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Evaluating the impact of gas extraction infrastructure on the occupancy of sagebrush-obligate songbirds

Max Mutter,[1,3] David C. Pavlacky, Jr.,[2] Nicholas J. Van Lanen,[2] and Richard Grenyer[1]

[1]*University of Oxford, School of Geography and the Environment, Oxford Centre for the Environment (Dyson Perrins Building),*
South Parks Road, Oxford OX1 3QY United Kingdom
[2]*Rocky Mountain Bird Observatory, 14500 Lark Bunting Lane, Brighton, Colorado 80603 USA*

Abstract. Development associated with natural gas extraction may have negative effects on wildlife. Here we assessed the effects of natural gas development on the distributions of three sagebrush-obligate birds (Brewer's Sparrow, *Spizella breweri*; Sagebrush Sparrow, *Amphispiza belli*; and Sage Thrasher, *Oreoscoptes montanus*) at a natural gas extraction site in Wyoming, USA. Two drivers of habitat disturbance were investigated: natural gas well pads and roadways. Disturbances were quantified on a small scale (minimum distance to a disturbance) and a large scale (landscape density of a disturbance). Their effects on the study species' distributions were assessed using a multi-scale occupancy model. Minimum distances to wells and roadways were found to not have significant impacts on small-scale occupancy. However, roadway and well density at the landscape-scale significantly impacted the large-scale occupancy of Sagebrush Sparrows and Sage Thrashers. The results confirmed our hypotheses that increasing road density negatively affects the landscape-scale occupancy rates of Sagebrush Sparrow and Sage Thrasher, but did not confirm our hypothesis that increasing well density would negatively impact large-scale occupancy. We therefore suggest that linear features that affect patch size may be more important than point features in determining sagebrush-obligate songbird occupancy when compared to structural effects such as habitat fragmentation and increased predation. We recommend that future well construction be focused along existing roadways, that horizontal drilling be used to reduce the need for additional roads, and that deactivation and restoration of roadways be implemented upon the deactivation of wells, we also recommend a possible mitigation strategy when new roads are to be built.

Key words: Amphispiza belli; *Brewer's Sparrow; gas infrastructure; multi-scale occupancy; natural gas;* Oreoscoptes montanus; *roads; sagebrush; Sagebrush Sparrow; Sage Thrasher; songbirds;* Spizella breweri.

Introduction

The extraction and consumption of natural gas have risen in the United States since the mid-1980s. Natural gas is now second only to petroleum in terms of U.S. energy production (USEIA 2012). This trend stands to continue into the future as the majority of known natural gas deposits in the developed world lie within U.S. borders and new opportunities are opening for international trade of U.S. natural gas (Chow et al. 2003, Johnson and Lefebrve 2013). In U.S. states, like Wyoming, which contain large natural gas deposits and have governments that rely heavily on tax income from resource extraction, it is important to assess how the added pressures of natural gas development projects will influence wildlife (Ingelfinger and Anderson 2004).

Many of the U.S. natural gas deposits lie in areas dominated by sagebrush (*Artemisia* spp.) landscapes (Gilbert and Chalfoun 2011), which provide habitat for over 350 species of plants and animals during one or more stages of their life cycle (Connelly et al. 2004). Scientists have witnessed drastic declines in several sagebrush-obligate species (Magee et al. 2011), including declines in abundance or spatial distribution of Brewer's Sparrow (*Spizella breweri*), Sagebrush Sparrow (*Artemisiospiza nevadensis*), and Sage Thrasher (*Oreoscoptes montanus*) (Dobkin and Sauder 2004). Evidence exists that energy-related development is contributing to this decline (Ingelfinger and Anderson 2004, Bayne et al. 2008, Gilbert and Chalfoun 2011).

The infrastructure associated with natural gas extraction comprises pumping equipment sited on concrete well pads and associated road networks for transportation, maintenance, and construction. The abundance of sagebrush-obligate songbirds has been shown to decline along roads associated with natural gas extraction (Ingelfinger and Anderson 2004). The presence of a road can cause some taxa to exhibit road avoidance behavior, alter both the physical and chemical environments, and facilitate the introduction of nonnative

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[3] E-mail: mfmutter@gmail.com

TABLE 1. Mean minimum distances to roads and natural gas well pads for all point count sites and mean road and natural gas well pad densities within a 2-km buffer measured from the center point of every grid cell in the high- and low-development strata in the Atlantic Rim Natural Gas Development Project Area, Wyoming, USA.

Covariates	High development	SE	Low development	SE
Minimum distance to road (km)	0.145	0.008	0.127	0.010
Minimum distance to well (km)	1.033	0.060	1.415	0.068
Road density (km/km^2)	2.634	0.166	2.785	0.244
Well density (wells/km^2)	1.210	0.382	0.481	0.165

species, leading to increases in competition with native species (Trombulak and Frissell 2000, Frair et al. 2008, van der Ree et al. 2011). Additionally, road networks can fragment large areas of continuous habitat into several smaller patches (Reed et al. 1996, Saunders et al. 2002). Such fragmentation has been shown to negatively affect many sagebrush-obligate songbirds that prefer large patch sizes (CalPIF 2004, Hansley and Beauvais 2004).

The construction and operation of well pads for resource extraction may also negatively impact some avian species. Anthropogenic noise has been shown to impede the activities of important seed dispersers, thus affecting the composition and functioning of the surrounding ecology (Francis et al. 2009). Anthropogenic noise has also been shown to decrease nesting success of passerines and alter vocal behavior (Parris and Schneider 2008). Passerines are much more likely to avoid noisy man-made structures than silent ones (Bayne et al. 2008); this has been observed specifically in relation to natural gas well pads (Francis et al. 2009). Additionally, well pad structures provide perches and potential nesting sites for raptors and nest predators such as Common Ravens (*Corvus corax*), which have been found in higher densities surrounding natural gas well pads (Ingelfinger and Anderson 2004).

Most previous studies investigating the effects of natural gas extraction and associated roadways on passerines focus on small-scale effects (Ingelfinger and Anderson 2004, Francis et al. 2009, 2011). To our knowledge no study has attempted to investigate both large-scale landscape changes and local impacts of gas development on sagebrush-obligate songbirds simultaneously. Additionally, previous studies have investigated either the impacts of roadways or the impacts of well pads and not attempted to isolate the effect of one vs. the other. Because these two features can be highly correlated in areas where natural gas extraction is ongoing, we feel it is important to explicitly evaluate the relative impacts of both roads and well pads on sagebrush-obligate occupancy simultaneously. Here we used detection data on three species of sagebrush-obligate songbirds (Brewer's Sparrow, *Spizella breweri*; Sagebrush Sparrow, *Amphispiza belli* (see Plate 1); and Sage Thrasher, *Oreoscoptes montanus*) to assess the relative effects of road and natural gas developments on the occupancy of these species at both the local and landscape scales in order to better inform management decisions and potential mitigation procedures.

METHODS

Study site

Our study was conducted on a mixture of private lands and public lands managed by the U.S. Bureau of Land Management (BLM) that fully contained the Atlantic Rim Natural Gas Development Project (ARIM) in southern Wyoming, USA. The 1093-km^2 study area was located south of Rawlins, Wyoming, between Highways 789 and 71 and bordered to the south by Highway 70. The vegetation of the study area was composed of shrub–steppe and semidesert shrubland dominated by mountain big sagebrush (*Artemisia tridentata*) and Wyoming big sagebrush (*A. tridentata wyomingensis*).

Sampling design

Prior to data collection, the ARIM study site was divided into two distinct strata; one stratum represented areas expected to undergo high levels of development and the other represented areas likely to be developed at a lower intensity. Predicted levels of development and subsequent stratification were based upon locations of existing roads and natural gas well pads, areas representing important wintering habitat for large ungulates, Greater Sage-Grouse (*Centrocercus urophasianus*) lek concentrations, and areas where the BLM believed companies were concentrating development efforts and activities (F. Blomquist, *personal communication*). Observed development generally followed the predictions with a higher average well pad density in the high-development stratum compared to the low-development stratum, while road densities were similar across the strata (Table 1). The sampling frame consisted of the set of 1-km^2 sampling units within the low- and high-development strata. Within each stratum, we used a spatially balanced sampling algorithm known as generalized random-tessellation stratification (Stevens and Olsen 2004) to select the 1-km^2 sampling units. The high- and low-development stratification was intended to balance sampling across a gradient of road and well pad densities. Sixteen sampling units were within the high-development stratum, and 15 sampling units were within the low-development stratum. The majority of wells in the area were constructed from 2008 onward, with new well construction concentrated in the high-development stratum. The sampling design followed the Integrated Monitoring in Bird Conservation Regions (IMBCR) framework of visual and aural detections with 16 point count stations nested within the 1-km^2 sampling unit (Hanni et al. 2012). The point count stations were arranged in a 4 × 4 matrix and were evenly spaced 250 m apart (Hanni et al. 2012). The point count plots consisted of nonoverlapping circular plots each with a radius of 125 m (5 ha).

Data collection

Avian detection data were collected between 15 May and 8 July of 2010, 2011, and 2012. In 2010, the high-development stratum was sampled more intensively than the low-development stratum. Beginning in 2011, the strata were sampled equally to improve the power to detect a difference between the strata (Table 2). Field technicians conducted 6-min point counts at the point count stations within a grid cell. Occasionally not all 16 point count stations within a grid cell were visited because permission could not be obtained to survey private lands, inclement weather during the survey, or an inability to adequately hear bird vocalizations because of ambient or road noise. A total of 62 grid cells and 726 point counts were completed throughout the three-year study (Table 2). Point counts were conducted during the morning; beginning one-half hour before sunrise and concluding no later than 11:00 hours Mountain Standard Time (MST). Surveyors recorded all birds detected visually and aurally, the distance from the observer to the bird with the use of a laser rangefinder, and the time within the count that the detection occurred.

We measured several covariates to represent the extent of oil and gas development at the local and landscape scales. We obtained natural gas well pad locations in 2012 from the Wyoming Oil and Gas Conservation Commission (WOGCC; data *available online*).[4] The Rawlins BLM Field Office provided a Geographic Information System (GIS) layer from digitized orthophotos and paper maps of roadways created from data collected in 2006. Improved (gravel) roads as well as primitive (two-track) roads were distinguished from each other in the attribute tables. Well pad and road locations were plotted along with the locations of visited point count stations using GIS (ESRI 2010). At the local scale, we calculated the minimum distance (km) between point count stations, and roads and well pads within the GIS environment. To measure covariates at landscape scale, we centered a circular 2 km radius buffer (12.6 km^2) on the mean Universal Transverse Mercator coordinates for the centroid of the grid. The 2 km radius was chosen to characterize landscape-scale impacts, because previous research indicated that habitat loss and fragmentation measured at this scale explained the occupancy rates of small understory-dwelling bird species (Westphal et al. 2007, Pavlacky et al. 2012). We calculated road density (km of road per km^2) and well pad density (number of well pads per km^2) within the landscape buffer. The road and well pad distances at the local scale ($\rho = -0.06$, $P = 0.05$), and road and well pad densities at the landscape scale ($\rho = 0.23$, $P = 0.08$) exhibited low Spearman rank correlation. The minimum distance to, and densities of, well pads and roads served as covariates in the occupancy models. Additionally, we used the low- and high-development strata and year of study as categorical group covariates.

TABLE 2. The number of 1-km^2 grid cells visited by year and strata in 2010, 2011, and 2012 in the Atlantic Rim Natural Gas Development Project Area, Wyoming, USA.

Strata	Year 2010	Year 2011	Year 2012	Total
High development	15 (153)	8 (121)	13 (175)	36 (449)
Low development	5 (56)	8 (88)	13 (133)	26 (277)
Total	20 (209)	16 (209)	26 (308)	62 (726)

Notes: The total number of point count stations visited by year and strata are shown in parentheses. Each 1-km^2 grid cell contained 16 evenly spaced point count stations. In some instances, not all of the point count stations within a grid cell were visited due to inclement weather or other uncontrollable circumstances. The study area was divided into areas of high and low development by the U.S. Bureau of Land Management.

Data analysis

We used a hierarchical, multi-scale occupancy model (Nichols et al. 2008) to approximate the nested hierarchy of the sampling design; with minute intervals nested within points counts, point counts nested within sampling grids, and sampling grids nested within the study areas (Pavlacky et al. 2012). The multi-scale occupancy model estimated the probability of detection p_i for grid cell i given the grid cell and point count plot were occupied, the probability of occupancy θ_r for point count plot r given the grid cell was occupied and the probability of occupancy ψ_i for grid cell i (Pavlacky et al. 2012). We interpreted ψ as large-scale occupancy, or the proportion of grid cells occupied within the landscape, and θ as small-scale occupancy, or the proportion of point count plots occupied when the grid cell was occupied (Pavlacky et al. 2012). The multi-scale occupancy model accounts for variation between the occupancy state of the grids, which allows the valid estimation of occupancy for non-independent points count plots within and between grids (Pavlacky et al. 2012).

Considering the home range sizes of the species (Brewer's Sparrow = 0.55–2.36 ha, Sage Thrasher = 0.81–5.81 ha, Sagebrush Sparrow = 0.65–5.81 ha; Poole 2005), the occupancy rate of the point count plots (4.9 ha) represented a conservative estimate of the number of

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[4] http://wogcc.state.wy.us/

territories within a grid cell (number of territories $= \hat{\theta} \times$ 16 point count plots) (Pavlacky et al. 2012). The occupancy rate of the grid cells represented a landscape-scale measure of resource use or range contraction, and subsumed all point count and detection information within each grid. We selected multi-scale occupancy as the state variables for investigating bird responses to oil and gas development at the territory and landscape scales because these population parameters reflect critical aspects of resource use and range contraction where abundance goes from at least one individual to zero (MacKenzie et al. 2006).

We binned each six-minute point count into three separate two-minute intervals and used a removal design to estimate the detection rates of singing birds (Pavlacky et al. 2012). Accordingly, once the target species was detected in a time interval, the subsequent time intervals were set to missing data (MacKenzie et al. 2006). The removal design was necessary because the bird detections in the minute intervals were collected without replacement. For example, if an individual was detected in time interval one, then the species was recorded, but if the same individual was detected in subsequent time intervals, then the species was not recorded. Program PRESENCE (Hines 2006) was the primary modeling environment for the model selection analysis. In addition, we fit the identical model using the RMark interface (R Development Core Team 2012, Laake 2013) for program MARK (White and Burnham 1999) to generate the occupancy predictions for the graphs. Because the Brewer's Sparrow occurred at every grid cell, we used the sine link function for this species to estimate the large-scale occupancy parameters for the $\psi(.)$, ψ(development), and ψ(year) models. The sine link performs better than the logit link when the parameter estimates are near the boundary of zero or one (White and Burnham 1999).

We used a sequential model-building strategy to determine the strength of evidence for a priori hypotheses for each species (Lebreton et al. 1992, Doherty et al. 2010). The global model for the analysis was

$$p(\text{develop} + \text{year})$$

$$\theta(\text{develop} + \text{road distance} + \text{well distance} + \text{year})$$

$$\psi(\text{develop} + \text{road density} + \text{well density} + \text{year}).$$

First, we built detection models using all subsets of covariates for p, while holding θ and ψ constant at the global models (four models). Next, we constructed small-scale models using all subsets of covariates for θ, while holding p constant at the most parsimonious detection model and ψ constant at the global model (16 models). Last, we built large-scale models using all subsets of covariates for ψ, while holding p and θ constant at the most parsimonious models (16 models). In addition, we evaluated post hoc hypotheses for the effect of an interaction between road and well density on the large-scale occupancy of the species. We constructed the post hoc model set by adding the interaction term to all models containing the road and well density covariates (eight models). A large interaction effect between road density and well density would provide evidence for the hypothesis that well density negatively affected occupancy rates at low or high road density.

Model selection and multi-model inference

We used information-theoretic model selection (Burnham and Anderson 2002) and ranked candidate models according to the Akaike information criterion (Akaike 1973) adjusted for sample size (AIC$_c$; Hurvich and Tsai 1989). We measured strength of evidence for alternate hypotheses using AIC$_c$ weights (w_i) and quantified the likelihood of modeled hypotheses given the data using evidence ratios (w_i/w_j). We conservatively used the number of grid cells sampled across years ($n = 62$) as our effective sample size for all calculations. We achieved multi-model inference by model averaging the beta parameter estimates ($\hat{\bar{\beta}}$) and the estimated occupancy rates ($\hat{\bar{\psi}}$), and we estimated unconditional standard errors for the entire candidate set models (Burnham and Anderson 2002). We quantified the importance of the covariates using cumulative AIC$_c$ weights [$w_+(j)$]. We gauged strength of evidence for effect sizes by evaluating the model-averaged beta parameter estimates ($\hat{\bar{\beta}}$) with respect to zero using unconditional 95% confidence intervals (Burnham and Anderson 2002).

Hypotheses and model justification

We used the method of multiple working hypotheses (Chamberlin 1965) to develop alternate hypotheses for the effects of oil and gas development on the occupancy rates of the Brewer's Sparrow, Sagebrush Sparrow, and Sage Thrasher. We allowed detection probability to vary by both the development strata and year covariates to account for spatial and temporal variation in detection probabilities. We predict the detection rates of species may differ by development strata or year if bird abundances and noise associated with development vary by strata or year. In addition, crew members often varied by year, and modeling detection by year may allow us to account for annual observer effects. We used local and landscape covariates to model oil and gas development hypotheses for each species. The effects of local covariates on small-scale occupancy reflected oil and gas disturbance at the local territory scale, while the effects of covariates on large-scale occupancy corresponded to oil and gas disturbance at the landscape scale. We allowed the small-scale occupancy (θ) parameter to vary by the development, year, distance from well, and distance from road covariates. We included the development and year covariates in the model set for estimating θ and ψ because the samples were drawn from a stratified design within each development

Plate 1. Sagebrush Sparrow *Amphispiza belli*. Photo credit: Bill Schmoker.

stratum and year combination. This approach allowed us to evaluate changes in occupancy rates associated with the expected level of development within and between years. To investigate the effect of oil and gas development at the local territory scale, we hypothesized that the small-scale occupancy of the species would (1) increase with increasing distance to road, (2) increase with increasing distance to well pad, (3) be greater in the low-development than the high-development strata, and (4) vary by year. These hypotheses follow previous research that indicates road and well pad development facilitates invasive species introduction, depredation, noise, and other disturbances that would negatively affect songbirds immediately adjacent to these developments (Trombulak and Frissell 2000, Ingelfinger and Anderson 2004, Francis et al. 2009). We used the development strata and year hypotheses to control for spatial and temporal variation in small-scale occupancy when evaluating the road and well pad hypotheses. We allowed the large-scale occupancy (ψ) parameter to vary by the development, year, well density, and road density covariates. To investigate the impacts of oil and gas development at the larger landscape scale, we hypothesized that the large-scale occupancy of Sage Thrashers and Sagebrush Sparrows would (1) decrease with increasing road density, (2) decrease with increasing well pad density, (3) be greater in the low-development than the high-development strata, and (4) vary by year. These hypotheses follow previous research that indicates high well pad densities disadvantage sagebrush-obligate songbirds (Gilbert and Chalfoun 2011) and that roads fragment large habitat patches into smaller ones, which are much less preferable to the species in our study (Saunders et al. 2002, CalPIF 2004, Hansley and Beauvais 2004). We did not evaluate hypotheses for the large-scale occupancy of the Brewer's Sparrow because this species was present at all grid cells.

Results

Detection

The best approximating detection model for the Brewer's Sparrow included a constant rate of detection ($\hat{p} = 0.83$, SE = 0.02; $w_i = 0.69$). The evidence ratio (ratio of the AIC_c weights for the models) indicated this model was two times more probable than the second best model including the effect of development ($w_i = 0.26$). The development strata [$w_+(j) = 0.29$] and year [$w_+(j) = 0.13$] demonstrated low ability to predict the detection rates of Brewer's Sparrows.

The best model for the detection of the Sagebrush Sparrow included the effects of development strata and

TABLE 3. Model selection for the small-scale occupancy (θ) of the Brewer's Sparrow (BRSP; *Spizella breweri*), Sagebrush Sparrow (SAGS; *Amphispiza belli*), and Sage Thrasher (SATH; *Oreoscoptes montanus*) in the Atlantic Rim Natural Gas Development Project Area, Wyoming, USA.

Model	K	$-2\log(L)$	AIC_c	ΔAIC_c	w_i
BRSP†					
θ(develop + year)	8	1329.74	1348.51	0.00	0.442
θ(develop + year + road distance)	9	1327.79	1349.32	0.81	0.295
θ(develop + year + well distance)	9	1329.66	1351.19	2.68	0.116
θ(develop + year + road dist + well distance)	10	1327.69	1352.09	3.58	0.074
SAGS‡					
θ(year + develop)	14	536.43	573.37	0.00	0.395
θ(year)	13	541.69	575.27	1.90	0.153
θ(year + develop + well distance)	15	535.69	576.12	2.75	0.100
θ(.)	11	549.15	576.43	3.06	0.086
θ(year + develop + road distance)	15	536.41	576.84	3.47	0.070
SATH§					
θ(develop)	11	906.10	933.38	0.00	0.465
θ(develop + road distance)	12	904.52	934.89	1.51	0.218
θ(develop + road + well distance)	13	901.76	935.34	1.96	0.174

Notes: The model selection metrics are the value of the minimized −2 log-likelihood function [$-2\log(L)$], number of parameters (K), Akaike information criterion adjusted for sample size (AIC_c), difference between model and minimum AIC_c values (ΔAIC_c), and AIC_c weight (w_i). Models with $\Delta\text{AIC}_c < 4$ are shown. Small-scale occupancy was interpreted as the proportion of point count plots occupied when the grid cell was occupied. Well distance refers to minimum distance to a well, and road distance refers to minimum distance to a road.

† All models were held constant at p(.) and ψ(road density + well density), where p is the probability of detection, and ψ is large-scale occupancy.

‡ All models were held constant at p(develop + year) and ψ(develop + road density + well density + year).

§ All models were held constant at p(year) and ψ(develop + road density + well density + year).

year ($w_i = 0.45$). There was nearly equal support ($\Delta\text{AIC}_c = 0.44$) for the second best model containing a constant rate of detection. Nevertheless, Sagebrush Sparrow detection was lower in the high-development than in the low-development stratum ($\hat{\hat{\beta}} = -1.47$; CI = −2.94, 0.00), and detection was lower in 2010 than in 2012 (the best model for the detection of the $\hat{\hat{\beta}} = -1.75$; CI = −2.58, −0.91), but detection in 2011 was similar to detection in 2012 ($\hat{\hat{\beta}} = 0.42$; CI = −1.03, 1.88). The development stratum [$w_+(j) = 0.59$] was the best predictor of Sagebrush Sparrow detection followed by year [$w_+(j) = 0.50$].

The best detection model for Sage Thrashers included the effect of year ($w_i = 0.63$). There was nearly three times more evidence for this model than for the second best model (a constant rate of detection; $w_i = 0.22$). The detection rate of Sage Thrashers was lower in 2010 than in 2012 ($\hat{\hat{\beta}} = -1.33$; CI = −2.23, −0.42), but detection in 2011 was similar to detection in 2012 ($\hat{\hat{\beta}} = -0.62$; CI = −1.54, 0.29). The year covariate [$w_+(j) = 0.87$] was the best predictor of Sage Thrasher detection, with less support for development strata [$w_+(j) = 0.16$].

Small-scale occupancy

We confirmed the hypothesis that the small-scale occupancy of Brewer's Sparrows varied by year and the hypothesis that occupancy was lower in the high-development stratum than in the low-development stratum. We found little support for the hypotheses that the small-scale occupancy of Brewer's Sparrows increased with increasing distance from roads or wells. The best approximating model for the small-scale occupancy of the Brewer's Sparrow contained the effects of year and development strata (Table 3). Brewer's

TABLE 4. Model-averaged parameter estimates, and unconditional lower (LCL) and upper (UCL) 95% confidence limits for the small-scale occupancy of the Brewer's Sparrow (BRSP), Sagebrush Sparrow (SAGS), and Sage Thrasher (SATH) in the Atlantic Rim Natural Gas Development Project Area, Wyoming, USA.

	BRSP			SAGS			SATH		
Parameter	Estimate	LCL	UCL	Estimate	LCL	UCL	Estimate	LCL	UCL
Development	−0.51	−0.87	−0.15	1.03	0.08	1.99	0.83	0.33	1.33
Road distance	−0.98	−2.33	0.37	−0.47	−2.75	1.81	−0.94	−2.45	0.56
Well distance	−0.02	−0.23	0.19	0.13	−0.24	0.49	−0.19	−0.42	0.04
Year 2010	0.96	0.52	1.41	2.08	−0.35	4.50	0.31	−0.21	0.84
Year 2011	−0.05	−0.44	0.34	1.01	0.21	1.82	0.09	−0.39	0.56

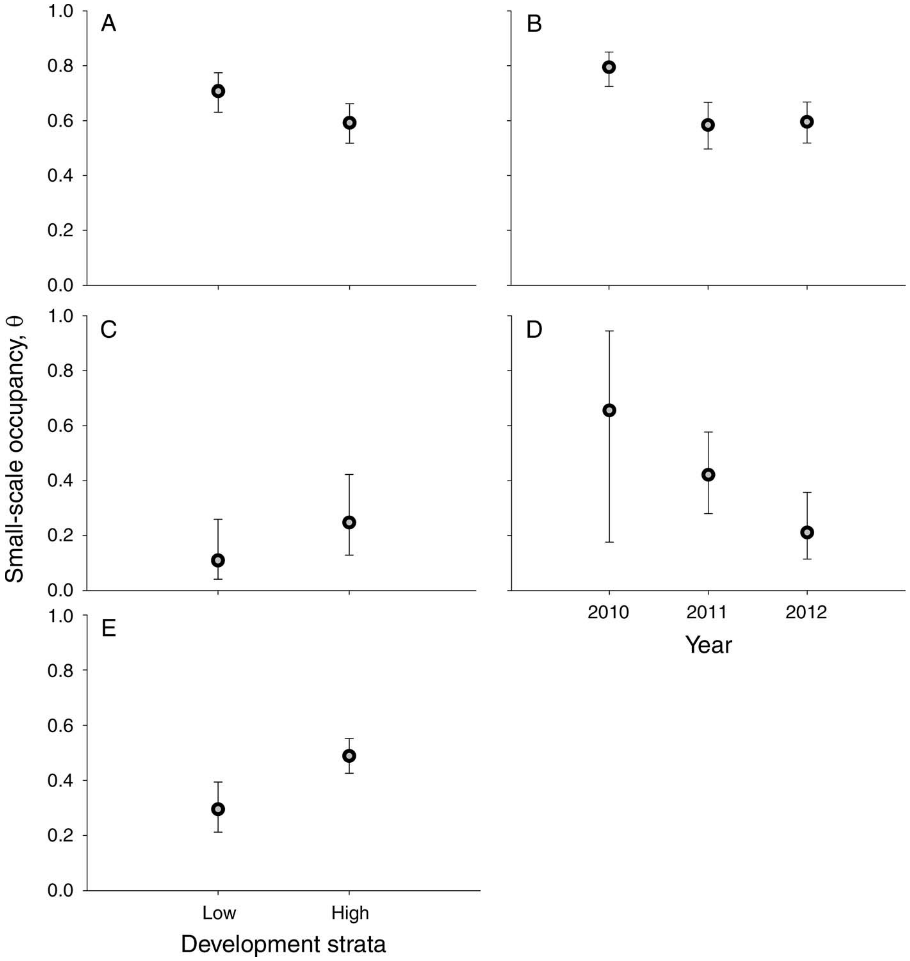

FIG. 1. The estimated probability of small-scale occupancy (θ) for the Brewer's Sparrow (*Spizella breweri*) by (A) development strata in 2012 and (B) year in the high-development stratum, for the Sagebrush Sparrow (*Amphispiza belli*) by (C) development strata in 2012 and (D) year in the high-development stratum, and for the (E) Sage Thrasher (*Oreoscoptes montanus*) for 2012 in the high-development stratum. The symbols are model-averaged estimates of occupancy at mean values for the other continuous covariates in the model, and the error bars are unconditional 95% confidence intervals.

Sparrow occupancy at point count locations was greater in 2010 than in 2012 and occupancy was lower in the high-development than in the low-development stratum (Table 4, Fig. 1). The CIs for all these effects excluded zero, indicating these variables likely impacted the estimated occupancy rates (Table 4). There was nearly equal support for the second best model including the effect of road distance (Table 3). However, the CI for the effect of road distance in this model overlapped zero, providing little support for an effect of road distance on small-scale Brewer's Sparrow occupancy (Table 4). The evidence ratio (ratio of the $\mathrm{AIC_c}$ weights for the models) showed the best model was three times more probable than the third best model, which included the distance to well covariate (Table 3). Year [$w_+(j) = 1.00$] and development strata [$w_+(j) = 0.93$] were the best predictors of small-scale occupancy for the Brewer's Sparrow, with less support for road distance [$w_+(j) = 0.40$] and well distance [$w_+(j) = 0.21$].

We confirmed our hypothesis that the small-scale occupancy of Sagebrush Sparrows varied by year. We found little support for the hypotheses that small-scale Sagebrush Sparrow occupancy increased with increasing distance to roads and wells and that occupancy would be higher in the low-development stratum. The best model for small-scale Sagebrush Sparrow occupancy contained the effects of year and development strata (Table 3). There was three times more evidence for the top model than the second best model without the development covariate. The occurrence of Sagebrush Sparrows at point count locations was greater in the high-development than in the low-development stratum, and was greater in 2011 than in 2012 (Table 4, Fig. 1). The CIs for these effects excluded zero, meaning they only contained positive or negative values, and thus showed evidence for having an influence on occupancy (Table 4). Year [$w_+(j) = 0.80$] and development strata [$w_+(j) = 0.65$] were the best predictors of the small-scale

TABLE 5. Model selection for the large-scale occupancy (ψ) of the Brewer's Sparrow (BRSP), Sagebrush Sparrow (SAGS), and Sage Thrasher (SATH) in the Atlantic Rim Natural Gas Development Project Area, Wyoming, USA.

Model	K	$-2\log(L)$	AIC_c	ΔAIC_c	w_i
BRSP†					
ψ(.)	6	1330.89	1344.45	0.00	0.400
ψ(develop)	7	1329.77	1345.88	1.43	0.195
ψ(well density)	7	1330.08	1346.19	1.74	0.167
ψ(road density)	7	1330.81	1346.93	2.48	0.116
ψ(year)	8	1329.17	1347.93	3.49	0.070
SAGS‡					
ψ(road density + well density)	11	538.82	566.10	0.00	0.709
ψ(road density + well density + develop)	12	538.46	568.83	2.73	0.181
SATH§					
ψ(well density + year + road density)	10	907.46	931.77	0.00	0.499
ψ(well density + year + road density+ develop)	11	906.10	933.38	1.61	0.223
ψ(well density + year)	9	913.76	935.22	3.45	0.089
ψ(well density + road density)	8	916.77	935.49	3.72	0.078

Notes: The model selection metrics are the value of the minimized −2 log-likelihood function [$-2\log(L)$], number of parameters (K), Akaike Information Criterion adjusted for sample size (AIC_c), difference between model and minimum AIC_c values (ΔAIC_c), and AIC_c weight (w_i). Models with $\Delta\text{AIC}_c < 4$ are shown. Large-scale occupancy (ψ) was interpreted as the proportion of grid cells occupied within the landscape.

† All models were held constant at p(.) and θ(develop + year).

‡ All models were held constant at p(develop + year) and θ(develop + year).

§ All models were held constant at p(year) and θ(develop).

occupancy of Sagebrush Sparrows, with less support for road [$w_+(j) = 0.39$] and well [$w_+(j) = 0.20$] distance.

We did not find strong evidence to support any of our hypotheses regarding the small-scale occupancy of Sage Thrashers. The best model for the small-scale occupancy of Sage Thrashers contained the development strata covariate (Table 3). The evidence ratio (ratio of the AIC_c weights for the models) indicated this model was two times more probable than the second best model including the effect of road distance (Table 3). Sage Thrasher occupancy at point count locations was greater in the high-development stratum than in the low-development stratum (Table 4, Fig. 1). The CI for the high-development strata excluded zero (Table 4). The development strata [$w_+(j) = 0.98$] was the most important predictor of small-scale occupancy of Sage Thrashers, with less support for well distance [$w_+(j) = 0.47$], road distance [$w_+(j) = 0.31$], and year [$w_+(j) = 0.08$].

Large-scale occupancy

We found little support for the hypotheses that Brewer's Sparrow occupancy at the landscape scale declined with increasing road density or well pad density, or that Brewer's Sparrow occupancy varied by development strata or year (Table 5). The best approximating model for large-scale Brewer's Sparrow occupancy included a constant rate of occupancy ($\hat{\psi} = 0.98$, SE = 0.02; CI = 0.89, 1.00; Table 5). This model was two times more probable than the second best model including the effect of development strata (Table 5). The CIs for road and well density included zero, indicating small effect sizes for these covariates (Table 6).

TABLE 6. Model-averaged parameter estimates, and unconditional lower (LCL) and upper (UCL) 95% confidence limits for the large-scale occupancy of the Brewer's Sparrow (BRSP), Sagebrush Sparrow (SAGS), and Sage Thrasher (SATH) in the Atlantic Rim Natural Gas Development Project Area, Wyoming, USA.

	BRSP†			SAGS			SATH		
Parameter	Estimate	LCL	UCL	Estimate	LCL	UCL	Estimate	LCL	UCL
Development	···	···	···	−0.53	−2.28	1.22	0.90	−0.62	2.43
Road density	−0.52	−3.15	2.10	−2.24	−4.05	−0.43	−1.54	−2.89	−0.19
Well density	2.15	−5.52	9.83	1.27	0.19	2.34	3.19	0.58	5.79
Year 2010	···	···	···	1.22	−0.82	3.26	1.90	0.11	3.68
Year 2011	···	···	···	−0.04	−2.25	2.18	2.72	0.58	4.87

† We estimated the continuous road density and well density effects using an "additive" design matrix and logit link function, and the categorical development and year effects using an identity design matrix and sine link function. We did not tabulate the sine link parameters because the design matrix and link function were not comparable to the logit link parameters.

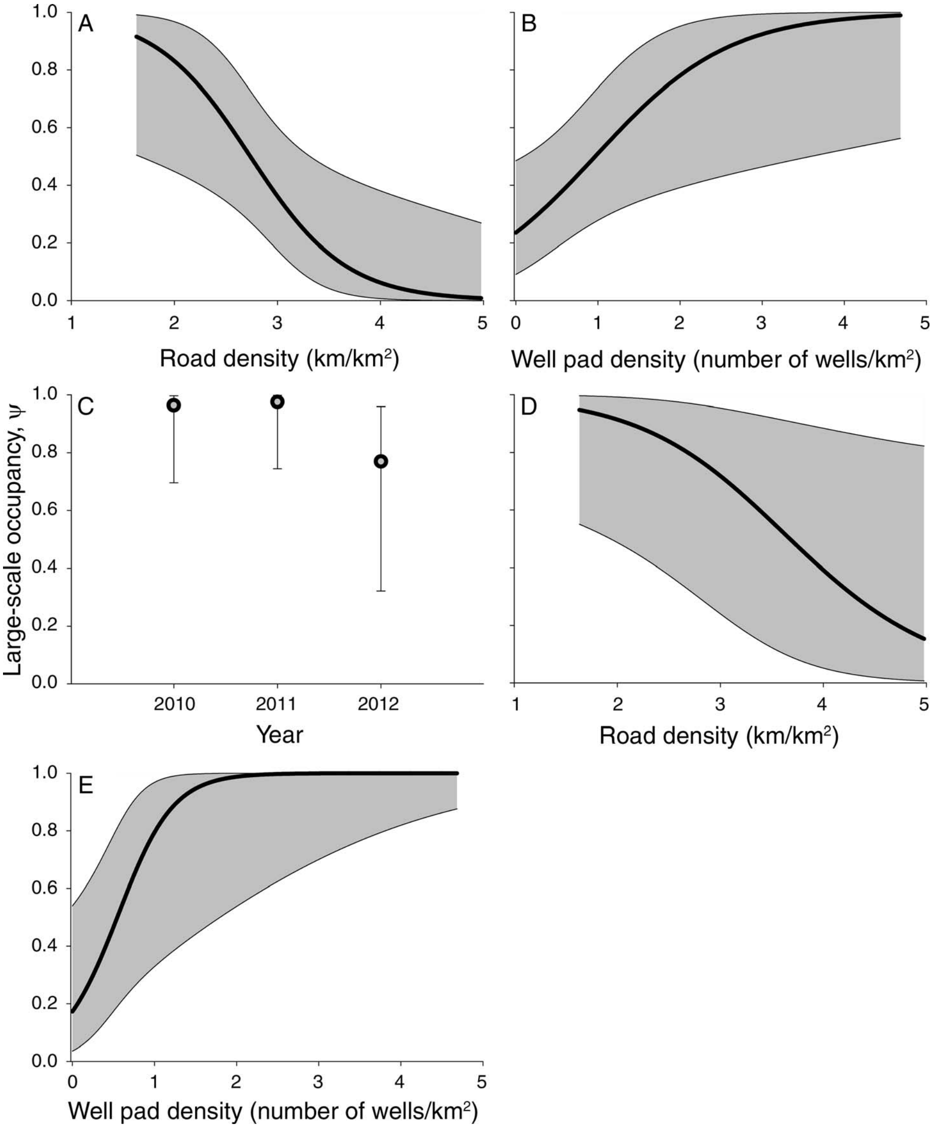

FIG. 2. The estimated probability of large-scale occupancy for the Sagebrush Sparrow by (A) road density and (B) well density for 2012 in the high-development stratum, and for the Sage Thrasher by (C) year in the high-development stratum, and by (D) road density, and (E) well density for 2012 in the high-development stratum. The thick trend lines are model-averaged estimates of occupancy at mean values for the other continuous covariates in the model, and the gray-shaded regions are unconditional 95% confidence intervals.

We confirmed the hypothesis that the large-scale occupancy of the Sagebrush Sparrow decreased with increasing road density. We found little support for the hypotheses that Sagebrush Sparrow occupancy at the landscape scale declined with increasing well pad density, or was lower in the high-development stratum. The best approximating model for large-scale Sagebrush Sparrow occupancy contained the effects of road and well density (Table 5). This model was four times more probable than the second best model including the effect of development strata (Table 5). The large-scale occurrence of Sagebrush Sparrows declined with increasing road density in the landscape and increased with increasing well density (Table 6, Fig. 2). The CIs for road and well density excluded zero, indicating large effect sizes for these covariates (Table 6). Road density [$w_+(j) = 0.99$] and well density [$w_+(j) = 0.99$] in the landscape were the best predictors of large-scale Sagebrush Sparrow occupancy, with less support for development strata [$w_+(j) = 0.20$] and year [$w_+(j) = 0.10$].

We confirmed the hypotheses that Sage Thrasher large-scale occupancy declined with increasing road density and varied by year. We found little support for the hypothesis that Sage Thrasher occupancy at the landscape scale declined with increasing well pad density and that occupancy was lower in the high-development stratum. The best model for the large-scale occupancy of

Sage Thrashers contained the effects of road density, well density and year (Table 4). There was two times more evidence for the best model than the second best model including the effect of development strata (Table 5). The large-scale occurrence of Sage Thrashers declined with increasing road density in the landscape, increased with increasing well density and was greater in 2010 and 2011 than in 2012 (Table 6, Fig. 2). The CIs for the effects of road density, well density, and year excluded zero, indicating large effect sizes for these covariates (Table 6). Well density [$w_{+}(j) = 1.00$], year [$w_{+}(j) = 0.85$] and road density [$w_{+}(j) = 0.83$] were the most important predictors of large-scale occupancy for Sage Thrashers, with less support for development strata [$w_{+}(j) = 0.32$].

The positive effect of well density on large-scale occupancy of Sagebrush Sparrows and Sage Thrashers was opposite our predictions. This provided the motivation to investigate post hoc whether interactions between road and well density could explain this result. For example, there was the possibility that high well densities only negatively affect occupancy when they are accompanied by high road densities. Although there was model selection support for the interactions, the CI for the interaction between road density and well density covered zero for the Brewer's Sparrow ($\hat{\beta} = 1.51$; CI = −8.80, 11.82), Sagebrush Sparrow ($\hat{\beta} = 1.33$; CI = −1.14, 3.79), and Sage Thrasher ($\hat{\beta} = 2.91$; CI = −1.39, 7.20), providing little support for an interaction between the covariates. The small interaction effects between road and well density provided very little evidence for the negative effect of well pad density on avian occupancy at low or high road density.

DISCUSSION

Our study showed no evidence of natural gas well pad avoidance by the sagebrush-obligate bird species we investigated. In contrast to our findings, Gilbert and Chalfoun (2011) showed that increasing well pad density significantly decreased Brewer's and Sagebrush Sparrow abundance in Wyoming sagebrush habitats. However, because their study did not account for the influence of roadways on these two species, it is possible the observed effects may have resulted from the roadways connected to the well pads, and not the well pads themselves. An investigation of potential correlation between well pad and road densities may partially explain the contrasting findings. However, Gilbert and Chalfoun (2011) found a "lag effect" in that a gas field that had been active for decades displayed a lower abundance of sagebrush-obligate songbirds than a gas field currently undergoing development. While gas development within the Atlantic Rim project area began as early as the 1950s, the vast majority of development has occurred within the last decade, putting our gas fields in the latter category of Gilbert and Chalfoun's study. The additional time since development may have allowed for the impact of lower fitness to be demonstrated in the population (Gilbert and Chalfoun 2011). The sagebrush-dependent species are known to exhibit high site fidelity (Knick and Rotenberry 2000), even though habitat fragmentation can dramatically reduce productivity (Knick and Rotenberry 2002). It is possible the species we investigated within the Atlantic Rim project area may be exhibiting strong site fidelity and returning to the same territories despite the lower fitness consequences of well pads being present. This idea is further supported by the fact that we generally observed decreasing occupancy from 2010 to 2012 (Fig. 1). Although we observed a positive response to well pad density, we caution that a time lag in population responses to habitat fragmentation may eventually give way to a long-term extinction debt (Tilman et al. 1994, Ewers and Didham 2006). Additionally, of our 405 count points, only 15 were less than 100 meters from a well pad. It is possible that only the areas immediately adjacent to well pads are avoided and our count points were not close enough to wells to reflect this. Future studies could improve our understanding of well pad effects by focusing on a number of different factors. A better understanding of the chronology of well pad development would improve the ability to evaluate the effects of oil and gas development on sagebrush birds. Stratifying sampling based on well density and distance could provide a more meaningful dataset. Additionally, determining the relationship between well pads, vegetation composition, and predator abundance would lead to a better understanding of how these structures affect the ecology of sagebrush-obligate birds.

The results of this study supported the hypothesis that increasing road density decreased avian occupancy at the large scale for two out of the three sagebrush-obligate songbirds we investigated (Sagebrush Sparrow and Sage Thrasher). Moreover, we discovered that road density was more detrimental to avian occupancy than well pad density in the surrounding landscape and that the negative effect of roads occurred at the landscape scale, with negligible effects of distance to roads at the territory scale: Landscape effects were more important than local effects (Knick and Rotenberry 2002). We suggest that the contribution of road networks to habitat fragmentation and the reduction of overall patch size (Saunders et al. 2002) are driving the negative effects on occupancy observed here. Road networks are an important driver of habitat fragmentation in the western United States (Leu et al. 2008), and the reproductive output of sagebrush-obligate birds are greatly reduced in fragmented shrub–steppe vegetation (Vander Haegen 2007). Several studies indicate that all three sagebrush obligates require large patch sizes (CalPIF 2004, Hansley and Beauvais 2004). However, Brewer's Sparrow has been shown to have the smallest territory size of the three species investigated, which may explain their lack of a negative response to road density

(Reynolds 1981). The data for the Sagebrush Sparrow and Sage Thrasher were well suited for modeling landscape effects at the grid scale, but because the occupancy rate of the Brewer's Sparrow was high in the study area ($\hat{\psi} = 0.98$, CI = 0.89, 1.00), an abundance model may be better suited for investigating the effects of oil and gas development at the grid scale for the Brewer's Sparrow. Roads can also impact the surrounding landscape by introducing invasive species, providing corridors for predators, and increasing ambient noise which can alter species' behavior (Trombulak and Frissell 2000). Previous work did not support these potential causes. For instance, Ingelfinger and Anderson (2004) found reduced density of sagebrush-obligate birds along roads with both high and low levels of traffic volume, which might suggest the reduced occupancy we observed in the Atlantic Rim is not driven by increased traffic and noise levels. Although several invasive species such as halogeton (*Halogeton glomeratus*), desert madwort (*Alyssum desertorum*), cheatgrass (*Bromus tectorum*), Russian thistle (*Salsola australis*), and bull thistle (*Cirsium vulgare*) have been noted in the Atlantic Rim study area, we're skeptical these introduced species are driving the reduced occupancy we witnessed along roads. Our uncertainty stems from the fact that Ingelfinger and Anderson (2004) observed the same negative impacts along roads; however, the roads in their study area were newly created and were unlikely to have had invasive species become introduced and established at the time of their study. More focused studies are needed on the relationships between landscape-scale road density, predator distribution, and vegetation composition at the local or territory scale. This would clarify whether roads reduce avian occupancy by reducing patch sizes or via some other mechanism and would better inform management and mitigation strategies. Future studies should also be of long enough duration to examine changes over the process of new road network development.

The effects of road density on sagebrush-obligate songbirds observed in this study have management implications for the design of road networks in oil and gas development areas. We recommend more horizontal drilling as a way to minimize the need for additional road construction by drilling multiple wells from a single pad. Our results suggested future development along existing roadways in a manner that minimizes the creation of new roadways and maintains the largest possible patch sizes will be an effective conservation strategy. Road closures and re-vegetation may restore areas of degraded sagebrush habitat and offset the impacts of future development.

More widely, we note that the infrastructure of natural gas extraction is quite similar in form despite differences in the extraction process (Ratner and Tiemann 2014). Both conventional and unconventional gas extraction (hydraulic fracturing ["fracking"], and coal bed natural gas extraction) require extensive road networks and share a basic well pad design. All types of natural gas extraction also require well head machinery (pumps and compressors) that are in place for long periods of time, often decades, and will generate noise and provide predator viewpoints. With the expansion of unconventional natural gas extraction worldwide, understanding the ecological effects of natural gas extraction will become increasingly important. Consequently, our findings of sensitivity to road network density at the landscape scale, evidence of species-specific responses to gas extraction infrastructure, and recommendations for subsequent study design may be of importance to land managers and conservationists well beyond our study area.

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