




Research Article

Greater Sage-Grouse Response to Bentonite Mining

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ABSTRACT The greater sage-grouse (*Centrocercus urophasianus*; sage-grouse) has undergone range contraction and population decline because of anthropogenic land surface disturbances; yet, there is little information on the effects of mining on sage-grouse populations. In the Bighorn Basin of Montana and Wyoming, USA, bentonite mining is a growing source of surface disturbance that contributes to loss of sagebrush (*Artemisia* spp.) habitat. We evaluated the response of sage-grouse to active and reclaimed bentonite mining, relative to nesting, brood-rearing, adult breeding, and adult winter habitat, through resource selection and habitat-specific mortality risk analyses, based on female sage-grouse ($n = 321$) monitored with telemetry from 2011–2015. A greater proportion of our monitored sample was exposed to mining disturbance during winter (65%) than during other seasons (range = 25%–34%). We observed avoidance of all mining disturbance for selection of nesting habitat ($n = 378$ nests), adult breeding habitat ($n = 1,978$ locations), and adult winter habitat ($n = 1,365$ locations). Evidence was inconclusive for avoidance of mining for brood-rearing habitat ($n = 754$ locations). We also observed increased adult breeding season mortality risk ($n = 62$ mortality events; $n = 285$ female sage-grouse) associated with active mining disturbance but observed no effect on nest success ($n = 207$ mortality events; $n = 378$ nests). Evidence was inconclusive for increased mortality risk associated with broods ($n = 48$ mortality events; $n = 157$ broods) and adults during winter ($n = 31$ mortality events; $n = 220$ female sage-grouse). Stakeholders in the Bighorn Basin should be flexible and proactive to minimize the negative effects of bentonite mining on sage-grouse habitat use and demographic rates. Stakeholders should prioritize the conservation of winter habitats because of the influence on a greater proportion of the population and because of the lower regulatory priority given to winter habitat and they should strive to perfect mining reclamation to return disturbed sites back to pre-disturbance conditions to minimize long-term effects of the mines on sage-grouse. © 2019 The Wildlife Society.

KEY WORDS bentonite mining, Bighorn Basin, *Centrocercus urophasianus*, greater sage-grouse, habitat selection, Montana, mortality risk, reproductive success, Wyoming.

Surface disturbance of arid rangelands in western North America has been increasing because of increasing human populations, which have led to increased food and energy demands. These arid ecosystems are less resilient to abnormal and more frequent disturbances such as conversion to agriculture, energy development, increased grazing pressure, and increased fire regimes (Chambers et al. 2016, 2017). Subsequent, natural recovery from disturbance is slower than more productive systems. For example, in Utah, USA, vegetation at sites was still not recovered 90 years after cultivation (Morris et al. 2011). These arid rangelands are less resistant to invasion from non-native plants (e.g., cheatgrass [*Bromus tectorum*]), which influences the frequency of disturbance from fire, potentially resulting in new

stable ecological states or novel ecosystems (Balch et al. 2013; Chambers et al. 2014, 2016, 2017). Anthropogenic surface disturbance increases the opportunity for plant communities to change to alternative stable states fundamentally changing the ecosystem, including the associated wildlife. For example, invasive plants can hinder the restoration of native plant communities after disturbance (Monsen 1992). Reclamation practices can be used to limit the long-term effect of anthropogenic disturbance, but they are more difficult to implement in arid rangelands (Allen 1995).

The greater sage-grouse (*Centrocercus urophasianus*; sage-grouse) was once commonly found across the sagebrush (*Artemisia* spp.) biome but has lost >40% of its historical range (Schroeder et al. 2004) and has experienced long-term population declines (0.83%/yr decline from 1965–2015; Western Association of Fish and Wildlife Agencies 2015). Since 2002, the United States Fish and Wildlife Service (USFWS) has received several petitions to list the sage-grouse under the United States Endangered Species Act

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(ESA) of 1973 (Stiver 2011). Subsequently, in 2010, the USFWS determined that sage-grouse warranted protection under the ESA throughout its range because of the present or threatened destruction, modification, or curtailment of habitat or range, and inadequacy of existing regulatory mechanisms; however, the formal listing was precluded because other non-listed species were under more severe threats of extinction (USFWS 2010). In 2015, the USFWS reported that the sage-grouse was no longer warranted for listing under the ESA because of increased regulatory mechanisms designed to limit the amount and timing of land surface disturbance such as those created through the Bureau of Land Management Greater Sage-Grouse Resource Management Plans and the Wyoming Governor's Executive Order for Greater Sage-Grouse Core Area Protection (USFWS 2015). Land surface disturbances such as agricultural development (Smith et al. 2016a), energy development (Kirol et al. 2015), residential development (Connelly et al. 2004), livestock grazing (Beck and Mitchell 2000), and fire (Lockyer et al. 2015) have contributed to habitat loss and fragmentation.

The effects of energy development, predominately extraction of oil and gas, have been cited as the leading cause of decline for sage-grouse in the eastern portion of their range (USFWS 2010). Documented negative effects from oil and gas development have included avoidance of disturbance for nesting (Lyon and Anderson 2003, Kirol et al. 2015), brood-rearing (Kirol et al. 2015), and winter (Doherty et al. 2008, Carpenter et al. 2010, Smith et al. 2014) habitat. There have also been documented lower demographic rates that have included higher adult female mortality (Holloran 2005, Holloran et al. 2010), higher nest failure (Dzialak et al. 2011), and higher chick mortality (Aldridge and Boyce 2007, Kirol et al. 2015) related to oil and gas development in sagebrush habitat. Avoidance and lower demographic rates in areas of oil and gas development were the likely contributors to observed lower lek attendance and greater lek abandonment (Holloran 2005, Walker et al. 2007, Harju et al. 2010, Hess and Beck 2012, Gregory and Beck 2014). Wind energy development, another source of energy-related disturbance that has been increasing in recent years, also displaces sage-grouse when selecting brood-rearing and adult female breeding habitat (LeBeau et al. 2017).

Mining activities are another potential source of land surface disturbance, of which little is known of their effects on sage-grouse, outside of anecdotal evidence that coal mining has displaced sage-grouse in Colorado (Braun 1998, Connelly et al. 2000). Mining within sage-grouse range has included gold, uranium, trona, coal, and bentonite. The nature of disturbance, and therefore the potential effects on sage-grouse, is not identical between mining and oil and gas development, or even among different types of mining. The actual surface area disturbed by a traditional 1-well oil or gas pad has a smaller footprint than a bentonite clay pit, but disturbance from oil and gas development can quickly become denser and more expansive across the landscape. In contrast, disturbance from bentonite mining has a smaller footprint than surface coal mining, but is more expansive.

However, the duration of active mining disturbance from coal mining is likely decades longer than from bentonite mining. Even though oil and gas development may be a significant disturbance factor across the eastern sage-grouse range, it may not be the most important cause of disturbance within a localized region that may provide habitat for large populations of sage-grouse (Chambers et al. 2016).

One such region is the Bighorn Basin of Montana and Wyoming, USA, where an economically important source of surface disturbance is from bentonite clay mining. Ten of the 33 (30%) designated sage-grouse core areas in Wyoming, and over 200 leks, occur in the Bighorn Basin (Hess and Beck 2012, Big Horn Basin Sage-grouse Local Working Group 2013, State of Wyoming 2015). Bentonite clay deposits in Wyoming contain 70% of the world's supply, and mines in the Bighorn Basin produced over 50% of Wyoming's total bentonite production during our study (Wyoming Mining Association 2016). Bentonite extraction is carried out by shallow open-pit mining that leads to loss of sagebrush and other vegetation. Individual bentonite mines are only a few hectares in size, but disturbance can become expansive as clay extraction moves relatively quickly along clay deposits (Schuman et al. 1985, 1994). In addition, mining support activities (e.g., exploration drilling, construction and maintenance of roads, haul trucking) increase disturbance and fragment habitat around mines. To date, most bentonite mining in the Bighorn Basin has occurred in salt desert shrub communities dominated by Gardner's saltbush (*Atriplex gardneri*) where clay is at or near the surface; however, mining operations will likely increase in sagebrush communities as easily accessible deposits are depleted. These mining activities may prevent or limit the ability of the sagebrush landscape in the Bighorn Basin to provide the space and resources to meet the life-history requirements of sage-grouse. Therefore, there is a need to assess whether bentonite mining affects the sage-grouse population in the Bighorn Basin. This information will help stakeholders make conservation decisions as bentonite mining expands into additional sage-grouse habitat in the Bighorn Basin and adjacent regions where bentonite deposits and sagebrush habitat overlap. Bentonite mines are reclaimed through backcasting of overburden, including top soil, from newly created adjacent mine pits, which is then seeded (Schuman et al. 1985, Wyoming Mining Association 2016). This limits the amount of top soil that must be stockpiled for long periods. Reclaimed mining disturbance may have lesser effects to sage-grouse because human activity is not present; however, reclamation of disturbed sagebrush plant communities to their pre-disturbance states is a long-term process (>30 yr; Liesenfeld 2012), so there could be lingering effects.

We evaluated resource selection and mortality risk relative to bentonite mining for the 4 most critical demographic rates and seasonal habitat requirements for sage-grouse populations: nest, brood, adult breeding, and adult winter mortality risk and habitat selection (Connelly et al. 2011, Taylor et al. 2012). We did not analyze habitat selection or mortality risk in summer because all sage-grouse moved away from areas where bentonite mining occurred, which was in lower

elevation (i.e., hotter and drier) areas, during summer to seek out more mesic sites. For each habitat requirement and demographic rate analysis, we examined 4 hypotheses: no effect from mining disturbance, effect from active mining disturbance only, effect from reclaimed mining disturbance only, and effect from all (i.e., summation of active and reclaimed mine disturbance) mining disturbance.

STUDY AREA

Our study included sage-grouse location and demographic data from 3 research sites in the Bighorn Basin of north-central Wyoming and extreme south-central Montana (Fig. 1). The landscape forming our study was approximately associated with the Carbon Sage-Grouse Core Conservation Area in Montana (State of Montana 2015), and the Shell, Hyattville, and Washakie Sage-Grouse Core Areas in Wyoming (State of Wyoming 2015). The 30-year (1981–2010) normal average annual precipitation and temperature were 35 cm and 7.1 °C, respectively (PRISM Climate Group 2016). Average precipitation and temperature during the years of our study (2011–2015) were 36 cm and 7.2 °C, respectively (PRISM Climate Group 2016). Elevations ranged from 1,180 m to 2,600 m. Plant communities were dominated by Wyoming big sagebrush (*A. tridentata wyomingensis*) at lower elevations and mountain big sagebrush (*A. t. vaseyana*) at higher elevations. Black sagebrush (*A. nova*) was common in localized areas at moderate elevations. Juniper (*Juniperus* spp.) occurred in

localized areas at moderate-to-high elevations. Coniferous forest dominated elevations above sagebrush and Gardner's saltbush dominated elevations below sagebrush. Sage-grouse winter habitat was mostly located in sagebrush at lower elevations, whereas breeding habitat occurred at a wide range of elevations (Pratt 2017). Anthropogenic disturbance was not widespread across the study area but was abundant in localized areas (Pratt 2017). Agricultural fields (row crops, hayfields, and pastures) were the most common disturbance (5.1% of study area) and were located along the major floodplains of the Bighorn Basin. Bentonite mining was present (0.2% and 0.9% of study area for active mining disturbance and reclaimed mining disturbance, respectively) in localized areas at lower elevations where sagebrush transitioned to saltbush. Land ownership included United States Bureau of Land Management (61%), private (23%), United States Forest Service (10%), and State of Wyoming or Montana (6%).

METHODS

During 2011–2015, we captured female sage-grouse by spotlighting and hoop netting (Giesen et al. 1982, Wakkinen et al. 1992) near leks during spring. We located and captured additional females during summer or winter at night-roosting locations of previously marked sage-grouse. We aged sage-grouse as yearlings or adults (Eng 1955). We marked females with very high frequency (VHF) radio-transmitters (22-g necklace-mounted VHF transmitter Model A4060, Advanced Telemetry Systems, Isanti, MN, USA), or with global positioning system (GPS) equipped platform transmitter terminals (22-g Solar Argos/GPS PTT-100 [Microwave Telemetry, Columbia, MD, USA] or Model 22 GPS PTT [North Star Science and Technology, King George, VA, USA]). We programmed GPS transmitters to acquire from 4 to 6 locations per day depending on season (Pratt et al. 2017). We located sage-grouse equipped with VHF-transmitters by triangulating on the ground from approximately 50 m away during April through August and located birds by fixed-wing aircraft (<200-m error; Dinkins et al. 2017) from September through March. We assigned locations for GPS-marked sage-grouse to season based on behavior (Pratt et al. 2017), whereas we assigned locations for VHF-marked sage-grouse based on population-average seasonal bounding dates (Pratt 2017). We rarified locations from GPS-marked sage-grouse to the sampling intensity of VHF-marked sage-grouse. We used locations from nesting females only once for the adult breeding season analysis. Average location sampling for VHF-marked sage-grouse was 1 location every 7 days, 16 days, and 26 days of exposure for broods, adults during the breeding season, and adults during winter, respectively. Very-high frequency transmitters were equipped with 8-hour mortality switches and we visited the sites of any birds with transmitters emitting mortality signals. We also confirmed mortalities for GPS-marked birds after the transmitter was consistently not moving. We visually confirmed nesting females equipped with VHF-transmitters after we relocated them in the same location on 2 occasions.

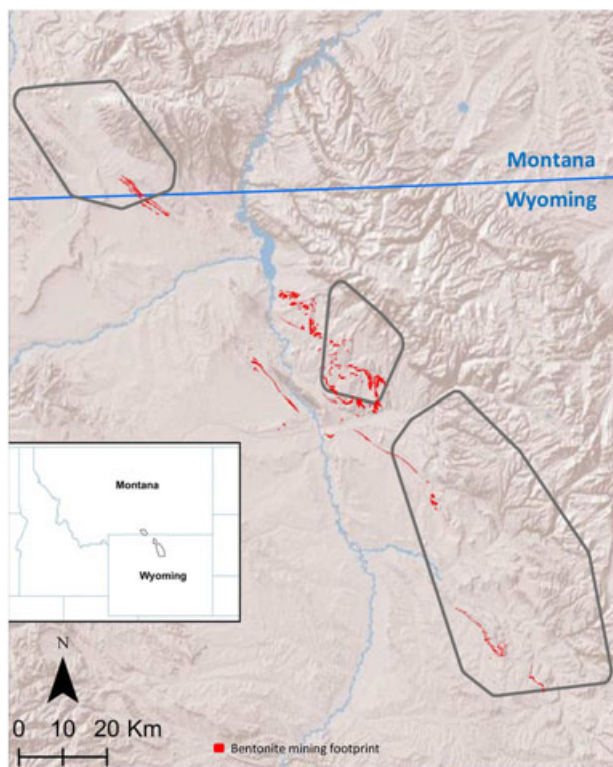


Figure 1. Approximate study area boundaries (gray outlines) for investigating greater sage-grouse response to bentonite mining (red polygons) in Bighorn Basin, USA, 2011–2015.

After observing a female sage-grouse on a nest, we monitored it every 4 days by triangulating from the nearest 2-track road until the conclusion of the nesting effort. We searched for nests from GPS-equipped females at the estimated nest location after the female left the area. We checked any GPS-equipped female that appeared to be incubating for ≥ 1 day for a nest (we discovered a nest in all cases except 1). We determined nest success (i.e., nests with ≥ 1 egg hatching) by examining egg shells after the female left the area (Sowls 1948). We defined brood success as ≥ 1 chick surviving to 35 days post hatch. We confirmed any female that had hatched a nest that we suspected to have lost her brood by checking her at night twice. In addition, we confirmed the presence of chicks from night roosting females at 35 days post hatch. Sage-grouse capture and monitoring were approved by University of Wyoming Animal Care and Use Committee (protocols 03142011 and 20140228JB00065) and were completed under permits from Wyoming Game and Fish Department (Chapter 33 Permit 800) and Montana Fish, Wildlife and Parks (Scientific Collector's Permits 2013-072, 2014-037, and 2015-76).

To control for the effects of environmental landscape attributes, we developed predictor variables for habitat-specific mortality risk and resource selection modeling that were based on several climate, topographic, and vegetation characteristics important to sage-grouse in our study area, including variables used in other sage-grouse resource selection studies (Table 1; Fedy et al. 2014, Smith et al. 2016b, Walker et al. 2016). Because many of these variables were highly correlated, we used principal components analysis to combine these environmental variables into 9 independent components (number determined by inspecting scree plot), which explained 70% of the variation in our environmental variables, to use as final predictor variables. We digitized bentonite mining disturbance using the World Imagery basemap (0.3-m resolution) within ArcGIS 10.0 (Environmental Systems Research Institute 2011) and classified it into active mining (including haul roads) disturbance or reclaimed mining disturbance. Reclaimed mining disturbance were mines that had the overburden and topsoil replaced and were seeded, but vegetation had not returned to pre-disturbance conditions. We measured bentonite variables as the proportion (%) disturbed within multiple, circular spatial regions around locations with radii that started at about maximum location error (i.e., 200 m for winter locations) and systematically increased by doubling in size until the radius of circular analysis regions was 3,200 m, which was the maximum extent we thought would still capture the variability in amount of disturbance within mining areas.

To evaluate population-level second-order resource selection (i.e., selection within the range of sage-grouse in the Bighorn Basin; Johnson 1980, Manly et al. 2002) relative to bentonite mining for nesting, brood-rearing, female breeding season, and female winter season habitat, we compared use locations to randomly selected available locations that were restricted to each research site. We delineated the extents of the research sites from minimum convex polygons

Table 1. Environmental variables used to create principal components used as predictor variables in greater sage-grouse resource selection and mortality-risk models, Bighorn Basin, USA, 2011–2015.

Description	Reference
Climate	
Average (30-year normal) seasonal (breeding, summer, winter) temp. (°C)	PRISM Climate Group (2016)
Average seasonal (breeding, winter) snow depth (cm)	Liston and Elder (2006a)
Grouse	
Distance to nearest lek (km)	
Topographic	
Compound topographic index ^a	Gessler et al. (1995)
Heat load index ^a	McCune and Keon (2002)
Slope (%) ^a	
Vector ruggedness measure ^a	Sappington et al. (2007)
Vegetation	
Herbaceous or ground	
Annual grass cover (%) ^a	Pratt (2017)
Bare ground (%) ^a	Pratt (2017)
Herbaceous cover (%) ^a	Pratt (2017)
Shrub	
Big sagebrush cover (%) ^a	Pratt (2017)
Black sagebrush (probability of presence) ^a	Pratt (2017)
Juniper (probability of presence) ^a	Pratt (2017)
Non-sagebrush cover (%) ^a	Pratt (2017)
Shrub cover (%) ^a	Pratt (2017)
Shrub height (cm) ^a	Pratt (2017)
Land cover	
Agriculture ^b	Homer et al. (2015)
Forest ^b	Homer et al. (2015)
Wetland ^b	Homer et al. (2015)
Vegetation index	
Seasonal (breeding, summer) soil-adjusted vegetation index ^a	Qi et al. (1994)

^a Calculated as mean and standard deviation at multiple scales (radius = 50, 100, 200, 400, 800, 1,600, and 3,200 m).

^b Calculated as proportion of area at the same multiple scales.

of use locations with areas of non-habitat masked out (i.e., closed canopy, developed, and non-terrestrial land covers; 2011 National Land Cover Database; Homer et al. 2015). We randomly selected 20 available locations per use location and confirmed that this number of available locations was large enough for convergence of estimated parameter coefficients (Northrup et al. 2013). We modeled relative probability of selection with generalized estimating equations (PROC GENMOD, SAS 9.4, SAS Institute 2012). We accounted for repeated observations from the same individual by assigning use and available locations into clusters and by selecting between independent and compound-symmetric correlation structures to estimate robust standard errors (Koper and Manseau 2009, Fieberg et al. 2010). To first account for the influence of environmental attributes on resource selection, we developed an environment-only model that included all 9 component variables. Our environmental model represented the hypothesis that sage-grouse were not responding to bentonite mining when selecting habitat. We then created models to represent the 3 bentonite hypotheses by adding the active bentonite, reclaimed bentonite, and all bentonite disturbance variables, measured at the most predictive scale, to the environmental

model for each of their respective hypotheses. We determined the scale of measurement and the model support for each hypothesis with quasi-likelihood criteria (QIC; Pan 2001). We considered a QIC value lower than the environmental model and an estimated 95% confidence interval for the mining coefficient that did not overlap 0 demonstrated strong evidence for an effect from mining. If the QIC value was lower than the environmental model but the 95% confidence interval overlapped 0, we considered it as weaker inconclusive evidence for an effect from mining. Because we investigated multiple scales of measurement, we used 95% Bonferonni corrected confidence intervals throughout, which reduces the likelihood of committing a Type 1 error but increases the likelihood of committing a Type 2 error, especially for analyses with smaller sample sizes. For habitat selection influenced by mining, we recorded the selection coefficients for all scales of measurement to determine if there was a maximum scale where avoidance was no longer detected.

We used mixed-effects Cox proportional hazards regression, which uses the variation in exposure time to a mortality event relative to covariates (Cox 1972; *coxme* R package, Therneau 2015; R version 3.4.1, R Core Team 2015), to evaluate the effect of bentonite mining on mortality risk for nests, broods, and seasonal female survival during the breeding and winter seasons. The values for the mining variables were the average for each experimental unit (i.e., each nest, brood, or adult-season combination) when modeling mortality risk and when reporting descriptive statistics on the exposure to mining disturbance. For the nest mortality risk analysis, we measured variables at each nest location. For the brood mortality risk analysis, we measured variables at brood locations and averaged measurements for each individual brood. For the adult seasonal mortality risk analyses, we measured variables at the relevant seasonal locations and averaged measurements over the lifetime of each individual female for that season. Therefore, covariates were time independent and represented the average habitat use for each experimental unit. In addition to the environmental landscape attributes, we also considered weather variables (temperature, precipitation, snow depth; Liston and Elder 2006*a, b*) when modeling mortality. We measured these weather variables with a linear predictor ($\alpha = 0-1$ by 0.05 increments; Gienapp et al. 2005) over the prior year, which allowed us to account for the appropriate timeframe over which weather influenced mortality. When selecting the final environmental model, we first determined which random effects should be included by comparing null models with all possible combinations of random effects from individual, age, transmitter type, research site, and year using Akaike's Information Criterion corrected for small sample sizes (AIC_c ; Burnham and Anderson 2002; *AICc-modavg* R package, Mazerolle 2017). We then employed variable reduction steps so there was a minimum of 10 mortality events per fixed-effect variable in the final environmental model (Harrell et al. 1984). We first selected the most predictive α -value for each weather variable and removed any non-informative variables (i.e., larger AIC_c

value than null model) by comparing single-variable models. We then compared all possible combinations of the remaining variables while restricting to the maximum allowed variables and selected the model with the lowest AIC_c value. When selecting the model with the lowest AIC_c value, we removed models from consideration with variables that demonstrated coefficient sign switching when moderately correlated variables ($0.3 \leq |r|$) occurred together or if the model included variables that did not meet the proportional hazards assumption, which is represented by a slope not different from 0 for Schoenfeld residuals (Schoenfeld 1982). Finally, like resource selection modeling, we added the appropriate bentonite mining variables to the final environmental models to represent the respective hypotheses and compared model support with AIC_c . We report survival estimates relative to adult females marked with VHF-transmitters in our largest research site during 2014, which was the cohort from which we obtained the largest sample of observations.

RESULTS

Resource Selection

We collected data from 321 female sage-grouse captured in the Bighorn Basin during 2011–2015 (Table 2). The proportion of monitored sage-grouse that were exposed to any amount of bentonite mining disturbance within 3,200 m (i.e., ≥ 1 location with mining disturbance within our largest measurement scale) was 25% for nests, 29% for broods, 34% for adult females during the breeding season, and 65% for females during winter. For nest-site resource selection, the model that included the amount of all bentonite mining disturbance measured within 800 m was the best-supported model (Table 3). The odds of selecting a nest site decreased by half if the amount of area disturbed by mining within 800 m increased from 0 to 12% (95% CI = 7–75%; Fig. 2). The odds of selection continued to decrease by half for every increment increase of 12%. We did not observe any nests with $>34\%$ of the surrounding area within 800 m disturbed by mining (Fig. 3).

For brood-rearing resource selection, the model that included only the amount of active mining within 400 m was the best-supported model (Table 3). However, we considered this inconclusive evidence for an effect from mining because the coefficient estimate overlapped zero. We did not observe any individual brood locations with $>4\%$ of the surrounding area (within 400 m) disturbed by active mining (Fig. 3), and we did not observe any broods with an average

Table 2. Sample sizes used for modeling habitat-specific mortality risk and resource selection for greater sage-grouse in Bighorn Basin, USA, 2011–2015.

Analysis	Mortality			
	events	Locations	Broods	Sage-grouse
Nest	207	378		246
Brood	48	754	157	128
Adult breeding	62	1,978		285
Adult winter	31	1,365		220

Table 3. Model selection statistics (K =number of parameters, ΔQIC = difference in quasi-likelihood criteria [QIC] between model and top model), scale of measurement, and mining variable coefficients for models representing hypotheses of effects from bentonite mining on greater sage-grouse habitat selection in Bighorn Basin, USA, 2011–2015.

Model statistics			Mining variable coefficient			
			Scale (m)	β	95% CI ^a	
Analysis hypothesis	K	ΔQIC				Lower
Nest						
All	11	0.0	800	-5.7	-10.4	-0.9
Reclaimed	11	0.6	800	-6.7	-12.9	-0.4
Active	11	4.7	200	-34.4	-85.6	16.8
Environmental	10	10.8				
Null	1	606.2				
Brood						
Active	11	0.0	400	-42.4	-109.4	24.5
All	11	5.6	200	-3.2	-7.3	0.9
Reclaimed	11	8.0	800	-3.8	-9.3	1.6
Environmental	10	12.0				
Null	1	760.4				
Breeding						
All	11	0.0	200	-2.9	-5.2	-0.5
Reclaimed	11	1.9	800	-3.8	-7.6	0.0
Active	11	7.7	400	-10.9	-21.7	-0.0
Environmental	10	18.9				
Null	1	2,492.7				
Winter						
All	11	0.0	800	-5.1	-8.7	-1.4
Reclaimed	11	0.7	800	-6.0	-10.8	-1.1
Active	11	30.5	800	-12.8	-25.5	-0.1
Environmental	10	45.3				
Null	1	1,726.4				

^a Bonferonni corrected confidence interval.

active mining disturbance >2% surrounding (within 400 m) all their observed locations.

The top model explaining adult female breeding habitat use included the amount of all mining disturbance within 200 m (Table 3). The odds of selecting locations by adult females during the breeding season decreased by half if the amount of area disturbed by mining within 200 m increased from 0 to 24% (95% CI = 13–100%; Fig. 2). We did not observe any individual breeding season female locations with >51% of the surrounding area (within 200 m) disturbed by mining (Fig. 3), and we did not observe any females with an average mining disturbance >19% surrounding (within 200 m) all their observed locations.

During winter, the top model explaining adult female habitat use included all mining disturbance within 800 m (Table 3). The odds of selecting locations by adult females during winter decreased by half if the amount of area disturbed by mining within 800 m increased from 0% to 14% (95% CI = 8–50%; Fig. 2). We did not observe any individual winter season female locations with >65% of the surrounding area (within 800 m) disturbed by mining (Fig. 3), and we did not observe any females with an average mining disturbance >25% surrounding (within 800 m) all their observed locations.

We observed that avoidance of mining disturbance was equally influenced by avoidance of reclaimed mine sites as active mine sites when sage-grouse selected nesting, adult

breeding, and adult winter habitat (Table 3). We also observed negative selection coefficients for mining when the amount of disturbance was measured approximately out to 2 km from sage-grouse locations (Fig. 4).

Mortality Risk

Our best-supported nest failure model was the environmental model; therefore, we found no evidence for increased risk of nest failure associated with bentonite mining disturbance (Table 4). Estimated nest survival to 26.5 days was 44% (95% CI = 35–53%).

For brood failure, the best-supported model included amount of active mining disturbance within 3,200 m (Table 4). However, we considered this inconclusive evidence for an effect from mining because the coefficient estimate overlapped zero. Estimated brood survival to 35 days was 69% (95% CI = 56–82%).

For the adult female breeding season mortality risk analysis, the model that included amount of active mining disturbance within 1,600 m was best supported (Table 4). The odds of mortality during the breeding season were 19 times (95% CI = 2–175) higher for females exposed to the most active mining (7%) than females with no active mining disturbance within 1,600 m (Fig. 5). Breeding season female survival to 89 days (i.e., median breeding season length; Pratt 2017) for females exposed to no active disturbance within 1,600 m was 87% (95% CI = 79–95%) and 14% (95% CI = 0–63%) for those exposed to 7% active disturbance (Fig. 6). We observed that the proportion of brood failures that were a result of the death of the brood-rearing female was higher for broods exposed to any amount of active mining disturbance (4 of 12; 33%) than for broods not exposed to mining (8 of 35; 23%), suggesting that higher female mortality could result in higher brood failure in areas with active mining.

For the adult female winter season mortality risk analysis, the model that included amount of active mining disturbance within 800 m was best supported (Table 4). However, we considered this inconclusive evidence for an effect from mining because the coefficient estimate overlapped zero. Estimated winter female survival to 127 days (i.e., median winter season length; Pratt 2017) was 92% (95% CI = 83–100%).

DISCUSSION

Our observations revealed that bentonite mining can have negative effects on sage-grouse populations in the Bighorn Basin through avoidance of mining surface disturbance and reduced demographic rates. We observed that sage-grouse avoided mining disturbance when selecting all their annual habitat requirements, except that we documented less evidence for avoidance by broods. We also did not investigate summer habitat use because sage-grouse selection of mesic areas naturally did not coincide with bentonite deposits and mining activity in our study area. We also observed that mining disturbance could hinder population growth by contributing to increased mortality for adult females during the breeding season and possibly for broods and adult females during winter. In general, our observations were consistent

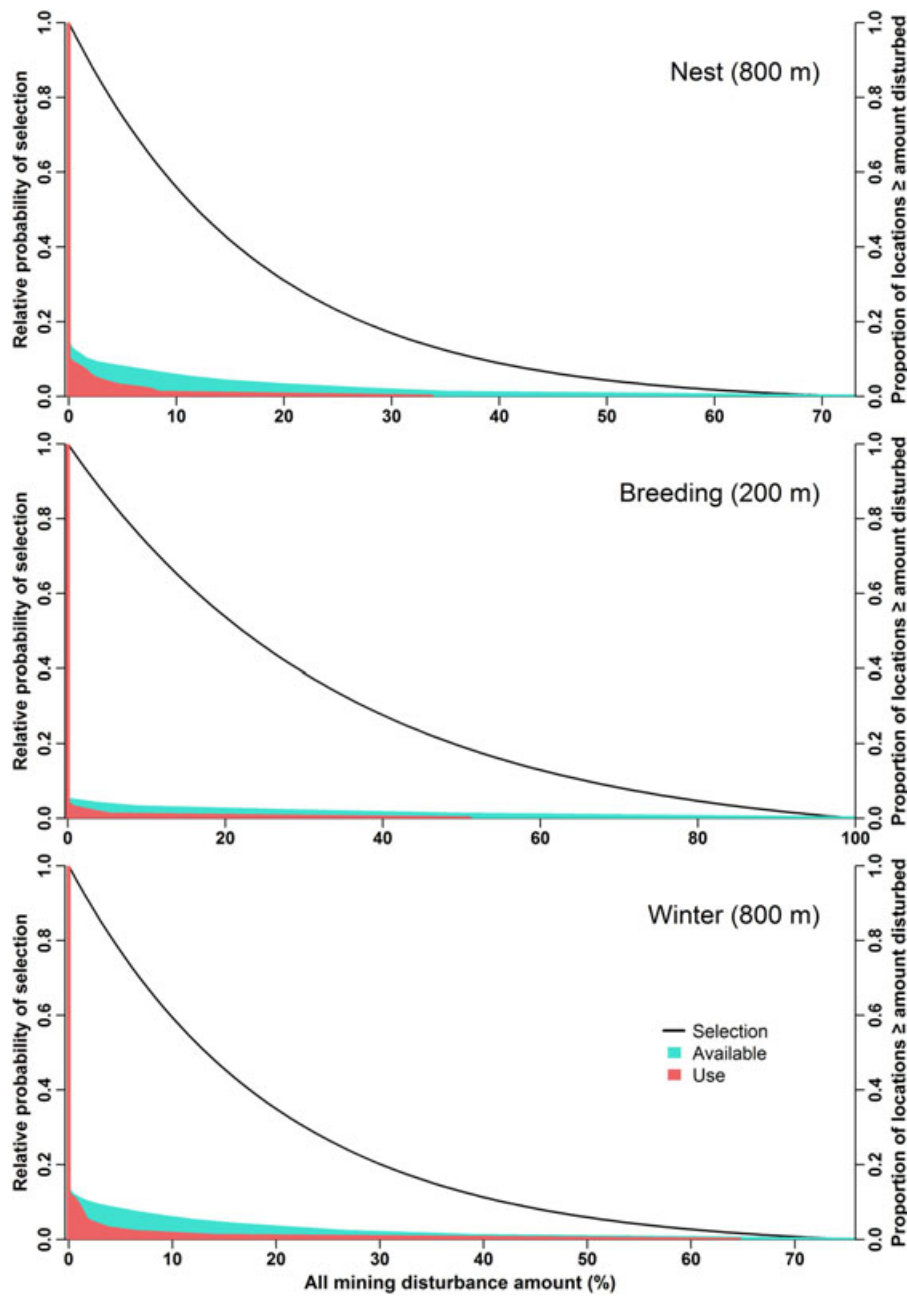


Figure 2. Relative probability of selection and distribution of use and available locations for greater sage-grouse relative to amount (%) of all bentonite mining disturbance in Bighorn Basin, USA, 2011–2015. The scale of measurement is indicated in parentheses next to season. The x-axis limits represent the range of available habitat.

with impacts observed from energy development, which was cited as the leading threat to sage-grouse populations in the eastern portion of their range (USFWS 2010). We documented avoidance for nest-site selection, which was consistent with natural gas development (Lyon and Anderson 2003, Kirol et al. 2015). Sage-grouse avoid natural gas development (Kirol et al. 2015) and wind energy development (LeBeau et al. 2017) when selecting brood-rearing habitat. Adult female sage-grouse avoided mining disturbance during the breeding season, which was also the case for wind energy development (LeBeau et al. 2017), and they avoided disturbance during winter, which was also the

case for oil and gas development (Doherty et al. 2008, Carpenter et al. 2010, Smith et al. 2014). One characteristic of bentonite mining that makes it different from oil and gas development and wind energy development, and potentially less intrusive, is the absence of vertical structures that may make land surface disturbance more visible. Even with this difference we documented similar avoidance behaviors.

Our results were inconclusive, but other research has documented increased brood failure risk associated with development in oil and gas producing fields (Aldridge and Boyce 2007, Kirol et al. 2015). Holloran (2005) and Holloran et al. (2010) reported increased female mortality in

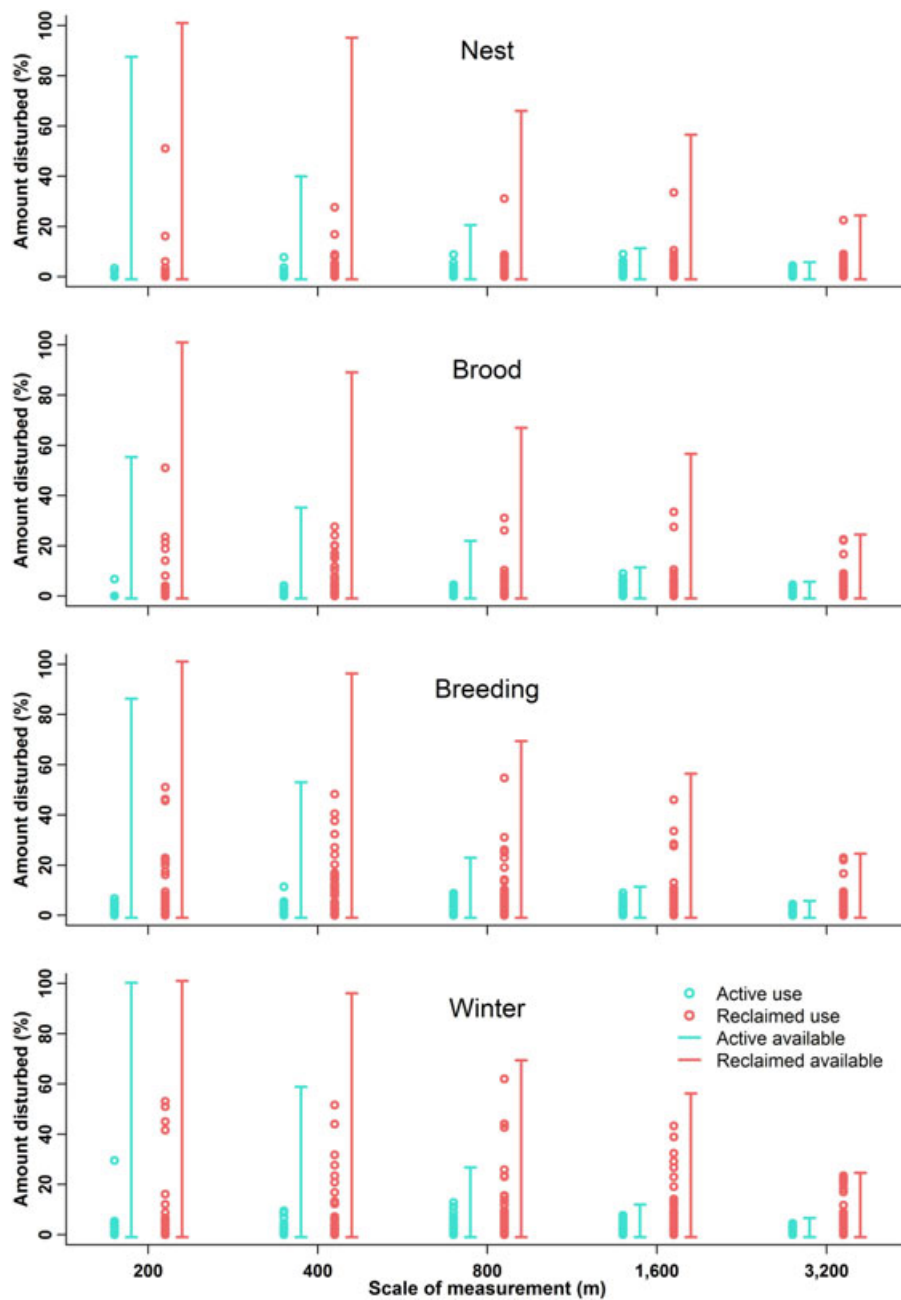


Figure 3. Range in the amount of surface area disturbed by active (turquoise) and reclaimed (red) bentonite mining around individual greater sage-grouse use (circles) and available (lines) locations in Bighorn Basin, USA, 2011–2015.

a natural gas field. We found evidence for increased female mortality near bentonite mining disturbance during the breeding season. Unlike Dzialak et al. (2011), who observed increased nest failure associated with oil and gas development, we found no evidence for increased risk associated with mining activity, similar to no observed effect from anthropogenic disturbance by Aldridge and Boyce (2007) and Kirol et al. (2015). Effects on mortality risk are inherently more difficult to detect because of smaller sample sizes, which are restricted to the number of events (i.e., deaths), and we took a more conservative approach by using Bonferroni corrected confidence intervals when estimating parameters. Also, avoidance of anthropogenic features can

preclude individuals from being exposed to the feature in question, again reducing power to detect effects. Based on the number of observed mortality events (Table 2), we should have had the greatest power to detect an effect on nest mortality risk though we did not, providing evidence that mining did not have a negative effect on nest success.

We documented an avoidance response from sage-grouse to active and reclaimed mining disturbance for nesting, adult breeding, and adult winter habitat. Even though reclaimed mine sites do not have the human activity of active mine sites, sagebrush is a vital component of breeding and winter habitat by providing escape cover, nest concealment cover, and food (Connelly et al. 2011). A vegetation survey of reclaimed

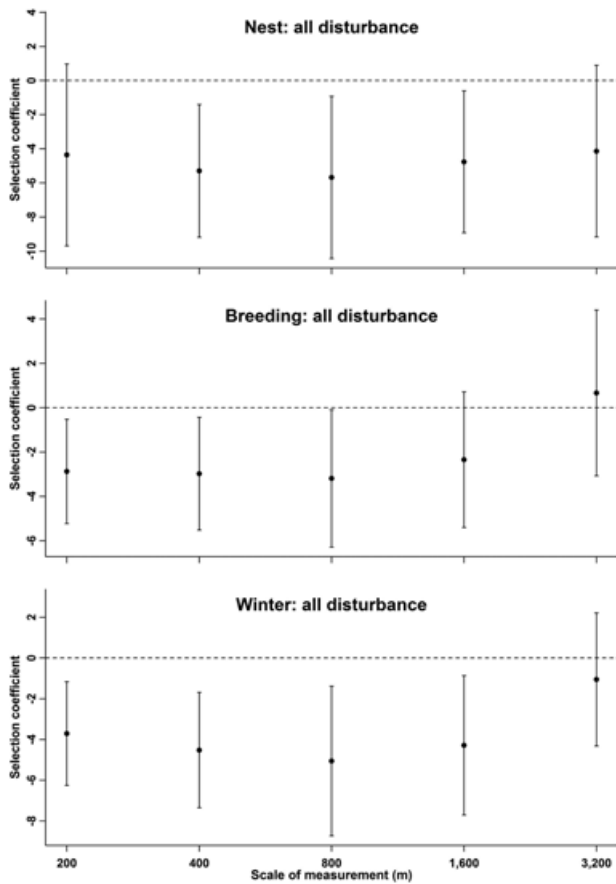


Figure 4. Greater sage-grouse resource selection coefficients for all bentonite mining disturbance in Bighorn Basin, USA, 2011–2015. Negative coefficients show evidence of avoidance of mining at that scale of measurement. Error bars are 95% Bonferroni corrected confidence intervals.

bentonite mine sites (from 10–35 years since initial seeding), in the same general area and timeframe as our study, recorded 70% of the 85 sites surveyed with <1% sagebrush cover with a maximum measured sagebrush cover of 6% (Liesenfeld 2012). Sagebrush cover measurements from a few similar, but undisturbed, adjacent sites ranged from 4–17% (Liesenfeld 2012). Reclamation of bentonite mines to pre-disturbance levels with a substantial shrub component is difficult because of inherent soil chemical and physical characteristics and climate limitations. Top soils in areas with bentonite mining are shallow and easily contaminated by saline-sodic subsoil and bentonitic material (Sieg et al. 1983, Schuman et al. 1985, Liesenfeld 2012). Sagebrush is notoriously difficult to reestablish because natural seed dispersal is limited, seed persistence in the soil is short-lived, years with favorable climatic conditions for seedling establishment are rare, and seedlings are not competitive (Shaw et al. 2005). Likelihood of success is increased with proper top soil salvage and handling to avoid contamination, using a site-specific seed source adapted to local conditions, timing seeding around precipitation events and during years with adequate precipitation, implementing practices (e.g., using micro-topography, snow fencing, fabric mulch) that retain soil moisture from precipitation, and reducing

Table 4. Model selection statistics (K = number of parameters, ΔAIC_c = difference in corrected Akaike's Information Criterion [AIC_c] between model and top model), scale of measurement, and mining variable coefficients for models representing hypotheses of effects from bentonite mining on greater sage-grouse demographic rates in Bighorn Basin, USA, 2011–2015.

Model statistics	Analysis hypothesis	K	ΔAIC_c	Mining variable coefficient		
				Scale (m)	β	95% CI ^a
					Lower	Upper
Nest						
	Environmental	8	0.0			
	All	9	0.1	1,600	-5.2	-15.4 4.9
	Reclaimed	9	0.2	1,600	-7.5	-24.0 9.1
	Active	9	0.7	200	36.1	-34.1 106.2
	Null	2	159.3			
Brood						
	Active	4	0.0	3,200	48.6	-5.2 102.4
	All	4	1.8	3,200	9.6	-4.0 23.2
	Environmental	3	2.1			
	Reclaimed	4	2.8	3,200	8.2	-8.0 24.3
	Null	2	49.0			
Breeding						
	Active	4	0.0	1,600	39.4	9.7 69.0
	All	4	3.5	1,600	12.0	1.1 22.9
	Reclaimed	4	5.8	3,200	14.5	-2.7 31.7
	Environmental	3	6.9			
	Null	1	185.5			
Winter						
	Active	5	0.0	800	43.9	-8.2 96.0
	All	5	1.5	1,600	8.9	-4.6 22.4
	Environmental	4	1.9			
	Reclaimed	5	2.3	1,600	9.3	-7.5 26.0
	Null	2	11.3			

^a Bonferroni corrected confidence interval.

competition and herbivory (Monsen et al. 1992, Lippitt et al. 1994, Schuman et al. 1998, Schuman and Belden 2002, Musselman et al. 2014). Encouraging conditions conducive for natural recolonization, such as creating islands of sagebrush, with more intensive but more successful methods that will provide a future seed source may be the most successful reclamation practices (Longland and Bateman 2002, Liesenfeld 2012, Davies et al. 2013, McAdoo et al. 2013, Balthrop 2016).

Avoidance of mining disturbance when selecting brood-rearing habitat was less apparent. As females transition from nesting habitat to early brood-rearing habitat, the shrub component becomes less vital; however, broods do not use areas far from a sagebrush edge unless herbaceous cover is substantial enough to provide concealment cover (Hagen et al. 2007, Connelly et al. 2011). We documented a small number of brood locations from GPS-marked brood-rearing females in reclaimed mine sites.

We did not document significant negative mortality effects from reclaimed mining disturbance so effects on demographic rates appear to be influenced by active mining with areas around active mine sites likely serving as avoided sink habitat (Kirol et al. 2015). Effects on survival appear to be temporary, lasting while mines are active; however, the effects of habitat loss can be long term until the plant community returns to pre-disturbance levels. Observations on early landscape disturbances from development suggested

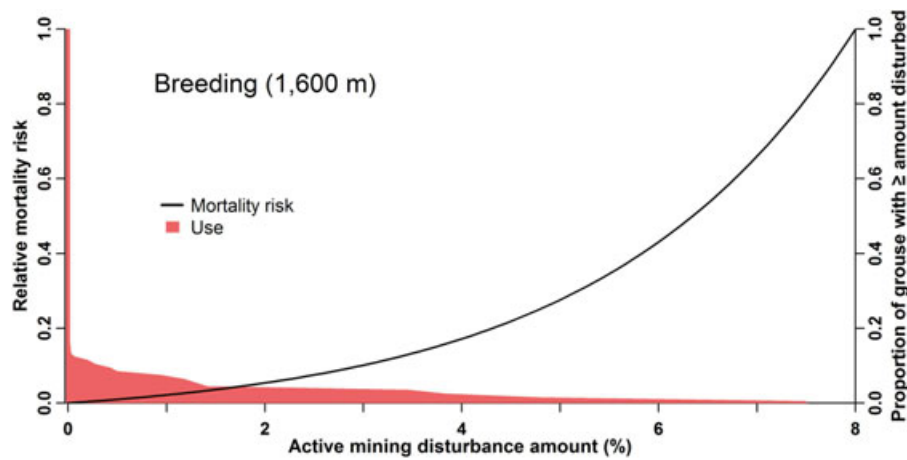


Figure 5. Greater sage-grouse relative mortality risk and distribution of average disturbance surrounding adult females during the breeding season relative to amount (% within 1,600 m) of active bentonite mining in Bighorn Basin, USA, 2011–2015.

that sage-grouse were displaced by disturbance and returned after the active disturbance ceased, but there was no evidence that populations would return to pre-disturbance levels (Braun 1998).

We found that the greatest proportion of our marked population was exposed to bentonite disturbance during winter when they demonstrated avoidance of disturbance up to the 1,600-m measurement scale. A greater proportion of sage-grouse were exposed to mining during winter because mining occurs where deposits are at or near the surface in low elevation sagebrush, which are used by wintering sage-grouse escaping colder summer ranges with more snow (Pratt et al. 2017). The Wyoming sage-grouse core areas were designed to protect the greatest breeding densities of sage-grouse (Doherty et al. 2011, State of Wyoming 2015) and they argue that they protect other seasonal requirements but do not explicitly incorporate other seasonal habitats if they occur separately from breeding range (the exception being designated winter concentration areas). Therefore, smaller core areas, and core areas associated with more migratory

populations, are less likely to provide adequate protection for winter habitat requirements (Smith et al. 2016b, Pratt 2017). These are both characteristics of some core areas in the Bighorn Basin, so in this region it is a greater priority to incorporate winter habitat and the loss of habitat from bentonite mining in conservation decisions.

One of the most insightful pieces of information to provide to managers are the mechanisms that cause avoidance or lower demographic rates associated with anthropogenic disturbance. This information could point to possible solutions to minimize the negative effects of the ever-increasing percentage of landscapes disturbed by anthropogenic activities. Avoidance of active mining disturbance could be a result of avoidance of increasing noise (Blickley et al. 2012a) or visual human activity that sage-grouse are perceiving as a predation risk (Frid and Dill 2002). Increased mortality rates could be a result of increased predator populations associated with anthropogenic activity (Connelly et al. 2000, Hagen 2011) or an effect that makes sage-grouse more vulnerable to predation or less attentive to

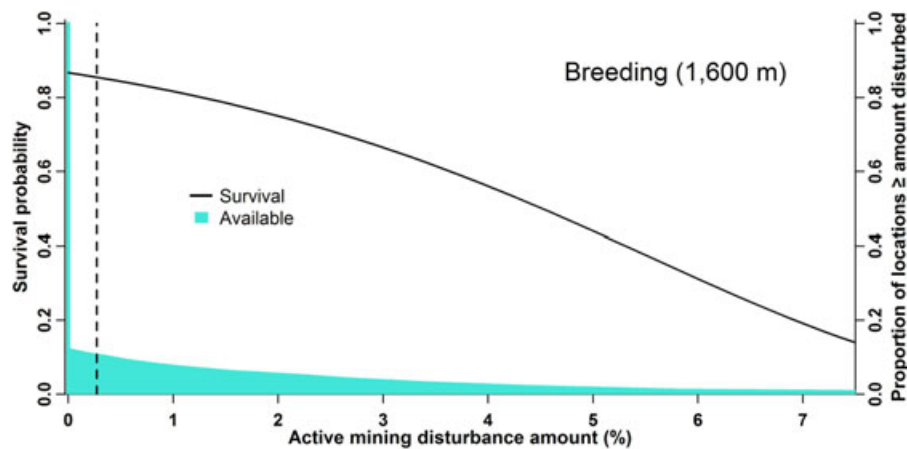


Figure 6. Greater sage-grouse estimated survival probability for adult females over 89 days during the breeding season and distribution of available locations relative to the amount (% within 1,600 m) of active bentonite mining in Bighorn Basin, USA, 2011–2015. Dashed vertical line represents the study area average disturbance amount. The x-axis limits represent the range of used habitat.

reproductive behaviors (e.g., stress; Blickley et al. 2012*b*). Though we did not investigate mechanisms of higher mortality risk, we did not observe any cases where mining activities were the direct cause of death. Perhaps unexpectedly, we did not document increased nest failure that could have been expected if common raven (*Corvus corax*) abundance increased with anthropogenic activity (Dinkins et al. 2016); however, research has suggested that established territorial pairs are likely the ravens responsible for sage-grouse nest depredations and not those associated with human activity (Bui et al. 2010).

MANAGEMENT IMPLICATIONS

We recommend that the bentonite industry be flexible when planning mining activities relative to the location and timing of disturbance, and that they are proactive relative to sage-grouse and sagebrush conservation. When siting a mine, the industry should be aware of potential negative effects on sage-grouse habitat quality within approximately 2 km because this was the distance from sage-grouse locations where we measured the amount of disturbance and detected avoidance behavior and increased mortality risk. Stakeholders should emphasize conservation and restoration of winter habitat in the Bighorn Basin when evaluating effects of bentonite mining on sage-grouse populations because of the tendency of mining disturbance to influence a greater proportion of the population's habitat requirements during winter and because of the lower regulatory priority given to winter habitat. Because bentonite mining, and other sources of surface disturbance, are likely to increase, the effectiveness of sagebrush habitat restoration needs to be improved. This is a daunting challenge given that reclamation of bentonite mines to pre-disturbance vegetation characteristics suitable as sage-grouse habitat is difficult.

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LITERATURE CITED

Aldridge, C. L., and M. S. Boyce. 2007. Linking occurrence and fitness to persistence: habitat-based approach for endangered greater sage-grouse. *Ecological Applications* 7:508–526.

Allen, E. B. 1995. Restoration ecology: limits and possibilities in arid and semiarid lands. Pages 7–15 in B. A. Roundy, E. D. McArthur, J. S. Haley, and D. K. Mann, compilers. *Proceedings: Wildland Shrub and Arid Land Restoration Symposium*. USDA General Technical Report INT-GTR-315. Intermountain Research Station, Forest Service, U.S. Department of Agriculture, Ogden, Utah, USA.

Balch, J. K., B. A. Bradley, C. M. D'Antonio, and J. Gomez-Dans. 2013. Introduced annual grass increases regional fire activity across the arid western USA (1980–2009). *Global Change Biology* 19:173–183.

Balthrop, D. C. 2016. Reestablishment of Wyoming big sagebrush by transplanting container grown seedlings. Thesis, University of Wyoming, Laramie, USA.

Beck, J. L., and D. L. Mitchell. 2000. Influences of livestock grazing on sage grouse habitat. *Wildlife Society Bulletin* 28:993–1002.

Big Horn Basin Sage-grouse Local Working Group. 2013. Sage-grouse conservation plan for the Big Horn Basin, Wyoming: five-year addendum, 2007–2013. Wyoming Game and Fish Department, Cheyenne, USA.

Blickley, J. L., D. Blackwood, and G. L. Patricelli. 2012*a*. Experimental evidence for the effects of chronic anthropogenic noise on abundance of greater sage-grouse leks. *Conservation Biology* 26:461–471.

Blickley, J. L., K. R. Word, A. H. Krakauer, J. L. Phillips, S. N. Sells, C. C. Taff, J. C. Wingfield, and G. L. Patricelli. 2012*b*. Experimental chronic noise is related to elevated fecal corticosteroid metabolites in lekking male greater sage-grouse (*Centrocercus urophasianus*). *PLoS ONE* 7:e50462.

Braun, C. E. 1998. Sage grouse declines in western North America: what are the problems? *Proceedings of the Western Association of Fish and Wildlife Agencies* 78:139–156.

Bui, T.-V. D., J. M. Marzluff, and B. Bedrosian. 2010. Common raven activity in relation to land use in western Wyoming: implications for greater sage-grouse reproductive success. *Condor* 112:65–78.

Burnham, K. P., and D. R. Anderson. 2002. *Model selection and multimodal inference: a practical information-theoretic approach*, second edition. Springer, New York, New York, USA.

Carpenter, J., C. Aldridge, and M. S. Boyce. 2010. Sage-grouse habitat selection during winter in Alberta. *Journal of Wildlife Management* 74:1806–1814.

Chambers, J. C., J. L. Beck, J. B. Bradford, J. Bybee, S. Campbell, J. Carlson, T. J. Christiansen, K. J. Clause, G. Collins, M. R. Crist, J. B. Dinkins, K. E. Doherty, F. Edwards, S. Espinosa, K. A. Griffin, P. Griffin, J. R. Haas, S. E. Hanser, D. W. Havlina, K. F. Henke, J. D. Hennig, L. A. Joyce, F. F. Kilkenny, S. M. Kulpa, L. L. Kurth, J. D. Maestas, M. A. Manning, K. E. Mayer, B. A. Meador, C. McCarthy, M. Pellant, M. A. Perea, K. L. Prentice, D. A. Pyke, L. A. Wiechman, and A. Wuenschel. 2017. Science framework for conservation and restoration of the sagebrush biome: linking the Department of the Interior's Integrated Rangeland Fire Management Strategy to long-term strategic conservation actions. Part 1. Science basis and applications. General Technical Report RMRS-GTR-360. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado, USA.

Chambers, J. C., J. L. Beck, S. Campbell, J. Carlson, T. J. Christiansen, K. J. Clause, J. B. Dinkins, K. E. Doherty, K. A. Griffin, D. W. Havlina, K. F. Henke, J. D. Hennig, L. L. Kurth, J. D. Maestas, M. Manning, K. E. Mayer, B. A. Meador, C. McCarthy, M. A. Perea, and D. A. Pyke. 2016. Using resilience and resistance concepts to manage threats to sagebrush ecosystems, Gunnison sage-grouse, and greater sage-grouse in their eastern range: a strategic multi-scale approach. USDA General Technical Report RMRS-GTR-356. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado, USA.

Chambers, J. C., B. A. Bradley, C. S. Brown, C. D'Antonio, M. J. Germino, J. B. Grace, S. P. Hardegree, R. F. Miller, and D. A. Pyke. 2014. Resilience to stress and disturbance, and resistance to *Bromus tectorum* L. invasion in cold desert shrublands of western North America. *Ecosystems* 17:360–375.

Connelly, J. W., S. T. Knick, M. A. Schroeder, and S. J. Stiver. 2004. Conservation assessment of greater sage-grouse and sagebrush habitats. Western Association of Fish and Wildlife Agencies, Cheyenne, Wyoming, USA.

Connelly, J. W., E. T. Rinkes, and C. E. Braun. 2011. Characteristics of greater sage-grouse habitats: a landscape species at micro- and macro-scales. *Studies in Avian Biology* 38:69–83.

Connelly, J. W., M. A. Schroeder, A. R. Sands, and C. E. Braun. 2000. Guidelines to manage sage grouse populations and their habitats. *Wildlife Society Bulletin* 28:967–985.

Cox, D. R. 1972. Regression models and life-tables. *Journal of the Royal Statistical Society B* 34:187–220.

Davies, K. W., C. S. Boyd, and A. M. Nafus. 2013. Restoring the sagebrush component in crested wheatgrass-dominated communities. *Rangeland Ecology and Management* 66:472–478.

Dinkins, J. B., M. R. Conover, C. P. Kiroi, J. L. Beck, and S. N. Frey. 2016. Effects of common raven and coyote removal and temporal variation in

- climate on greater sage-grouse nesting success. *Biological Conservation* 202:50–58.
- Dinkins, J. B., K. J. Lawson, K. T. Smith, J. L. Beck, C. P. Kirol, A. C. Pratt, M. R. Conover, and F. C. Blomquist. 2017. Quantifying overlap and fitness consequences of migration strategy with seasonal habitat use and a conservation policy. *Ecosphere* 8:e01991.
- Doherty, K. E., D. E. Naugle, H. Copeland, A. Pocewicz, and J. Kiesecker. 2011. Energy development and conservation tradeoffs: systematic planning for sage-grouse in their eastern range. *Studies in Avian Biology* 38:505–516.
- Doherty, K. E., D. E. Naugle, B. L. Walker, and J. M. Graham. 2008. Greater sage-grouse winter habitat selection and energy development. *Journal of Wildlife Management* 72:187–195.
- Dzialak, M. R., C. V. Olson, S. M. Harju, S. L. Webb, J. P. Mudd, J. B. Winstead, and L. D. Hayden-Wing. 2011. Identifying and prioritizing greater sage-grouse nesting and brood-rearing habitat for conservation in human-modified landscapes. *PLoS ONE* 6:e26273.
- Eng, R. L. 1955. A method for obtaining sage grouse age and sex ratios from wings. *Journal of Wildlife Management* 19:267–272.
- Environmental Systems Research Institute. 2011. ArcGIS Desktop: Release 10. Environmental Systems Research Institute, Redlands, California, USA.
- Fedy, B. C., K. E. Doherty, C. L. Aldridge, M. O'Donnell, J. L. Beck, B. Bedrosian, D. Gummer, M. J. Holloran, G. D. Johnson, N. W. Kaczor, C. P. Kirol, C. A. Mandich, D. Marshall, G. McKee, C. Olson, A. C. Pratt, C. C. Swanson, and B. L. Walker. 2014. Habitat prioritization across large landscapes, multiple seasons, and novel areas: an example using greater sage-grouse in Wyoming. *Wildlife Monographs* 190:1–39.
- Fieberg, J., J. Matthiopoulos, M. Hebblewhite, M. S. Boyce, and J. L. Frair. 2010. Correlation and studies of habitat selection: problem, red herring or opportunity? *Philosophical Transactions of the Royal Society B* 365:2233–2244.
- Frid, A., and L. M. Dill. 2002. Human caused disturbance stimuli as a form of predation risk. *Conservation Ecology* 6:art11.
- Gessler, P. E., I. D. Moore, N. J. McKenzie, and P. J. Ryan. 1995. Soil-landscape modelling and spatial prediction of soil attributes. *International Journal of Geographical Information Systems* 9:421–432.
- Gienapp, P., L. Hemerik, and M. E. Visser. 2005. A new statistical tool to predict phenology under climate change scenarios. *Global Change Biology* 11:600–606.
- Giesen, K. M., T. L. Schoenberg, and C. E. Braun. 1982. Methods for trapping sage grouse in Colorado. *Wildlife Society Bulletin* 10:224–231.
- Gregory, A. J., and J. L. Beck. 2014. Spatial heterogeneity in response of male greater sage-grouse lek attendance to energy development. *PLoS ONE* 9:e97132.
- Hagen, C. A. 2011. Predation on greater sage-grouse: facts, process, and effects. *Studies in Avian Biology* 38:95–100.
- Hagen, C. A., J. W. Connelly, and M. A. Schroeder. 2007. A meta-analysis of greater sage-grouse (*Centrocercus urophasianus*) nesting and brood-rearing habitats. *Wildlife Biology* 13:42–50.
- Harju, S. M., M. R. Dzialak, R. C. Taylor, L. D. Hayden-Wing, and J. B. Winstead. 2010. Thresholds and time lags in effects of energy development on greater sage-grouse populations. *Journal of Wildlife Management* 74:437–448.
- Harrell, F. E., K. L. Lee, R. M. Califf, D. B. Pryor, and R. A. Rosati. 1984. Regression modelling strategies for improved prognostic prediction. *Statistics in Medicine* 3:143–152.
- Hess, J. E., and J. L. Beck. 2012. Disturbance factors influencing greater sage-grouse lek abandonment in north-central Wyoming. *Journal of Wildlife Management* 76:1625–1634.
- Holloran, M. J. 2005. Greater sage-grouse (*Centrocercus urophasianus*) population response to natural gas field development in western Wyoming. Dissertation, University of Wyoming, Laramie, USA.
- Holloran, M. J., R. C. Kaiser, and W. A. Hubert. 2010. Yearling greater sage-grouse response to energy development in Wyoming. *Journal of Wildlife Management* 74:65–72.
- Homer, C. G., J. A. Dewitz, L. Yang, S. Jin, P. Danielson, G. Xian, J. Coulston, N. D. Herold, J. D. Wickham, and K. Megown. 2015. Completion of the 2011 National Land Cover Database for the conterminous United States—representing a decade of land cover change information. *Photogrammetric Engineering and Remote Sensing* 81:345–354.
- Johnson, D. H. 1980. The comparison of usage and availability measurements for evaluating resource preference. *Ecology* 61:65–71.
- Kirol, C. P., J. L. Beck, S. V. Huzurbazar, M. J. Holloran, and S. N. Miller. 2015. Identifying greater sage-grouse source and sink habitats for conservation planning in an energy development landscape. *Ecological Applications* 25:968–990.
- Koper, M., and M. Manseau. 2009. Generalized estimating equations and generalized linear mixed-effects models for modeling resource selection. *Journal of Applied Ecology* 46:590–599.
- LeBeau, C. W., G. D. Johnson, M. J. Holloran, J. L. Beck, R. M. Nielson, M. F. Kauffman, E. J. Rodemaker, and T. L. McDonald. 2017. Greater sage-grouse habitat selection, survival, and wind energy infrastructure. *Journal of Wildlife Management* 81:690–711.
- Liesenfeld, Z. J. 2012. Investigation of sagebrush reclamation success on bentonite mined areas in the Big Horn Basin (Wyoming, USA). Thesis, University of Wyoming, Laramie, USA.
- Lippitt, L., M. W. Fidelibus, and D. A. Bainbridge. 1994. Native seed collection, processing, and storage for revegetation projects in the western United States. *Restoration Ecology* 2:120–131.
- Liston, G. E., and K. Elder. 2006a. A distributed snow-evolution modeling system (SnowModel). *Journal of Hydrometeorology* 7:1259–1276.
- Liston, G. E., and K. Elder. 2006b. A meteorological distribution system for high-resolution terrestrial modeling (MicroMet). *Journal of Hydrometeorology* 7:217–234.
- Lockyer, Z. B., P. S. Coates, M. L. Casazza, S. Espinosa, and D. J. Delehanty. 2015. Nest-site selection and reproductive success of greater sage-grouse in a fire-affected habitat of northwestern Nevada. *Journal of Wildlife Management* 79:785–797.
- Longland, W. S., and S. L. Bateman. 2002. Viewpoint: the ecological value of shrub islands on disturbed sagebrush rangelands. *Journal of Range Management* 55:571–575.
- Lyon, A. G., and S. H. Anderson. 2003. Potential gas development impacts on sage grouse nest initiation and movement. *Wildlife Society Bulletin* 31:486–491.
- Manly, B. F. J., L. L. McDonald, D. L. Thomas, T. L. McDonald, and W. P. Erickson. 2002. Resource selection by animals: statistical design and analysis for field studies. Second edition. Kluwer Academic, Boston, Massachusetts, USA.
- Mazerolle, M. J. 2017. AICcmodavg: model selection and multimodel inference based on (Q)AIC(c). R package version 2.1—<https://CRAN.R-project.org/package=AICcmodavg>. Accessed 15 Jul 2017.
- McAdoo, J. K., C. S. Boyd, and R. L. Sheley. 2013. Site, competition, and plant stock influence transplant success of Wyoming big sagebrush. *Rangeland Ecology and Management* 66:305–312.
- McCune, B., and D. Keon. 2002. Equations for potential annual direct incident radiation and heat load. *Journal of Vegetation Science* 13:603–606.
- Monsen, S. B. 1992. The competitive influences of cheatgrass (*Bromus tectorum*) on site restoration. Symposium on Ecology, Management, and Restoration of Intermountain Annual Rangelands, Boise, Idaho, USA.
- Monsen, S. B., S. E. Meyer, and S. L. Carlson. 1992. Sagebrush establishment enhanced by snowfencing. Pages 6–8 in Rangeland Technology Equipment Council 1992 Annual Report. Technology and Development Program 2200-Range. U.S. Forest Service, Technology and Development Center, Missoula, Montana, USA.
- Morris, L. R., T. A. Monaco, and R. L. Sheley. 2011. Land-use legacies and vegetation recovery 90 years after cultivation in Great Basin sagebrush ecosystems. *Rangeland Ecology and Management* 64:488–497.
- Musselman, R. C., W. D. Shepperd, F. W. Smith, and L. A. Asherin. 2014. Survival and growth of aspen and serviceberry planted on reclaimed surface mined land with landscape fabric and irrigation. *Journal of American Society of Mining and Reclamation* 3:16–40.
- Northrup, J. M., M. B. Hooten, C. R. Anderson Jr., and G. Wittemyer. 2013. Practical guidance on characterizing availability in resource selection functions under a use-availability design. *Ecology* 94:1456–1463.
- Pan, W. 2001. Akaike's Information Criterion in generalized estimating equations. *Biometrics* 57:120–125.
- Pratt, A. C. 2017. Partial migration, habitat selection, and the conservation of greater sage-grouse in the Bighorn Basin of Montana and Wyoming. Dissertation, University of Wyoming, Laramie, USA.

- Pratt, A. C., K. T. Smith, and J. L. Beck. 2017. Environmental cues used by greater sage-grouse to initiate altitudinal migration. *Auk: Ornithological Advances* 134:628–643.
- PRISM Climate Group. 2016. PRISM Climate Data. <http://www.prism.oregonstate.edu/>. Accessed 15 Jun 2016.
- Qi, J., A. Chehbouni, A. R. Huete, Y. H. Kerr, and S. Sorooshian. 1994. A modified soil adjusted vegetation index. *Remote Sensing of Environment* 48:119–126.
- R Core Team. 2015. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.
- Sappington, J. M., K. M. Longshore, and D. B. Thompson. 2007. Quantifying landscape ruggedness for animal habitat analysis: a case study using bighorn sheep in the Mojave Desert. *Journal of Wildlife Management* 71:1419–1426.
- SAS Institute. 2012. The SAS system for windows version 9.4. SAS Institute, Cary, North Carolina, USA.
- Schoenfeld, D. 1982. Residuals for the proportional hazards regression model. *Biometrika* 69:239–241.
- Schroeder, M. A., C. A. Aldridge, A. D. Apa, J. R. Bohne, C. E. Braun, S. D. Bunnell, J. W. Connelly, P. A. Deibert, S. C. Gardner, M. A. Hilliard, G. D. Kobriger, S. M. McAdam, C. W. McCarthy, J. J. McCarthy, D. L. Mitchell, E. V. Rickerson, and S. J. Stiver. 2004. Distribution of sage-grouse in North America. *Condor* 106: 63–376.
- Schuman, G. E., and S. E. Belden. 2002. Long-term survival of direct seeded Wyoming big sagebrush seedlings on a reclaimed mine site. *Arid Land Research and Management* 16:309–317.
- Schuman, G. E., D. T. Booth, and J. R. Cockrell. 1998. Cultural methods for establishing Wyoming big sagebrush on mined lands. *Journal of Range Management* 51:223–230.
- Schuman, G. E., E. J. DePuit, and K. M. Roadifer. 1994. Plant responses to gypsum amendments of sodic bentonite mine spoil. *Journal of Rangeland Management* 47:206–209.
- Schuman, G. E., E. J. DePuit, J. A. Smith, and L. A. King. 1985. Reclamation of bentonite mined lands in the Northern Great Plains. *Environment Geochemistry and Health* 7:42–47.
- Shaw, N. L., A. M. DeBolt, and R. Rosentreter. 2005. Reseeding big sagebrush: techniques and issues. USDA Forest Service Proceedings RMRS P38. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado, USA.
- Sieg, C. H., D. W. Uresk, and R. M. Hansen. 1983. Plant-soil relationships on bentonite mine spoils and sagebrush-grassland in the Northern High Plains. *Journal of Range Management* 36: 289–294.
- Smith, J. T., J. S. Evans, B. H. Martin, S. Baruch-Mordo, J. M. Kiesecker, and D. E. Naugle. 2016a. Reducing cultivation risk for at-risk species: predicting outcomes of conservation easements for sage-grouse. *Biological Conservation* 201:10–19.
- Smith, K. T., J. L. Beck, and A. C. Pratt. 2016b. Does Wyoming's Core Area policy protect winter habitats for greater sage-grouse? *Environmental Management* 58:585–596.
- Smith, K. T., C. P. Kirol, J. L. Beck, and F. C. Blomquist. 2014. Prioritizing winter habitat quality for greater sage-grouse in a landscape influenced by energy development. *Ecosphere* 5:art15.
- Sowls, L. K. 1948. The Franklin ground squirrel, *Citellus franklinii* (Sabine), and its relationship to nesting ducks. *Journal of Mammalogy* 29:113–137.
- State of Montana. 2015. Executive order amending and providing for implementation of the Montana sage grouse conservation strategy. Office of the Governor, Executive Order No. 12-2015, Helena, Montana, USA.
- State of Wyoming. 2015. Greater sage-grouse core area protection. Executive Department, Executive Order 2015-4, Cheyenne, Wyoming, USA.
- Stiver, S. J. 2011. The legal status of greater sage-grouse: organizational structure of planning efforts. *Studies in Avian Biology* 38:33–49.
- Taylor, R. L., B. L. Walker, D. E. Naugle, and L. S. Mills. 2012. Managing multiple vital rates to maximize greater sage-grouse population growth. *Journal of Wildlife Management* 76:336–347.
- Therneau, T. M. 2015. coxme: mixed effects Cox models. R package version 2. 2-5. <https://CRAN.R-project.org/package=coxme>. Accessed 15 Jul 2015.
- U.S. Fish and Wildlife Service [USFWS]. 2010. Endangered and threatened wildlife and plants: 12-month findings for petitions to list the greater sage-grouse (*Centrocercus urophasianus*) as threatened or endangered. *Federal Register* 75:13909–14014.
- U.S. Fish and Wildlife Service [USFWS]. 2015. Endangered and threatened wildlife and plants; 12-month finding on a petition to list greater sage-grouse (*Centrocercus urophasianus*) as an endangered or threatened species. *Federal Register* 80:59858–59942.
- Wakkinen, W. L., K. P. Reese, J. W. Connelly, and R. A. Fischer. 1992. An improved spotlighting technique for capturing sage grouse. *Wildlife Society Bulletin* 20:425–426.
- Walker, B. L., A. D. Apa, and K. Eichhoff. 2016. Mapping and prioritizing seasonal habitats for greater sage-grouse in northwestern Colorado. *Journal of Wildlife Management* 80:63–77.
- Walker, B. L., D. E. Naugle, and K. E. Doherty. 2007. Greater sage-grouse population response to energy development and habitat loss. *Journal of Wildlife Management* 71:2644–2654.
- Western Association of Fish and Wildlife Agencies. 2015. Greater sage-grouse population trends: an analysis of lek count databases 1965–2015. Western Association of Fish and Wildlife Agencies, Cheyenne, Wyoming, USA.
- Wyoming Mining Association. 2016. Wyoming Mining Association. <http://www.wyomingmining.org>. Accessed 15 Jan 2016.

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