Distance effects of gas field infrastructure on pygmy rabbits in southwestern Wyoming

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Abstract. As domestic energy development activity continues in the western United States, wildlife conservation planning in affected regions is increasingly important. The geologic basins where oil and gas energy exploration is occurring are primarily sagebrush steppe rangelands. Sagebrush steppe habitats may support more than 20 vertebrate species of conservation concern, and for many of these species, information is lacking on the effects of gas energy development. In earlier work, we demonstrated a negative relationship among development density of gas field infrastructure and pygmy rabbits (Brachylagus idahoensis). We now examine the spatial relationship among gas field infrastructure, pygmy rabbits, and their habitat on four major gas fields in southwest Wyoming. Using data collected from 120 plots over three years (2011–2013) and 2012 National Agriculture Imagery Program (NAIP) imagery, we evaluated (1) whether well pads are more likely to be located in areas of pygmy rabbit habitat, (2) whether the presence and abundance of pygmy rabbits are related to distance from infrastructure, and, if so, (3) how much of the total surface area on a gas field is affected. Well pads on three gas fields occurred in higher quality pygmy rabbit habitat than did a set of randomly generated points, and the abundance and probability of pygmy rabbits being present were lower within approximately 0.5–1.5 km of the nearest road and 2 km of well pads and utilities. Buffering a digital layer of roads and well pads on one gas field revealed that nearly 82% of the (4417 km²) surface area was within 1 km of infrastructure, and over 95% of the gas field surface area was within 2 km. This need not be the case on future gas fields. Directional and horizontal well drilling technologies now make it possible for gas to be recovered from a greater area per well pad, enabling future gas field developments that require fewer well pads, roads, and pipeline corridors. Such changes would enable increased well pad spacing and provide the opportunity to locate gas field infrastructure in areas of poor quality wildlife habitat, avoid high priority habitat, and conserve a greater amount of on-field wildlife habitat overall.

Key words: Brachylagus idahoensis; distance thresholds; gas energy development; gas field infrastructure; gas field planning; habitat conversion; pygmy rabbit; Wyoming.

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INTRODUCTION

In addition to historic impacts associated with Euro-American settlement, sagebrush ecosystems have been increasingly altered as road systems, transmission line networks, and energy extraction activities have expanded to meet recent societal demands (Leu et al. 2008, Theobald 2013, Venter et al. 2016). As economic, political, and social pressures continue to mount in
the sagebrush biome, sagebrush habitats will continue to be adversely impacted (Chambers and Wisdom 2009). For example, Utah, Nevada, and Idaho were the USA’s fastest growing states in 2016; the human population in Utah is projected to increase by 180% by 2065; and the America First Energy Plan calls for reducing environmental protection policy while aggressively pursuing fossil fuel reserves on federal lands (Anonymous 2016, U.S. Census Bureau 2017, The White House 2017). The effects on ecological systems of continued human population growth and energy resource extraction in the Great Basin region are complex and poorly understood at best (Torregrosa and DeVoe 2008).

In reporting their decision that the pygmy rabbit (Brachylagus idahoensis) did not warrant federal protection, the U.S. Fish and Wildlife Service (USFWS) explained that while oil and gas energy development activity was occurring in all three major geologic basins within the pygmy rabbit range of distribution, their interpretation of the existing information was that oil and gas energy extraction had little potential to negatively impact pygmy rabbits (Federal Register 2010:60546). In a review of the potential impact of energy and residential development on sensitive wildlife in Wyoming, Pocewicz et al. (2014) also considered pygmy rabbits only moderately vulnerable. While not explicitly stated in either report, both appeared to be gauging the degree to which the energy development footprint might directly overlap pygmy rabbit habitat across broad landscapes. However, an estimated 3.7 million ha of additional sagebrush habitat may be directly impacted by new oil and gas energy development, and adverse impacts on species that inhabit sagebrush habitats must be anticipated (Cope et al. 2009), and planned for.

Pygmy rabbits are a Species of Greatest Conservation Need in every state where they occur except in Washington, where they are endangered (USFWS 2015). Highly reliant on big sagebrush (Artemesia tridentata) for food and cover, pygmy rabbits typically associate with tall, dense stands of big sagebrush on deep, friable soils (Katzner and Parker 1997, Gabler et al. 2001, Ulmschneider et al. 2004). This combination of habitat features typically occurs on the lower sections of hillsides and in basin bottoms where soils are deeper. Concern over the long-term cumulative effects of sagebrush habitat loss and degradation was the primary impetus that led the USFWS to formally consider pygmy rabbits for listing (Federal Register 2010).

It is becoming clear that pygmy rabbits are adversely impacted by sagebrush habitat fragmentation (Lee 2008) and that the impacts extend beyond the physical footprint of disturbance. Pygmy rabbits shift habitat use away from fragmented edges associated with energy development as well as other sources of habitat fragmentation (Wilson 2010, Pierce et al. 2011, Edgel 2013). Pygmy rabbits have been documented on gas fields (Estes-Zumpf et al. 2009), but little was known about the effects of oil and gas energy development on pygmy rabbits at the time of the USFWS listing decision. Since then, an empirical analysis of pygmy rabbit survey data from southwestern Wyoming demonstrated that otherwise-suitable pygmy rabbit habitat became less suitable as gas field road density increased (Germaine et al. 2014). After modeling the relationship between gas field development density and pygmy rabbits, Germaine et al. (2017) found that pygmy rabbits experienced sharp declines in abundance and became more likely to be absent than present once ~1.5–2% of the surface area on gas fields had been converted to gas field infrastructure (i.e., roads, well pads, buried utilities).

While conceptualizing the current study, we surmised that wise gas field planning—optimizing the efficiency of gas field development with regard to traffic flow and commodity extraction—would likely result in gas field roads and wells being positioned in the lower portion of basins and hillsides when possible. Doing so would minimize the vertical drilling distance from the surface to oil and gas reserves and minimize the total vertical relief that trucks and other heavy equipment would traverse on a daily basis. However, it is the lower portion of hillsides and basin bottoms where soils are deepest and sagebrush tallest, making these areas potentially the most suitable pygmy rabbit habitat as well.

In addition, a number of other species of elevated conservation concern breed in or otherwise inhabit patches of tall sagebrush vegetation and may be impacted by gas energy development. Brewer’s sparrows (Spizella breweri) and sagebrush sparrows (Artemisiospiza nevadensis)
became less abundant near gas field roads (Ingelfinger and Anderson 2004) and were inversely related to well density, as were vesper sparrows (Poecetes gramineus; Gilbert and Chalfoun 2011). Greater sage-grouse (Centrocercus urophasianus) and mule deer (Odocoileus hemionus), two species undergoing long-term declines, have both demonstrated avoidance of gas well pads and other gas field infrastructure and have not shown evidence of habituating over time (Green et al. 2017, Sawyer et al. 2017).

Our goal in this study was to examine the spatial relationship among gas field infrastructure, pygmy rabbits, and their habitat on four major gas fields in southwest Wyoming, a focal area for domestic gas energy development and a region where gas energy development is expected to intensify through 2035 (National Petroleum Council 2007, CREG 2015). In earlier work, we found that 4.9–13.5% of the pre-existing shrub steppe vegetation on individual gas fields was converted to gas field infrastructure such as roads, well pads, and pipelines (Germaine et al. 2017). Pairing this observation with the distance-based effects observed by others (summarized above), we now ask whether pygmy rabbits are affected by proximity to gas energy infrastructure and if so, what proportion of the vegetated areas remaining on developed gas fields might no longer be part of the realized niche for pygmy rabbits? With this question guiding us, our specific objectives were to evaluate: (1) whether individual well pads within a gas field are more likely to be located in areas of modeled suitable pygmy rabbit habitat than would be expected at random, (2) whether the presence and abundance of pygmy rabbits are related to the distance from the nearest gas field infrastructure, and, if so, (3) how much area on a gas field remains unaffected by development. Finally, because there are a number of other sensitive sagebrush-obligate wildlife species present in the system we studied, we asked (4) whether well pads are more likely to be located in tall, dense sagebrush stands than would be expected at random.

**Study Area and Methods**

Detailed descriptions of our study area, pygmy rabbit surveys, and digitization of our study area gas fields are presented elsewhere (Germaine et al. 2017), and we summarize these details here. This study was conducted in four major gas energy development areas in southwest Wyoming: the Continental Divide–Creston–Blue Gap (CCB), Jonah, Moxa Arch, and Pinedale Anticline Project Area (PAPA) gas fields in Carbon, Lincoln, Sublette, and Sweetwater counties, Wyoming (Fig. 1).

Area topography is rolling hills, washes and ephemeral drainages, and basins. Predominant soils are mixed loams, with Tertiary shales and sandstones the predominant geologic parent material (Munn and Arneson 1998). The area is primarily shrub steppe habitat, predominantly covered by Wyoming big sagebrush (Artemisia tridentata wyomingensis) and Basin big sagebrush (A. t. tridentata), with rabbit brush (Chrysothamnus spp.) co-dominant in some areas. Understory vegetation is primarily grass–forb (Beetle and Johnson 1982, Knight 1994, Davies et al. 2006). Big sagebrush inhabits deep, well-drained soils (Thatcher 1959, West 1988) and covers broad expanses across mesic basins, but is patchily distributed in more xeric areas (Knight 1994). Area elevation ranges from 1915 to 2291 m.

We surveyed pygmy rabbits during 2011–2013 at 33, 29, 28, and 30 plots on the CCB, Jonah, Moxa Arch, and PAPA gas fields, respectively, for a total of 120 plots. Plots were distributed among five strata that encompassed the range of well pad density present on each field based on a digital point file of existing gas wells (Biewick et al. 2011) and then randomly located within the area defined by each strata. This resulted in 6–10 randomly located plots per well pad density strata on each gas field. Plots were on public land, within 4.4 km of the perimeter of energy development (based on a minimum convex polygon bounding all well pads) on each field, and separated from one another by ≥1 km. Each plot was 400 × 400 m in size and contained >50% high-quality pygmy rabbit habitat based on the Wyoming Natural Diversity Database predictive pygmy rabbit species distribution model (WGFD 2010).

We surveyed all plots for pygmy rabbits and their sign during May–September 2011, July–November 2012, and June–September 2013. We surveyed each plot twice per year for two consecutive years, searching all patches of potential
pygmy rabbit habitat in the plot as well as all potential habitat within 50 m of the external plot boundary. Sign included live pygmy rabbits, their pellets, burrows, and trails. Surveyors were trained by an experienced pygmy rabbit biologist and provided with a sample of pygmy rabbit, cottontail (*Sylvilagus* spp.), and jackrabbit (*Lepus townsendii*) pellets for reference. Sign was screened on site to determine whether it met criteria specific to pygmy rabbits (UDWR 2003, Ulmschneider et al. 2004, MNHP 2008) and categorized as fresh or old (Ulmschneider et al. 2004, Sanchez et al. 2009). Confirmed sign was recorded with corresponding UTM location coordinates.

To consider a plot occupied by pygmy rabbits, we required that one of the following combinations of sign be observed within a 40 m diameter area during at least one of the two surveys of the plot in any one year: two or more live pygmy rabbits, or any two of the following: a live pygmy rabbit, an active pygmy rabbit burrow, or an active trail segment (required to terminate at a burrow or be associated with pygmy rabbit pellets) showing signs of recent pygmy rabbit use; or any of these types of sign combined with fresh pygmy rabbit pellets. We set these criteria to reduce the possibility of interpreting sign associated with dispersing juveniles as an occupied plot because our interest was in plots containing...
resident pygmy rabbits. We indexed pygmy rabbit abundance by tallying the number of active burrows present, with the final index value for the year being an average of the values calculated for each of the two surveys conducted in that year.

Our initial study identified well pads, adjacent areas disturbed during pad installation and well drilling activities, roads connecting well pads to main roads, and buried utility (pipe) lines as the primary factors impacting pygmy rabbits on gas fields, and it is these infrastructure elements that we focus on in this study (Table 1). These and all other gas field infrastructure were attributed and digitized from 2012 National Agriculture Imagery Program imagery (NAIP 2012) and a digital dataset of oil and gas well pad scars (Garman and McBeth 2014) using ArcGIS (version 10.3.1), where all infrastructure within a 1 km (3.14 km²) radius buffer originating at the centroid of unoccupied pygmy rabbit survey plots and at the point associated with the greatest concentration of fresh pygmy rabbit sign on occupied plots were digitized. We measured the area covered by shrub steppe vegetation using a high-resolution map of rangeland vegetative cover types in Wyoming (Homer et al. 2009) after masking out all areas converted to gas field infrastructure. Attributes in the Homer et al. (2009) vegetation dataset include the percent cover of shrub vegetation, of which sagebrush is the primary component.

To evaluate the spatial distribution of gas well pads relative to the distribution of modeled pygmy rabbit habitat (objective 1), we selected a random sample of 200 well pads and generated a random sample of 200 points on each gas field. To help ensure spatial independence, both well pads and random points were separated by at least 1 km, except on the Jonah and PAPA gas fields where 500 and 600 m minimum spacing was enforced, respectively, due to the denser spacing of well pads. We then identified the slope, elevation (obtained from the National Elevation Dataset available at: https://www.usgs.gov/lands/resources/eros/edna), and pygmy rabbit habitat suitability value associated with each selected well pad and random point based on an existing pygmy rabbit habitat suitability model (WGFD 2010). The WGFD (2010) model uses only climatic, edaphic, and vegetative predictor variables and does not account for anthropogenic disturbances when predicting habitat suitability. We then compared the frequency distributions of pygmy rabbit habitat suitability, slope, and elevation values for well pads and for random points using Kolmogorov-Smirnov tests. We also compared the average habitat suitability value between well pads and random points on each gas field via two sample t-tests, using 1-tailed probabilities because we anticipated finding gas well pads at lower slope and elevation, and higher habitat suitability values. These tests were conducted using Systat (Systat 2007) software.

To understand how pygmy rabbit presence and abundance varied with distance to gas field infrastructure (objective 2), we measured straight-line distances from plot focal points (i.e., locations of pygmy rabbit sign and centroids of unoccupied plots) to the nearest well pad, gas field road (inclusive of all roads having graded, improved beds, and open to traffic), buried utility line, and disturbance element of any type. We then used boosted regression trees (BRT; Elith

| Infrastructure element | Definition |
|------------------------|------------|
| Buried utility         | Surface area associated with underground pipelines used to transport gas and other extracted commodities |
| Well pad†              | Area of compacted soil containing gas well head, pumps, storage tanks, and other gas energy extraction infrastructure |
| Well pad residual disturbance† | Disturbed area adjacent to a well pad where original vegetation was removed and top soil and vehicles were kept during drilling. Areas were either reseeded or not at the time of our surveys |
| Road classes 210 and 209 | Surface improved with a loose gravel surface, and surface improved with a maintained loose or hardened surface; generally, these roads connected main travel arteries with gas well pads (i.e., spur roads) or are main arteries on gas fields, county highways, and primary Bureau of Land Management and U.S. Forest Service roads |

Note: Gas fields included the Continental Divide–Creston–Blue Gap (CCB), Jonah, Moxa Arch, and Pinedale Anticline Project Area (PAPA) fields. † These two variables were merged prior to data summarization and analysis and are referred to as well pads in this paper.
et al. 2008) to model the distance relationship between each element type and pygmy rabbit presence, and between each element type and pygmy rabbit abundance. We first analyzed the relationship between pygmy rabbits (presence, abundance) and the nearest gas field infrastructure element of any kind. We then modeled the relationship between pygmy rabbits and distances to three distinct gas field infrastructure elements (buried utilities, well pads, and roads) to identify which infrastructure elements were most influential in explaining differences in pygmy rabbit presence and abundance. We constructed eight models: one model for each response variable (presence, index of abundance) and each set of covariates (nearest element of any kind, nearest specific element) in each of the two survey years. We used BRT for all analyses and fit the models using a learning rate of 0.001, a tree complexity of 3 (fits a model with three-way interactions), and a bag fraction of 0.75 using the gbm package in R (Ridgeway 2013) and code written by Elith et al. (2008). We used ten-fold cross-validation to identify the optimal number of trees for the model (Elith et al. 2008). Variable importance was evaluated based on the contribution to model fit attributable to each explanatory variable, averaged across all trees; importance values for all variables in a model sum to 100% (Friedman et al. 2000). Covariates included in each model were calendar year (to account for any inter-annual variation due to weather related influences or other factors not captured by our variables), gas field, and the shrub variable that was identified as most influential for each survey year in our previous analysis of rabbit presence (i.e., shrub cover >10% in survey year 1, and shrub cover >13% in survey year 2, see Germaine et al. [2017] for details). Once we modeled the distance relationships, we buffered well pads and roads (the two infrastructure elements for which we had wall-to-wall digital coverage across our gas fields) by threshold distances (at which pygmy rabbits began to decline) identified by the BRT models and then summed the amount of unaffected area remaining (objective 3). We did this only for the CCB gas field, which has the lowest well density of the four fields we studied.

To determine the relationship between well pad locations and sagebrush cover and height in general (objective 4), we used an approach similar to objective 1. However, here we selected a random sample of well pads from among those for which we had pre-disturbance data on percent canopy cover and height of big sagebrush (Homer et al. 2012), and contrasted pre-disturbance attribute values against those at the random points used in objective 1. As in objective 1, minimum spacing of sampled well pads was 1 km for Moxa and CCB, 600 m for PAPA, and 500 m for the Jonah gas field. Sample sizes were limited by the size of gas fields and density of well pads within them. At each sampled location, we recorded the big sagebrush height and percent canopy cover values associated with each pixel and then compared the distributions of each variable between well pads and random points on each gas field using Kolmogorov-Smirnov and 1-tailed tests as in objective 1.

### Results

Well pads were distributed less frequently in poor pygmy rabbit habitat and more frequently in suitable pygmy rabbit habitat than expected by chance on one gas field (PAPA K-S = 0.18, \(P = 0.003\)), but did not differ on the other three gas fields (Moxa Arch K-S = 0.11, \(P = 0.22\); Jonah K-S = 0.95, \(P = 0.33\); CCB K-S = 0.10, \(P = 0.33\); Fig. 2A). Average pygmy rabbit habitat suitability values were higher at well pads than at random points on three of the four gas fields (Table 2).

Well pads were distributed more frequently on flatter slopes than were our random points on one gas field (PAPA K-S = 0.18, \(P = 0.003\)), but the distribution of slopes did not differ between well pads and random points on the remaining three gas fields (Moxa Arch K-S = 0.10, \(P = 0.270\); CCB K-S = 0.11, \(P = 0.220\); Jonah K-S = 0.90, \(P = 0.393\); Fig. 2B). Average slope values were flatter at well pads than at random points on three gas fields, while on the fourth gas field this difference was marginally significant (Table 2). However, the actual difference in slope values between well pads and random points was in all cases less than one degree, which is likely of little biological significance.

On one gas field, well pads occurred less frequently at lower elevations and more frequently...
at mid-elevations than randomness would predict (CCB K-S = 0.165, P = 0.009), while on three gas fields the frequency distribution of well pad elevations did not differ from random (Jonah K-S = 0.11, P = 0.178; Moxa Arch K-S = 0.11, P = 0.220; PAPA K-S = 0.10, P = 0.270; Fig. 2C). The average elevation at well pads on two gas fields was lower than the average elevation of random points, but this was not the case on the remaining two gas fields, and in all cases, the difference was <10 m and therefore of questionable biological significance (Table 2).

Our models relating pygmy rabbits with distance to the nearest gas field infrastructure explained 25–26% of the variability in rabbit presence, and 28–33% of the variability in rabbit abundance (pseudo $r^2$ values, Table 3), with the gas field and distance to infrastructure variables having the highest importance values in nearly all models. Partial dependence plots are useful
for interpreting the relationship between explanatory and response variables and indicated a positive relationship between increasing distance from the nearest gas field infrastructure element and both presence and abundance of pygmy rabbits across both survey years. That is, presence and abundance of rabbits began to decrease with increasing proximity to the nearest gas field infrastructure element, beginning at approximately 700 m–1 km distant for presence and abundance, respectively (Fig. 3).

We then modeled the relationship between pygmy rabbits and the distance to individual gas field infrastructure. Our models including gas field, calendar year, shrub cover, and distance to individual gas field infrastructure explained 22–33% of the variability in rabbit presence and 41–46% of the variability in rabbit abundance (pseudo $r^2$ values; Appendix S1: Table S1). Increasing proximity to roads, well pads, and utility lines nearly always corresponded with lower probability of presence and abundance of pygmy rabbits, with effects apparent within approximately 0.5–1.5 km of roads and 2 km of well pads and utilities (Fig. 4). Identifying one type of infrastructure that was most influential to pygmy rabbits proved difficult. BRT importance values indicated that distance to roads and to well pad complexes each ranked highest in two of the four models. However, distance effects on pygmy rabbits were greatest for well pad complexes and utilities (Fig. 4). Once we identified these distance thresholds, we buffered well pads and roads on the CCB gas field (the least-densely developed gas field in our study) to distances of 1 and 2 km, based on our distance-modeling results. Nearly 82% of the area on this gas field lies within 1 km of a gas well pad and road, and over 95% of the gas field area lies within 2 km of a well pad or road (Fig. 5).

Well pads did not occur more frequently in areas of taller shrubs than did our random points on any of the gas fields (PAPA K-S = 0.11, $P = 0.627$; Moxa K-S = 0.10, $P = 0.350$; Jonah K-S = 0.08, $P = 0.856$), although there was a trend in this direction on the CCB gas field (K-S = 0.13, $P = 0.085$). Average shrub height at well pads and random points also did not differ on any gas field (Table 4). Gas well pads occurred more frequently in areas containing high percent cover of big sagebrush than randomness would predict on the PAPA gas field (K-S = 0.20, $P = 0.042$), but not on the other three gas fields (Moxa K-S = 0.11, $P = 0.223$; Jonah K-S = 0.12, $P = 0.308$; CCB K-S = 0.08, $P = 0.617$). Average percent cover of big sagebrush vegetation at gas well pads and random locations on each of four gas fields (Continental Divide–Creston–Blue Gap [CCB], Jonah, Moxa Arch, and Pinedale Anticline Project Area [PAPA]) in southwestern Wyoming, 2011–2013.

| Gas field     | Random site (mean ± 1 SE) | Well pad (mean ± 1 SE) | t Score | $P$‡ |
|---------------|---------------------------|------------------------|--------|-----|
| Habitat suitability†‡ |                           |                        |        |     |
| CCB           | 0.383 ± 0.016             | 0.426 ± 0.016          | −1.863 | 0.032 |
| Jonah         | 0.752 ± 0.005             | 0.758 ± 0.005          | −0.945 | 0.173 |
| Moxa Arch     | 0.500 ± 0.018             | 0.544 ± 0.016          | −1.855 | 0.032 |
| PAPA          | 0.656 ± 0.016             | 0.737 ± 0.010          | −4.274 | <0.001 |
| Slope         |                           |                        |        |     |
| CCB           | 2.10 ± 0.190              | 1.66 ± 0.099           | 2.042  | 0.021 |
| Jonah         | 1.92 ± 0.112              | 1.68 ± 0.101           | 1.580  | 0.057 |
| Moxa Arch     | 2.24 ± 0.176              | 1.78 ± 0.146           | 2.013  | 0.022 |
| PAPA          | 2.71 ± 0.189              | 1.83 ± 0.100           | 4.164  | <0.001 |
| Elevation§    |                           |                        |        |     |
| CCB           | 130.21 ± 3.913            | 141.12 ± 3.564         | −2.062 | 0.980 |
| Jonah         | 45.81 ± 1.333             | 42.70 ± 1.237          | 1.710  | 0.044 |
| Moxa Arch     | 108.01 ± 3.697            | 98.86 ± 3.444          | 1.810  | 0.036 |
| PAPA          | 109.24 ± 3.625            | 113.78 ± 4.147         | −0.822 | 0.794 |

‡ One-tailed probability values, Bonferroni adjusted for comparisons across 4 gas fields.
§ Based on probability values reported in WGFD (2010).
† Meters above base elevation on each gas field.

Table 2. Mean values of pygmy rabbit (Brachylagus idahoensis) habitat suitability, slope, and elevation at well pads and random locations on each of four gas fields (Continental Divide–Creston–Blue Gap [CCB], Jonah, Moxa Arch, and Pinedale Anticline Project Area [PAPA]) in southwestern Wyoming, 2011–2013.
pads did not differ on any of the gas fields (Table 4).

**DISCUSSION**

We used empirical data to evaluate how the spatial arrangement of gas field features influenced pygmy rabbits and their habitat. We found evidence that gas well pads converged on modeled pygmy rabbit habitat: Gas well pads occurred more frequently in suitable pygmy rabbit habitat and less frequently in poor pygmy rabbit habitat than random points did on one gas field, and average pygmy rabbit habitat suitability values were higher at well pads than at random points on three of the four gas fields we studied. Also, the influence of gas field infrastructure on pygmy rabbits extended far beyond the physical disturbance footprint. Pygmy rabbit presence and abundance were lower as far as 2 km from the nearest gas well pad, road, or utility corridor. We were unable to identify a single type of gas field infrastructure which had the greatest distance effects on pygmy rabbits, and we conclude that roads, well pad complexes, and buried utility corridors were all highly influential, with distance effects extending the greatest distances from well pad complexes and buried utilities.

Our spatial buffers represented the distances from gas field well pads and roads at which pygmy rabbit presence and abundance declined relative to populations occurring farther away. On the 4,417-km² CCB gas field, 95% of the surface area fell within 2 km of built gas field infrastructure; after accounting for distance effects extending beyond the margins of well pads and gas field roads, only 4.7% of the gas field area remained unaffected. Due to natural variation in soils and vegetation, the residual 4.7% unaffected area may not all be suitable pygmy rabbit habitat. Had we buffered a digital layer representing buried utility lines (we digitized utility corridors within our plot buffers on each gas field, but a wall-to-wall layer did not exist for entire gas fields at the time of our study), the amount of affected area would have been even greater. Finally, it is worth noting that the CCB was the least-densely developed gas field that we studied, and it is likely that the proportion of affected area is greater on the other gas fields.

The effects of habitat disturbances on pygmy rabbits have been studied in relatively few settings. Working in a mosaic study area where big sagebrush cover had been reduced by mechanical treatments on approximately 50–60% of the acreage (Greenwood 2004), Lee (2008) documented decreased pygmy rabbit use of disturbed stands relative to undisturbed areas, and Pierce et al. (2011) recorded less pygmy rabbit sign ≤100 m from the disturbed habitat edge than farther from it. Lee (2008) also observed that pygmy rabbit use of large, continuous remnant sagebrush stands was higher than use of fragmented patches of sagebrush.

The system that Lee (2008) and Pierce et al. (2011) studied was one in which treated areas

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**Table 3. Importance of predictor variables, including distance to the nearest gas field infrastructure element, in explaining variability in pygmy rabbit (Brachylagus idahoensis) presence and a pygmy rabbit abundance index in southwest Wyoming between 2011 and 2013.**

| Variable | Presence, survey year 1 (pseudo $r^2$: 0.25) | Presence, survey year 2 (pseudo $r^2$: 0.26) | Abundance index, survey year 1 (pseudo $r^2$: 0.28) | Abundance index, survey year 2 (pseudo $r^2$: 0.33) |
|----------|---------------------------------------------|---------------------------------------------|---------------------------------------------|---------------------------------------------|
| Gas field (%) | 42.0 | 59.6 | 44.5 | 42.1 |
| Distance to nearest gas field infrastructure element (%) | 36.7 | 26.6 | 23.9 | 43.6 |
| Shrub cover (%) | 15.4 | 12.8 | 31.5 | 14.2 |
| Calendar year (%) | 5.9 | 1.0 | 0.1 | 0.1 |

**Notes:** We report values for four models: a model for each survey year (1 and 2) for presence and for the abundance index. A single vegetation variable was included in each model: shrub cover >10% in models for survey year 1 and shrub cover >13% for survey year 2 models (see Methods). Importance values for all metrics in each model sum to 100%.
Fig. 3. Partial dependence plots from boosted regression tree models showing the relation between the presence of pygmy rabbits and distances to gas field infrastructure. Partial dependence plots show the response for a single variable in the model while holding all other variables constant. The top two plots show the relation between pygmy rabbit presence, gas field, shrub cover, and the distance to the nearest gas field infrastructure (all elements pooled) in sample years 1 (A) and 2 (B). The bottom two plots show the relationship between presence and the distance to three specific types of infrastructure in sample years 1 (C) and 2 (D). Y axes for all graphs are on a logit scale and are centered to have a mean response of zero over the data distribution. Tick marks along the top of the plots indicate the distribution of values in the dataset. Plots for each model are shown in order (from left to right) of variable importance. See Table 3 and Appendix S1: Table S1 for importance values for all predictors in each model.
Fig. 4. Partial dependence plots from boosted regression tree models showing the relation between an index of pygmy rabbit abundance (based on number of burrows) and distances to gas field infrastructure. Partial dependence plots show the response for a single variable in the model while holding all other variables constant. The top two plots show the relation between the abundance index, gas field, shrub cover, and the distance to the nearest gas field infrastructure (all elements pooled) in sample years 1 (A) and 2 (B). The bottom two plots show the relationship between the abundance index and the distance to three specific types of infrastructure in sample years 1 (C) and 2 (D). Tick marks along the top of the plots indicate the distribution of values in the dataset. Plots for each model are shown in order (from left to right) of variable importance. See Table 3 and Appendix S1: Table S1 for importance values for all predictors in each model.
experienced 40–90% reductions in big sagebrush density (Greenwood, 2004). Within the footprint of gas field infrastructure, there is 100% conversion to a de-vegetated state, and areas adjacent to gas field infrastructure are often disturbed, effecting a landscape mosaic with high contrast between disturbed and undisturbed patches. Edgel et al. (2018) studied the spatial distribution of radio-tagged pygmy rabbits along one such disturbance, a gas pipeline right of way, before, during, and after installation of the pipeline. For pygmy rabbits living adjacent to the right of way, core use-areas shrank in size and centers of activity moved farther from the right of way after construction; movements across the right of way declined once construction began and remained depressed after construction was complete (Edgel et al. 2018). Working in a different disturbed system, Wilson (2010) also found that pygmy rabbit home range activity moved farther away from stand thinning treatments and that pygmy rabbits became less likely to enter treated areas. Although some disturbed areas on gas fields are reseeded (e.g., utility corridors, borrow areas, areas adjacent to well pads), these areas may not possess vegetative characteristics required by pygmy rabbits for decades (BLM 2007). Other infrastructures such as roads, well

Fig. 5. Continental Divide–Creston–Blue Gap Gas Field, south-central Wyoming. Shown are the gas field road network and buffered areas extending 1 and 2 km from roads (see legend). Areas shaded purple represent the residual 5% of area on this gas field more than 2 km away from a nearest road. We found that pygmy rabbit (Brachylagus idahoensis) presence and abundance were lower within 1–2 km of a road, gas well pad, or buried utility line. A wall-to-wall digital utility line data layer did not exist at the time of our study, so these were not buffered in this exercise.
pads, and equipment parking areas are maintained in a de-vegetated state for the effective life of the gas field.

Our last objective explored the potential for gas field infrastructure to occur in big sagebrush habitats that possessed height and canopy closure characteristics capable of supporting other sagebrush-obligate wildlife. Brewer’s sparrows (S. breweri), sagebrush sparrows (A. nevadensis), sage thrashers (Oreoscoptes montanus), greater sage-grouse (C. urophasianus), and other wildlife associate with patches of tall, dense sagebrush during at least one season (Martin and Carlson 1998, Reynolds et al. 1999, Rotenberry et al. 1999) and may therefore be vulnerable to gas energy development of these areas (e.g., Ingelfinger and Anderson 2004, Gilbert and Chalfoun 2011). We found no evidence that gas well pads were located more frequently in areas characterized simply by having greater shrub heights or greater big sagebrush cover on any of the gas fields. Pygmy rabbit burrows occur more often on flatter slopes (Weiss and Verts 1984, Gabler et al. 2001), and on a local scale (i.e., a gas field), pygmy rabbits occur more frequently at lower elevations (Wilde 1978, Himes and Drohan 2007) where soils are deeper. While slope may affect pygmy rabbit energetics, big sagebrush stands generally occur on low gradient slopes and are taller at the lower local elevations where soils are deepest (Knight 1994).

The trends identified in our models relating pygmy rabbits with proximity to disturbance were overwhelmingly negative. However, our year-1 model trend lines suggest slightly elevated pygmy rabbit presence and abundance close to roads and gas well pads. Because of our study design, some rabbit survey plots in areas with a low overall density of gas well development were randomly located close to a well pad or a road and contained higher numbers of rabbits. It may be that close proximity to a well pad or road may have a lower impact on pygmy rabbits if the overall density of gas field infrastructure in the vicinity is low. Pygmy rabbits also appear able to persist in small patches of habitat, albeit in reduced numbers (Lee 2008, Pierce et al. 2011), although the ability of pygmy rabbits to persist over time in disturbed habitat fragments on gas fields and elsewhere remains to be studied.

**Conclusions**

We found gas field well pads to be located within areas of modeled suitable pygmy rabbit habitat more often than by chance, and the damping effects of gas field infrastructure on pygmy rabbit numbers extended 0.6–2 km beyond the element footprint. Accounting for surface area within these threshold distances, as little as 5% of the land area on a gas field may remain unimpaired for pygmy rabbits under current gas field design standards. This need not be the case on future gas fields. Emerging directional and horizontal well drilling technologies offer the potential for gas to be recovered from a greater area per well pad (Applegate and Owens 2014), resulting in a need for fewer well pads, roads, and pipeline corridors (Garman 2017). Future gas field planning could also capitalize on flexible well pad spacing configurations to position well pads and roads in areas of poor quality wildlife habitat, avoid high priority habitat patches, and conserve a greater amount of on-field wildlife habitat overall (Garman 2017).

The number of gas wells in the SW Wyoming region is expected to continue to increase

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**Table 4. Mean values for shrub height and percent big sagebrush cover at well pads and random locations on each of four gas fields in southwestern Wyoming, 2011–2013.**

| Gas field | Random site (mean ± 1 SE) | Well pad (mean ± 1 SE) | t Score | P† |
|-----------|---------------------------|------------------------|---------|----|
| Shrub height (cm) | | | | |
| CCB       | 15.60 ± 0.575            | 14.59 ± 0.611          | −1.198  | 0.884 |
| Jonah     | 22.43 ± 0.663            | 22.61 ± 0.735          | 0.183   | 0.427 |
| Moxa      | 16.28 ± 0.427            | 15.43 ± 0.315          | −1.601  | 0.945 |
| Arch      | 22.50 ± 0.644            | 21.80 ± 0.943          | −0.614  | 0.730 |
| Big sagebrush cover (%) | | | | |
| CCB       | 6.75 ± 0.334             | 6.35 ± 0.322           | −0.847  | 0.801 |
| Jonah     | 13.01 ± 0.428            | 12.83 ± 0.463          | −0.288  | 0.613 |
| Moxa      | 4.06 ± 0.259             | 3.81 ± 0.303           | −0.623  | 0.733 |
| Arch      | 11.74 ± 0.422            | 12.86 ± 0.666          | 1.419   | 0.079 |

*Note: Differences are considered statistically significant at P ≤ 0.05.*
† One-tailed test with Bonferroni-adjusted probability values.
through 2035 (CREG 2015). The most effective wildlife conservation strategy at the landscape scale involves minimizing the energy development footprint, avoiding high priority wildlife habitats, and reducing anthropogenic activity during sensitive biological periods (Northrup and Wittemyer 2013, Jones et al. 2015). Landscape scale planning for locating gas fields notwithstanding, minimizing the surface area converted to on-field infrastructure during gas field development, and locating gas field infrastructure away from pygmy rabbit habitat may lessen the impacts of gas energy development on pygmy rabbits.

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