains from females associated with Roberts Creek Mountain. Age class was a binomial covariate, which delineated second year females from after second year females; min age was a continuous covariate, which represented the females minimum age. Season was a binomial covariate which delineated females captured in the spring from females captured in the fall; ID represented estimate nest initiation date; (.) denotes intercept-only model. Year denotes full annual variation. We also considered annual constraints related to annual precipitation (precipitation), and winter snowpack (snowpack). Week allowed for variation among 7-day fixed periods. Stage allowed for the laying, early incubation, and primary incubation phases to estimate separately. Model weights (w_i) and difference in corrected Akaike's Information Criterion (ΔAIC_c) are relative only to the subset of models within each group. Linear and quadratic daily and weekly trends are clearly denoted. All covariates were z-standardized prior to analysis. We retained the highest ranked model (lowest ΔAIC_c) in the multivariable model section and considered it as the baseline covariate model for the power-line impact analysis.

^b The difference in Akaike's Information Criterion between the top ranked and selected model.

^c The relative likelihood of a model (i.e., Akaike weights).

^d The number of estimated parameters in a given model.

Table SB5. Performance of all models used to assess the influence of environmental variables on greater sage-grouse pre-fledging chick survival in Eureka County, Nevada, 2005–2012. Models based on analyses previously published in Gibson et al. (2017).

Model ^a	ΔAIC_c^b	w_i^c	K^d	Deviance
$\varphi(\text{week} + \text{DSI} + \text{TPC} + \text{DMove} + \text{GH} + \text{DSpring} + \text{NSI}) \hat{p}(\text{week} + \text{year})$	0.00	0.98	24	1,999.89
$\varphi(\text{week} + \text{DSI} + \text{POP} + \text{TPC} + \text{DMove} + \text{GH} + \text{DSpring}) \hat{p}(\text{week} + \text{year})$	9.23	0.01	24	2,009.11
$\varphi(\text{week} + \text{DSI} + \text{TPC} + \text{DMove} + \text{GH} + \text{DSpring}) \hat{p}(\text{week} + \text{year})$	10.70	0.00	23	2,012.83
$\varphi(\text{week} + \text{DSI} + \text{TPC} + \text{DMove} + \text{GH} + \text{POP} + \text{SC}) \hat{p}(\text{week} + \text{year})$	19.19	0.00	24	2,019.08
$\varphi(\text{week} + \text{DSI} + \text{elev} + \text{TPC} + \text{DMove} + \text{GH} + \text{DSpring}) \hat{p}(\text{week} + \text{year})$	19.49	0.00	24	2,019.38
$\varphi(\text{week} + \text{DSI} + \text{TPC} + \text{DMove} + \text{GH} + \text{POP} + \text{MAge}) \hat{p}(\text{week} + \text{year})$	20.38	0.00	24	2,020.27
$\varphi(\text{week} + \text{DSI} + \text{TPC} + \text{DMove} + \text{GH} + \text{POP} + \text{MT}) \hat{p}(\text{week} + \text{year})$	21.78	0.00	24	2,021.67
$\varphi(\text{year} + \text{week} + \text{DMove}) \hat{p}(\text{week} + \text{year})$	28.93	0.00	26	2,024.29
$\varphi(\text{week} + \text{DSI} + \text{TPC} + \text{DMove} + \text{GH}) \hat{p}(\text{week} + \text{year})$	29.34	0.00	22	2,033.71
$\varphi(\text{week} + \text{DSI} + \text{DMove} + \text{TPC}) \hat{p}(\text{week} + \text{year})$	30.72	0.00	21	2,037.31
$\varphi(\text{year} + \text{week} + \text{TPC}) \hat{p}(\text{week} + \text{year})$	33.40	0.00	26	2,028.76
$\varphi(\text{year} + \text{week} + \text{NSI}) \hat{p}(\text{week} + \text{year})$	41.50	0.00	26	2,036.85
$\varphi(\text{year} + \text{week} + \text{elev}) \hat{p}(\text{week} + \text{year})$	44.44	0.00	26	2,039.79
$\varphi(\text{year} + \text{week} + \text{spring}) \hat{p}(\text{week} + \text{year})$	45.81	0.00	26	2,041.17
$\varphi(\text{week} + \text{DMove} + \text{TPC}) \hat{p}(\text{week} + \text{year})$	49.08	0.00	20	2,057.89
$\varphi(\text{year} + \text{week} + \text{MAge}) \hat{p}(\text{week} + \text{year})$	49.82	0.00	26	2,045.17
$\varphi(\text{year} + \text{week} + \text{GH}) \hat{p}(\text{week} + \text{year})$	50.47	0.00	26	2,045.83
$\varphi(\text{year} + \text{week} + \text{SC}) \hat{p}(\text{week} + \text{year})$	50.62	0.00	26	2,045.98
$\varphi(\text{year} + \text{week} + \text{pop}) \hat{p}(\text{week} + \text{year})$	50.91	0.00	26	2,046.27
$\varphi(\text{year} + \text{week} + \text{TR}) \hat{p}(\text{week} + \text{year})$	51.00	0.00	26	2,046.36
$\varphi(\text{year} + \text{week} + \text{TSC}) \hat{p}(\text{week} + \text{year})$	52.97	0.00	26	2,048.33
$\varphi(\text{year} + \text{week} + \text{FR}) \hat{p}(\text{week} + \text{year})$	55.30	0.00	26	2,050.65
$\varphi(\text{year} + \text{week} + \text{FC}) \hat{p}(\text{week} + \text{year})$	55.70	0.00	26	2,051.06
$\varphi(\text{year} + \text{week}) \hat{p}(\text{week} + \text{year})$	56.80	0.00	25	2,054.42
$\varphi(\text{year} + \text{week} + \text{SH}) \hat{p}(\text{week} + \text{year})$	57.39	0.00	25	2,055.02
$\varphi(\text{year} + \text{week} + \text{HD}) \hat{p}(\text{week} + \text{year})$	57.72	0.00	26	2,053.08
$\varphi(\text{year} + \text{week} + \text{GC}) \hat{p}(\text{week} + \text{year})$	57.91	0.00	26	2,053.27
$\varphi(\text{year} + \text{week} + \text{FH}) \hat{p}(\text{week} + \text{year})$	58.64	0.00	26	2,054.00
$\varphi(\text{year} + \text{week} + \text{all}) \hat{p}(\text{week} + \text{year})$	58.85	0.00	26	2,054.21
$\varphi(\text{year} + \text{week} + \text{all}) \hat{p}(\text{week} + \text{year})$	58.85	0.00	26	2,054.21
$\varphi(\text{year} + \text{week} + \text{RGH}) \hat{p}(\text{week} + \text{year})$	59.03	0.00	26	2,054.39
$\varphi(\text{year} + \text{week} + \text{NSC}) \hat{p}(\text{week} + \text{year})$	59.03	0.00	26	2,054.39
$\varphi(\text{week} + \text{DSI}) \hat{p}(\text{week} + \text{year})$	61.76	0.00	19	2,072.78
$\varphi(\text{week}) \hat{p}(\text{week} + \text{year})$	79.55	0.00	18	2,092.75
$\varphi(\text{year}) \hat{p}(\text{year})$	223.05	0.00	16	2,240.61
$\varphi(\cdot) \hat{p}(\cdot)$	365.73	0.00	2	2,412.59

^a We modeled probability of apparent survival (φ) and detection probabilities (\hat{p}); (\cdot) denotes intercept-only model. Week denotes that each week was allowed to estimate independently from other weeks. The drought severity index (DSI) constrained annual chick survival with the first principle component axis from a principle components analysis that included many weather metrics (mean maximum monthly summer temperature, mean minimum monthly summer temperature, spring precipitation, summer precipitation, breeding season precipitation, water year precipitation, and mean monthly winter snowpack) thought to influence primary productivity (see Gibson et al. 2017). We also modeled NSI as an index of selected nest-site characteristics for each brood based on the nest-site vegetation composition (see Gibson et al. 2016, 2017). We modeled weekly time-varying covariates that represent the total (TPC) percent cover of shrubs, forbs (FC), and grasses (GC) within 400 m² at each weekly brood location. We modeled weekly time-varying covariates that represent total (TSC), sagebrush (SC), and other (NSC) shrub cover within 400 m² at each weekly brood location. We modeled time-varying covariates that represented average dead grass (RGH), average live grass (GH), forb (FH), and shrub (SH) heights within 400 m² at each weekly brood location. HD represents the broods hatch date (in Julian days). DMove is a weekly time-varying covariate that represents the average daily distance a brood moved based on the Euclidian distance between 2 subsequent weekly brood locations. Spring is a time-varying covariate that represents the distance between weekly brood locations and the nearest water spring. Elev is a time-varying covariate that represents elevation of the brood survey location. MAge represents a current minimum age of the mother. Models that considered interactions (denoted by \times) between covariates included the additive parameters within the model. All variables were z-standardized prior to analysis. See Gibson et al. (2017) for analytical procedures. We retained the highest ranked model (lowest ΔAIC) in the multivariable model section and considered it as the baseline covariate model for the power-line impact analysis.

^b The difference in Akaike's Information Criterion between the top ranked and selected model.

^c The relative likelihood of a model (i.e., Akaike weights).

^d The number of estimated parameters in a given model.

FEMALE SURVIVAL

Model Modifications

We modified the analyses reported in Blomberg et al. (2013) by the following: 1) inclusion of an additional year of data (i.e., 2012); 2) inclusion of additional predictor variables; and 3) transitioning the modeling framework from a known-fate analysis to that of a nest survival model.

Table SB6. Performance of all nest survival models used to assess the influence of environmental characteristics on monthly survival of adult female greater sage-grouse in Eureka County, Nevada, 2003–2012. Models based on analyses previously published in Blomberg et al. (2013c).

Model ^a	ΔAIC_c^b	w_i^c	K^d	Deviance
Elev + seasons + pre-breeding + age _{min} + hatch _{summer} + fledge _{fall}	0.00	0.26	9	1,511.44
Seasons + pre-breeding + age _{min} + hatch _{summer} + fledge _{fall}	0.51	0.20	8	1,513.96
PJ + seasons + pre-breeding + age _{min} + hatch _{summer} + fledge _{fall}	1.01	0.16	9	1,512.45
Road + seasons + pre-breeding + age _{min} + hatch _{summer} + fledge _{fall}	1.40	0.13	9	1,512.84
Month + winter + pre-breeding + age _{min} + hatch _{summer} + fledge _{fall}	5.50	0.02	13	1,508.90
Month + winter + pre-breeding + age _{min}	10.36	0.00	11	1,517.77
Seasons	11.77	0.00	4	1,533.25
Month + winter + hatch _{summer} + fledge _{fall}	13.62	0.00	11	1,521.04
Month + winter + elev	14.55	0.00	10	1,523.98
Month + winter + fledge _{fall}	14.60	0.00	10	1,524.03
Month + winter + hatch _{summer}	15.48	0.00	10	1,524.91
Month + winter + pre-breeding + age _{min} ²	15.74	0.00	12	1,521.14
Month + winter + pre-breeding	16.01	0.00	10	1,525.44
Month + winter + PJ	16.75	0.00	10	1,526.17
Month + winter + age _{min}	16.76	0.00	10	1,526.19
Month + winter	17.15	0.00	9	1,528.59
Month + winter + fire	17.71	0.00	10	1,527.14
Year + month + winter	25.69	0.00	18	1,519.00
(.)	62.91	0.00	1	1,590.40
Year	73.17	0.00	10	1,582.60

^a Month + winter ($K=9$) allows survival during March–October to estimate independently but constrained to estimate together from November–February. Seasons ($K=4$) constrains monthly survival into seasonal blocks (i.e., Mar–May, Jun–Jul, Aug–Oct, and Nov–Feb) that estimate independently from each other. Year ($K=10$) allows survival each year (2003–2012) to estimate independently from another. Elev is a monthly (Mar–Oct) time-varying covariate that represents the average elevation from all locations of a radio-marked female during that month. PJ is a monthly (Mar–Oct) time-varying covariate that represents the average proportion of area classified as Pinyon-Juniper within 5 km from all locations of a radio-marked female during that month. Fire is a monthly (Mar–Oct) time-varying covariate that represents the average proportion of area classified as exotic grasslands within 5 km from all locations of a radio-marked female during that month. Road is a monthly (Mar–Oct) time-varying covariate that represents the average distance between each location of a radio-marked female and the nearest road. Pre-breeding is a binomial (yes/no) variable modeled on post-breeding months (Aug–Feb) that delineates young-of-year individuals from females that have survived at least one breeding season. Age_{min} represents the minimum age for each female each year. Hatch_{summer} is a binomial (yes/no) variable modeled on the season immediately following hatching (Jun–Jul) that delineates females that successfully hatched a nest from those that did not. Fledge_{fall} is a binomial (yes/no) variable modeled on the season immediately following fledging (Aug–Oct) that delineates females that successfully fledged at least one chick from those that did not. We retained the highest ranked model (lowest ΔAIC_c) in the multivariable model section and considered it as the baseline covariate model for the power-line impact analysis.

^b The difference in Akaike’s Information Criterion between the top ranked and selected model.

^c The relative likelihood of a model (i.e., Akaike weights).

^d The number of estimated parameters in a given model.

Table SB7. Performance of all multistate robust design models used to assess the influence of environmental characteristics on annual survival and lek movement rates of male greater sage-grouse in Eureka County, Nevada, 2003–2012. Models based on analyses in Gibson et al. (2014).

Model ^a	ΔAIC_c^b	w_i^c	K^d	Deviance
$\varphi(\text{prec} + \text{pop}) \psi_{AB}(\cdot) \psi_{BA}(\cdot) p \sim c(\text{year} + \text{month} + \text{lek})$	0.00	0.19	29	4,368.59
$\varphi(\text{elev} + \text{prec} + \text{pop}) \psi_{AB}(\cdot) \psi_{BA}(\cdot) p \sim c(\text{year} + \text{month} + \text{lek})$	0.12	0.17	30	4,366.62
$\varphi(\text{prec} + \text{pop}) \psi_{AB}(\text{pop}) \psi_{BA}(\cdot) p \sim c(\text{year} + \text{month} + \text{lek})$	1.10	0.11	30	4,367.60
$\varphi(\text{prec} + \text{pop}) \psi_{AB}(\text{age}) \psi_{BA}(\cdot) p \sim c(\text{year} + \text{month} + \text{lek})$	1.77	0.08	30	4,368.27
$\varphi(\text{prec} \times \text{temp} + \text{pop}) \psi_{AB}(\cdot) \psi_{BA}(\cdot) p \sim c(\text{year} + \text{month} + \text{lek})$	1.87	0.07	31	4,366.28
$\varphi(\text{prec} + \text{temp} + \text{pop}) \psi_{AB}(\cdot) \psi_{BA}(\cdot) p \sim c(\text{year} + \text{month} + \text{lek})$	1.99	0.07	30	4,368.49
$\varphi(\text{WF} + \text{prec} + \text{pop}) \psi_{AB}(\cdot) \psi_{BA}(\cdot) p \sim c(\text{year} + \text{month} + \text{lek})$	2.03	0.07	30	4,368.53
$\varphi(\text{elev} + \text{prec}) \psi_{AB}(\cdot) \psi_{BA}(\cdot) p \sim c(\text{year} + \text{month} + \text{lek})$	2.09	0.07	29	4,370.68
$\varphi(\text{elev} + \text{year}) \psi_{AB}(\cdot) \psi_{BA}(\cdot) p \sim c(\text{year} + \text{month} + \text{lek})$	2.45	0.05	36	4,356.36
$\varphi(\text{prec} + \text{pop}) \psi_{AB}(\text{age}^2) \psi_{BA}(\cdot) p \sim c(\text{year} + \text{month} + \text{lek})$	3.51	0.03	31	4,367.92
$\varphi(\text{WF} + \text{prec}) \psi_{AB}(\cdot) \psi_{BA}(\cdot) p \sim c(\text{year} + \text{month} + \text{lek})$	3.61	0.03	29	4,372.20
$\varphi(\text{elev} \times \text{WF} + \text{prec}) \psi_{AB}(\cdot) \psi_{BA}(\cdot) p \sim c(\text{year} + \text{month} + \text{lek})$	4.28	0.02	31	4,368.69
$\varphi(\text{prec}) \psi_{AB}(\cdot) \psi_{BA}(\cdot) p \sim c(\text{year} + \text{month} + \text{lek})$	5.08	0.01	28	4,375.75
$\varphi(\text{prec} \times \text{temp}) \psi_{AB}(\cdot) \psi_{BA}(\cdot) p \sim c(\text{year} + \text{month} + \text{lek})$	6.53	0.01	30	4,373.03
$\varphi(\text{prec} + \text{temp}) \psi_{AB}(\cdot) \psi_{BA}(\cdot) p \sim c(\text{year} + \text{month} + \text{lek})$	6.69	0.01	29	4,375.28
$\varphi(\text{WF} + \text{year}) \psi_{AB}(\cdot) \psi_{BA}(\cdot) p \sim c(\text{year} + \text{month} + \text{lek})$	7.76	0.00	36	4,361.67
$\varphi(\text{temp} + \text{pop}) \psi_{AB}(\cdot) \psi_{BA}(\cdot) p \sim c(\text{year} + \text{month} + \text{lek})$	11.60	0.00	29	4,380.18

(Continued)

Table SB7. (Continued)

Model ^a	ΔAIC_c^b	w_i^c	K^d	Deviance
$\varphi(\text{pop}) \psi AB(.) \psi BA(.) p \sim c(\text{year} + \text{month} + \text{lek})$	11.82	0.00	28	4,382.49
$\varphi(\text{pop}) \psi AB(.) \psi BA(.) p \sim c(\text{year} + \text{month} + \text{lek})$	11.82	0.00	28	4,382.49
$\varphi(\text{WF}) \psi AB(.) \psi BA(.) p \sim c(\text{year} + \text{month} + \text{lek})$	14.15	0.00	28	4,384.82
$\varphi(.) \psi AB(.) \psi BA(.) p \sim c(\text{year} + \text{month} + \text{lek})$	16.70	0.00	27	4,389.45

^a Annual variation in apparent survival (φ) or lek movement rates (ψ) was constrained by an index of average maximum summer temperature (temp), annual precipitation from August to July (prec), the elevation of the lek (elev), and the population (pop) a male was associated with (Cortez Mountains or Roberts Creek Mountain). Our base detection model constrained detection (p) and recapture (c) to a common intercept with additive variation between the parameters, which allowed for p and c to vary temporally among primary (year) and secondary (month) occasions by a constant amount, as well as spatially by lek. Age denotes minimum age of male during each encounter, and (.) denotes constancy over time. Main effects are included in models in which an interaction is specified. All variables were z-standardized prior to analysis. See Gibson et al. (2014) for parameter estimates, model results, and analytical procedures. We retained the highest ranked model (lowest ΔAIC_c) in the multivariable model section and considered it as the baseline covariate model for the power-line impact analysis.

^b The difference in Akaike's Information Criterion between the top ranked and selected model.

^c The relative likelihood of a model (i.e., Akaike weights).

^d The number of estimated parameters in a given model.

RECRUITMENT AND POPULATION GROWTH

Model Modifications

We modified the analyses reported in Blomberg et al. (2012) by the following: 1) inclusion of 2 additional years of data (i.e., 2011–2012); 2) inclusion of additional predictor variables; and 3) including increased model parameterization that allowed for lek specific estimates of *per capita* recruitment and lambda. Additional predictor variables included average values for various metrics of vegetation composition (e.g., total percent vegetation cover, percent sagebrush cover) that were derived from vegetation surveys conducted at random locations within 5 km from each lek (mean number of surveys per lek = 26.85).

Table SB8. Performance of all Pradel models used to assess the influence of environmental characteristics on *per capita* recruitment (f) of male greater sage-grouse in Eureka County, Nevada, 2003–2012. Model design, structure, and results based on analyses previously published in Blomberg et al. (2012).

Model ^a	ΔAIC_c^b	w_i^c	K^d	Deviance
$f(\text{prec} \times \text{WF}_{1000} + \text{TC} + \text{elev})$	0.00	1.00	35	6,414.16
$f(\text{prec} + \text{TC} + \text{elev} + \text{WF}_{1000})$	26.67	0.00	34	6,442.98
$f(\text{prec} + \text{PC} + \text{elev})$	27.38	0.00	33	6,445.82
$f(\text{prec} + \text{TC} + \text{RD} + \text{FRich} + \text{WF} + \text{FC})$	28.65	0.00	36	6,440.67
$f(\text{year} + \text{TC} + \text{FRich})$	29.65	0.00	37	6,439.52
$f(\text{prec} + \text{TC} + \text{FRich})$	30.21	0.00	33	6,448.66
$f(\text{year} + \text{TC} + \text{WF}_{1000})$	32.06	0.00	36	6,444.08
$f(\text{year} + \text{lek})$	32.40	0.00	43	6,429.29
$f(\text{year} + \text{TC} + \text{FC})$	32.54	0.00	37	6,442.41
$f(\text{year} + \text{TC})$	33.06	0.00	36	6,445.08
$f(\text{prec} + \text{TC} + \text{WF}_{1000})$	34.21	0.00	33	6,452.65
$f(\text{year} + \text{TC} + \text{SH})$	34.85	0.00	37	6,444.72
$f(\text{year} + \text{elev})$	42.08	0.00	36	6,454.10
$f(\text{prec} + \text{elev} + \text{WF}_{1000})$	45.49	0.00	33	6,463.94
$f(\text{year} + \text{WF}_{1000})$	46.39	0.00	36	6,458.41
$f(\text{year} + \text{RD})$	49.07	0.00	36	6,461.09
$f(\text{year} + \text{FC})$	49.54	0.00	36	6,461.56
$f(\text{year} + \text{SH})$	50.47	0.00	35	6,464.63
$f(\text{lek})$	55.80	0.00	39	6,461.35
$f(\text{year} + \text{FRich})$	60.34	0.00	36	6,472.36
$f(\text{year})$	61.76	0.00	34	6,478.06
$f(\text{year} + \text{DSpring})$	61.93	0.00	36	6,473.95
$f(\text{year} + \text{FH})$	62.24	0.00	36	6,474.26
$f(\text{prec})$	62.47	0.00	31	6,485.18
$f(\text{year} + \text{RGH})$	62.50	0.00	36	6,474.52
$f(\text{year} + \text{pop})$	63.04	0.00	36	6,475.06
$f(\text{year} + \text{GC})$	64.40	0.00	36	6,476.42
$f(\text{year} + \text{TSC})$	64.93	0.00	36	6,476.95
$f(\text{year} + \text{SC})$	65.00	0.00	36	6,477.02
$f(\text{year} + \text{NSC})$	65.10	0.00	36	6,477.12
$f(\text{year} + \text{GH})$	65.22	0.00	36	6,477.24

(Continued)

Table SB8. (Continued)

Model ^a	ΔAIC_c^b	w_i^c	K^d	Deviance
$f(\text{elev})$	72.35	0.00	31	6,495.05
$f(.)$	84.10	0.00	30	6,508.93

^a All models had identical constraints on survival and detection that allowed survival to vary by year ($K=9$) and detection to vary by year ($K=10$) and lek ($K=11$). Elev and slope represents lek elevation and slope, respectively. Year and lek allowed *per capita* recruitment to vary independently by year and lek, respectively. Prec constrained *per capita* recruitment to vary as a function of total precipitation recorded during the year prior. RDist and DSpring represent distance from lek to nearest road and spring or water source, respectively. Horizontal cover variables included average non-sagebrush shrub cover (NSC), average sagebrush shrub cover (SC), average total shrub cover (TSC), average forb cover (FC), average grass cover (GC), and average total vegetation cover (TC). Vertical cover variables included average shrub height (SH), average forb height (FH), average live grass height (GH), and average residual grass height (RGH). FRich represents average forb taxa richness across all vegetation surveys associated with each lek. WF represents the amount of habitat surrounding each lek within 5 km that was converted to exotic grasslands by wildfire; (.) denotes intercept-only model. Main effects are included in models in which an interaction is specified. All variables were z-standardized prior to analysis. See Blomberg et al. (2012) for parameter estimates, model results, and analytical procedures. We retained the highest ranked model (lowest ΔAIC) in the multivariable model section and considered it as the baseline covariate model for the power-line impact analysis.

^b The difference in Akaike's Information Criterion between the top ranked and selected model.

^c The relative likelihood of a model (i.e., Akaike weights).

^d The number of estimated parameters in a given model.

Table SB9. Performance of all Pradel models used to assess the influence of environmental characteristics on population growth (λ) of male greater sage-grouse in Eureka County, Nevada, 2003–2012. Model design, structure, and results based on analyses in Blomberg et al. (2012).

Model ^a	ΔAIC_c^b	w_i^c	K^d	Deviance
$\lambda(\text{TC} + \text{prec} \times \text{WF} + \text{elev})$	0.00	0.37	35	6,404.81
$\lambda(\text{TC} + \text{RDist} + \text{prec} \times \text{WF} + \text{elev})$	0.69	0.26	36	6,403.35
$\lambda(\text{TC} + \text{RDist} + \text{prec} \times \text{WF})$	0.79	0.25	35	6,405.59
$\lambda(\text{TC} + \text{RDist} + \text{prec} \times \text{WF} + \text{DSpring} + \text{elev})$	2.37	0.11	36	6,405.03
$\lambda(\text{FC} + \text{prec} \times \text{WF} + \text{DSpring} + \text{elev})$	9.83	0.00	35	6,414.64
$\lambda(\text{FC} + \text{SH} + \text{prec} \times \text{WF} + \text{DSpring} + \text{elev})$	11.86	0.00	36	6,414.52
$\lambda(\text{WF} \times \text{prec} + \text{elev})$	12.23	0.00	34	6,419.18
$\lambda(\text{WF} \times \text{prec})$	25.70	0.00	33	6,434.79
$\lambda(\text{elev} \times \text{prec} + \text{WF})$	31.28	0.00	34	6,438.22
$\lambda(\text{lek} + \text{prec})$	39.80	0.00	41	6,431.67
$\lambda(\text{TPC} + \text{prec} + \text{RDist})$	41.11	0.00	33	6,450.19
$\lambda(\text{TPC} + \text{prec} + \text{RDist} + \text{WF})$	41.72	0.00	34	6,448.66
$\lambda(\text{TPC} + \text{prec})$	42.29	0.00	32	6,453.50
$\lambda(\text{TPC} + \text{prec} + \text{RDist} + \text{WF} + \text{DSpring})$	43.40	0.00	35	6,448.21
$\lambda(\text{year} + \text{lek})$	52.25	0.00	48	6,428.83
$\lambda(\text{elev} + \text{prec})$	53.35	0.00	32	6,464.57
$\lambda(\text{lek})$	56.03	0.00	40	6,450.07
$\lambda(\text{TPC})$	58.01	0.00	31	6,471.36
$\lambda(\text{year} + \text{elev})$	65.32	0.00	39	6,461.51
$\lambda(\text{prec})$	65.38	0.00	31	6,478.73
$\lambda(\text{elev})$	68.75	0.00	31	6,482.09
$\lambda(\text{slope})$	69.42	0.00	31	6,482.76
$\lambda(\text{SH})$	71.73	0.00	31	6,485.08
$\lambda(\text{FH})$	76.20	0.00	31	6,489.54
$\lambda(\text{RDist})$	76.35	0.00	31	6,489.70
$\lambda(\text{FC})$	76.73	0.00	31	6,490.07
$\lambda(\text{year})$	77.50	0.00	38	6,475.86
$\lambda(\text{year} + \text{WF})$	79.15	0.00	39	6,475.35
$\lambda(.)$	80.20	0.00	30	6,495.67
$\lambda(\text{DSpring})$	80.28	0.00	31	6,493.62
$\lambda(\text{FRich})$	81.75	0.00	31	6,495.09
$\lambda(\text{SC})$	82.01	0.00	31	6,495.36
$\lambda(\text{WF})$	82.06	0.00	31	6,495.41
$\lambda(\text{GC})$	82.08	0.00	31	6,495.42
$\lambda(\text{TSC})$	82.11	0.00	31	6,495.45
$\lambda(\text{RGH})$	82.11	0.00	31	6,495.46
$\lambda(\text{NSC})$	82.29	0.00	31	6,495.64
$\lambda(\text{GH})$	82.31	0.00	31	6,495.66

^a All models had identical constraints on survival and detection that allowed survival to vary by year ($K=9$) and detection to vary by year ($K=10$) and lek ($K=11$). Elev and slope represents lek elevation and slope, respectively. Year and lek allowed population growth to vary independently by year and lek, respectively. Prec constrained population growth to vary as a function of total precipitation recorded during the year prior. RDist and DSpring represent distance from lek to nearest road and spring or water source, respectively. Horizontal cover variables included average non-sagebrush shrub cover (NSC), average sagebrush shrub cover (SC), average total shrub cover (TSC), average forb cover (FC), average grass cover (GC), and average total vegetation cover (TC). Vertical cover variables included average shrub height (SH), average forb height (FH), average live grass height (GH), and average residual grass height (RGH). FRich represents average forb taxa richness across all vegetation surveys associated with each lek. WF represents the amount of habitat surrounding each lek within 5 km that was converted to exotic grasslands by wildfire; (.) denotes intercept-only model. Main effects are included in models in which an interaction is specified. All variables were z-standardized prior to analysis. See Blomberg et al. (2012) for parameter estimates, model results, and analytical procedures. We retained the highest ranked model (lowest ΔAIC) in the multivariable model section and considered it as the baseline covariate model for the power-line impact analysis.

^b The difference in Akaike's Information Criterion between the top ranked and selected model.

^c The relative likelihood of a model (i.e., Akaike weights).

^d The number of estimated parameters in a given model.