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Avoidance of unconventional oil wells and roads exacerbates habitat loss for grassland birds in the North American great plains



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ABSTRACT

Oil development in the Bakken shale region has increased rapidly as a result of new technologies and strong demand for fossil fuel. This region also supports a particularly high density and diversity of grassland bird species, which are declining across North America. We examined grassland bird response to unconventional oil extraction sites (i.e. developed with hydraulic fracturing and horizontal drilling techniques) and associated roads in North Dakota. Our goal was to quantify the amount of habitat that was indirectly degraded by oil development, as evidenced by patterns of avoidance by birds. Grassland birds avoided areas within 150 m of roads (95% CI: 87-214 m), 267 m of single-bore well pads (95% CI: 157-378 m), and 150 m of multi-bore well pads (95% CI: 67-233 m). Individual species demonstrated variable tolerance of well pads. Clay-colored sparrows (Spizella pallida) were tolerant of oil-related infrastructure, whereas Sprague's pipit (Anthus spragueii) avoided areas within 350 m (95% CI: 215-485 m) of single-bore well pads. Given these density patterns around oil wells, the potential footprint of any individual oil well, and oil development across the region, is greatly multiplied for sensitive species. Efforts to reduce new road construction, concentrate wells along developed corridors, combine numerous wells on multi-bore pads rather than build many single-bore wells, and to place well pads near existing roads will serve to minimize loss of suitable habitat for birds. Quantifying environmental degradation caused by oil development is a critical step in understanding how to better mitigate harm to wildlife populations.

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1. Introduction

An increasing proportion of fossil fuels are being extracted with new, unconventional technologies (EIA, 2011). In grasslands of the United States and Canada, oil extraction activity has undergone rapid expansion beginning around 2001, when horizontal drilling and hydraulic fracturing (i.e. fracking) techniques enabled profitable extraction of difficult-to-access oil resources (i.e., shale oil, tight oil; North Dakota Industrial Commission, 2012). In western North Dakota, industry predicts that 2000 new oil wells will be drilled annually from 2014 to 2034 (North Dakota Industrial Commission, 2012). These oilproducing regions of North Dakota, Montana, and Canada, commonly referred to as the Williston Basin and Bakken formations, also encompass areas of unusually high grassland bird abundance and diversity (Sauer and Peterjohn, 1999). Grasslands in the region provide important breeding habitat for species of conservation priority such as the

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Sprague's pipit (*Anthus spragueii*), Baird's sparrow (*Ammodramus bairdii*), and chestnut-collared longspur (*Calcarius ornatus*) (Knopf, 1996; North Dakota Game and Fish Department, 2012). Further contributing to conservation concerns, many grassland bird species have experienced long-term population declines (Sauer and Peterjohn, 1999; Johnson and Igl, 2001) and have demonstrated sensitivity to habitat fragmentation (Reino et al., 2009; Ribic et al., 2009) and anthropogenic disturbances (Hamilton et al., 2011).

Petroleum extraction activity can be detrimental to bird populations through numerous mechanisms (Northrup and Wittemyer, 2013; Souther et al., 2014). Increased vehicle traffic can increase direct avian mortality near roads (Orłowski, 2008), and disturbance by heavy machinery can destroy nests (Van Wilgenburg et al., 2013). Petroleum extraction leads to direct habitat loss through construction of well pads and access roads, as well as through associated activities like gravel mining, waste disposal, construction of industrial facilities, compressor stations, and housing developments. Habitat quality may be reduced around oil-related infrastructure as a result of increased human activity around wells, light pollution (Longcore and Rich, 2004), spills and pollutants (Souther et al., 2014), dust from vehicle traffic (Farmer, 1993), increased anthropogenic noise (Sun and Narins, 2005; Slabbekoorn

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and Ripmeester, 2008), and the presence of tall structures in an otherwise open landscape (Thompson et al., 2014). Changes in habitat quality that extend beyond the gravel surface of an oil well pad or road may greatly exacerbate the cumulative effect of oil extraction on wildlife (Sutter et al., 2000; Renfrew et al., 2005).

Few studies have examined the response of grassland-obligate birds to oil extraction and virtually none have examined unconventional oil development, which employs hydraulic fracturing and/or horizontal drilling techniques, in grassland systems. Species in open ecosystems may be more sensitive to anthropogenic disturbances than species in forested areas (Benítez-López et al., 2010). Studies in grassland and sage-brush systems have more commonly examined avian response to natural gas-specific extraction activities. Natural gas developments negatively affected greater sage-grouse (Centrocercus urophasianus, e.g. Holloran, 2005; Walker et al., 2007), Baird's sparrow and Sprague's pipit (Hamilton et al., 2011), Brewer's sparrow (Spizella breweri), and sage sparrow (Artemisiospiza belli; Ingelfinger and Anderson, 2004). Similarly, Baird's sparrow, chestnut-collared longspur, and Sprague's pipit were significantly less abundant near conventional oil wells in Alberta, Canada, but no significant effect of gas wells was observed for these three species (Linnen, 2008).

While infrastructure may appear similar, unconventional oil development could have different effects on habitat quantity and quality than conventional oil development due to different implementation and maintenance requirements (e.g. injection of fracking fluid, higher traffic levels, different well pad size, different well and road density, and varying landscape configurations). Our objective was to quantify any potential avoidance of oil-related infrastructure (gravel roads, single-bore oil wells, and multi-bore oil wells) by birds in a grassland ecosystem that was undergoing rapid oil development.

2. Methods

2.1. Study area

We conducted our study in northwestern North Dakota in 2012–2014. This area contains numerous publicly accessible grasslands (U.S. Forest Service, U.S. Fish and Wildlife Service, State School Trust Lands), as well as extensive privately owned grasslands. Management of grasslands varied, with some grasslands managed explicitly for conservation purposes (e.g. U.S. Fish and Wildlife National Wildlife Refuges) and others primarily used for grazing (North Dakota state school trust lands and most private lands) or multiple uses (U.S. Department of Agriculture National Grasslands). Study sites were located in seven counties (Billings, Burke, Divide, Dunn, Mountrail, McKenzie, and Williams) that have undergone extensive oil development. The northern portion of our study region is within the Prairie Pothole Region, and sites there were generally mixed-grass prairies with extensive wetlands in a flat to undulating landscape. Sites in the southern portion of the study area were typically shorter-grass prairies with more topographic relief and fewer wetlands.

2.2. Study design

We focused on 3 oil-related infrastructures: gravel roads (22 surveys, covering 159.7 ha), single-bore well pads (56 surveys, 387.4 ha), and multi-bore well pads (13 surveys, 114.5 ha). Single-bore well pads, developed with hydraulic fracturing and horizontal drilling, were the most common oil-related infrastructure on the landscape at the time of the study. Multi-bore well pads were considered a best-management practice to reduce the overall footprint of numerous single-bore well pads. Because construction of new roads is associated with oil development and well pads are confounded with roads (i.e. a well pad is always near a road), we also considered potential avoidance of gravel roads. Throughout the text, we refer to a "well pad" or "well" as the contiguous gravel surface that houses all pumping units, storage tanks, natural gas flares, power-lines, and any other associated

infrastructure. Finally, we included several method evaluation sites (13 surveys, 114.5 ha), which were areas of grassland habitat located at least 0.5 km away from infrastructure (well pads or roads). We conducted these surveys to confirm that survey methods did not induce a pattern suggesting avoidance, in the absence of any edge feature.

Most sites were located on state- or federally owned grasslands, but we included sites on private land when access could be negotiated. We restricted well site selection to wells that were listed as actively producing oil and where construction and drilling had been completed at least 6 months prior to the intended survey date. A smaller number of older, conventionally developed wells existed on the landscape and these were focal wells in 4 of 56 single-bore well surveys. We used recent aerial imagery to determine if adequate grassland surrounded a well pad such that surveys could extend at least 300 m from the target feature without encountering other confounding landscape features (e.g. wooded areas, ravines, other oil wells) and while staying within a homogeneous habitat type (e.g. not crossing fences). It was critical that habitat within each rectangular survey did not change in any systematic way, other than in proximity to the edge of interest. Road sites were placed perpendicular to secondary gravel roads and >500 m from any nearby oil well. When ditches were separated from the interior of the patch with a fence, surveys began inside fences and excluded grass in ditches. We selected method evaluation sites that were >500 m from any oil-related feature and we situated method evaluation surveys parallel to any features that might influence bird density (roads, woodlands, wetlands). Both road and method evaluation sites followed the same criteria as well sites; grassland within any single rectangular survey was as homogeneous as possible. Most study sites were located on native grasslands (rather than introduced grasses or hay fields) and the surrounding landscape (within a 1000 m) was dominated by grassland, pasture, or hay (range: 40–100%, x =80%), with smaller amounts of crop (0–56%, x = 13%), open water (0-32%, x = 2%), wooded areas (0-12%, x = 1%) and wetlands (0-10%, x = 1%; 2011 National Land Cover Database; Homer et al., 2015).

Using recent aerial imagery and ArcGIS (10.1 ESRI, Redlands, California), we generated a rectangular survey area, measuring approximately 150 m in width and extending approximately 500 m from the edge of focal feature (well pad or road, Fig. 1). The exact shape of each survey polygon varied depending on the layout of the well pad, access roads, and surrounding landscape. Some surveys did not extend to 500 m, others went farther than 500 m and many were irregularly shaped to avoid wetlands.

Within each survey area, we generated a systematic transect route with transect legs spaced at 50 m intervals (square-wave pattern, Fig. 1). The transect route was created so that no part of the survey polygon would be >25 m from the surveyor's path. We chose this pattern because 25 m is a range where detection of available grassland birds is virtually 100% (Diefenbach et al., 2003). Throughout the study, we looked for evidence of detection bias caused by noise from wells or roads by visually examining histograms of bird detections binned by distance from transect (Buckland et al., 2005). We observed uniform rates of detection from 0 to 25 m, both near and far from well and road edges, and therefore confirmed consistent detection of available birds given these methods (Buckland et al., 2005; Appendix A). We also chose this transect method because walking back and forth made it easier to accurately track individual birds and avoid double-counting.

2.3. Bird survey technique

We initiated all surveys during morning hours, when wind speeds $<24 \text{ km h}^{-1}$, and with no more than light or intermittent precipitation, but occasionally weather changed partway through a survey. All surveys were completed between 27 May and 17 July when singing activity was at its peak and before the appearance of most fledglings. In 2012, we used a digital sound level recorder to record noise levels at various distances from oil wells to quantify noise levels associated with well



Fig. 1. Example of survey layout and transect configuration. Method evaluation surveys (A) were not associated with any edges and were >500 from oil wells or roads. Oil well surveys extended from the edge of a well pad (B, C), in any direction that best fit the landscape (e.g. did not approach other wells or confounding features). Road surveys extended from roads (D). Surveys randomly started at either the near or far end of each transect (E, F).

infrastructure. Chronic mechanical noise is indicated as a potential mechanism causing avian avoidance of natural gas infrastructure in other regions (Francis et al., 2011), and these basic measurements at our sites allowed us to compare noise levels to other oil and gas developments. To take recordings, an observer held the sound meter at chestlevel for one minute, facing away from the wind, and recorded average dBA reading during that time interval.

Before conducting the survey, we placed flagging at corners of the route to aid the surveyor in following the transect and accurately assessing bird locations. A surveyor began at either end of a transect (selected by coin flip) and proceeded to slowly walk the route while recording the species and location of detected birds onto a detailed printed map (scale 1:2200). Surveyors walked at any pace that was comfortable given the density of birds at the site, but the goal was to complete an individual survey in no more than 2.5 h to minimize changes in bird behavior associated with time of day (x = 81 min.). Surveyors noted the location of each bird on the printed map, based on its position when first detected. For uncommon species like Sprague's pipit and Baird's sparrow, we also recorded the locations of birds that were detected outside of the strictly defined survey area (either by noting the location on the map or by recording the location using a GPS unit).

2.4. Data analysis

We divided surveyed areas into sub-areas based on 50-m distance intervals from the edge of a feature (e.g. 0–50 m, 51–100 m, etc.). For method evaluation sites, we used one randomly chosen narrow end of the survey area as the "edge." Because few surveys extended more than 550 m from any edge, we did not use data from distances >550 m. For Baird's sparrow and Sprague's pipit observations that were recorded outside of the survey area, we examined the distance from our pre-defined survey area to these observations and generated larger polygons that would contain these observations. Larger polygons were of the same proportions as the original survey (i.e. rectangular) and also excluded non-homogeneous habitat (i.e. excluded wetlands, did not cross fences or roads). An additional 150 m buffer contained most Baird's sparrows and 250 m contained most Sprague's pipits. This translated to about 4 times more area surveyed for Baird's sparrow and 6 times more for Sprague's pipit. Birds observed farther than this were omitted.

To assess density patterns, we combined data over all years and sites. parsed by edge type. We summed the area surveyed within each distance bin and the total number of birds associated with each bin for a particular edge type. Some sites were surveyed in multiple years, but repeated surveys were treated independently. We calculated density (birds ha⁻¹) for each 50-m distance bin for grassland bird species combined and for individual species (when sample sizes allowed), thereby reducing data to 11 pooled density estimates for each analysis. It was appropriate to pool data in this manner because year and site effects were not of interest and because our study design was balanced over sites and years (i.e. areas near and far from wells were sampled equally at sites and years; Murtaugh, 2007). We hypothesized that if there was no evidence of avoidance, density would vary randomly with distance and data would be best fit by a straight line without slope (i.e. null or intercept-only model). Conversely, a pattern of avoidance would exhibit a 2-part response: density would be low near the feature and increase with distance, then plateau when the feature was no longer influencing density patterns. Given bird density (y) and distance from feature (x), a pattern of avoidance would take the following form: $y[x < x.star] = a + b^* x$; $y[x \ge x.star] = a + b^* x.star$, where a = intercept, b = slope and *x.star* is a breakpoint after which the slope becomes zero, that is, the feature no longer affects bird density. Finally, we considered the case where our surveys may not have extended beyond the area influenced by a feature; that situation would be best modeled with a simple linear model that allowed an increase or decrease in slope. We refer to these models as null (no effect of feature), plateau (increases or decreases to a plateau), and slope (increases or decreases continuously with distance), respectively.

We used package "segmented" (Muggeo, 2008) in R statistical software (R Core Team, 2014) to fit the plateau model by constraining the slope after the breakpoint to zero. We compared models using Akaike's information criteria (AIC; Burnham and Anderson, 2002). When analyzing data, observations were weighted by the total area surveyed in each distance bin. We did this because survey areas were not all exactly rectangular and because not all surveys polygons could extend to 550 m, so the area surveyed waned with increasing distance from the feature. We modeled individual species and types of edges when samples were \geq 18. We concluded evidence of avoidance when either the plateau or slope model was the top-supported model or competitive (i.e. within 2 AIC units, Burnham and Anderson, 2002) and when estimates of slope were positive. Because models were nested, the slope model was not considered competitive when within 2 AIC units of the null (and the plateau when within 2 AIC units of the slope model; Arnold, 2010). For sparse data, or when breakpoints may have existed near distance zero or 550 m, the plateau model often did not converge. When the plateau model was supported by model selection, we report the breakpoint parameter (with 95% CI) as an estimate of distance of avoidance (with the lower confidence bound truncated at zero when negative numbers were estimated). Sometimes, the plateau model had >1 possible solution, and in order to deal with this, we repeatedly ran the plateau model (100 times) with varying starting values for the breakpoint, and selected the solution with the highest likelihood

Additionally, we compared model fit using un-pooled data and a mixed model framework that incorporated random intercept terms for site and year with package "Ime4" (Bates et al., 2014). We followed recommendations of Bolker et al. (2009) for fitting and comparing models. Un-pooled data were more problematic than pooled data and the plateau model failed to converge for less numerous species. Detailed methods, results, and figures for this analysis are included in Appendix B. For instances where this analysis converged on all 3 models, we report results from both analyses.

3. Results

During 2012–2014, we conducted 56 surveys at single well pads (5, 18, and 5 sites surveyed for 1, 2, or 3 years, respectively), 13 surveys at multi-bore well pads (3 sites surveyed in 1 year and 5 in 2 years), 22 at road edges (9, 5, and 1 sites surveyed in 1, 2, or 3 study years) and 13 at method evaluation sites (6, 2, 1 sites surveyed in 1, 2, or 3 years). Four observers conducted surveys with overlap between surveyors and years (2012 – ST; 2013 – ST, CS, AW; 2014 – ST, CS). In 2012, we found a significant, negative relationship between distance to well and overall sound level ($\beta = -0.0171$, p < 0.01); measurements within 50 m of well pad edges were louder (x = 44.9 dBA) than those taken farther away (\geq 300 m, x = 38.9 dBA). Higher readings near wells were caused by mechanical noise from pump-jacks, trucks temporarily idling on the well pad, natural gas flares, or passing traffic, but the most consistent source of noise was wind.

In 3 years of study, the most commonly detected species were grasshopper sparrow (*Ammodramus savannarum*, n = 678), Savannah sparrow (*Passerculus sandwichensis*, n = 422), clay-colored sparrow (*Spizella pallida*, n = 228), bobolink (*Dolichonyx oryzivorus*, n = 210), chestnut-collared longspur (n = 197), western meadowlark (*Sturnella neglecta*, n = 81), brown-headed cowbird (*Molothrus ater*, n = 72), Baird's sparrow (n = 72), Sprague's pipit (n = 53), and red-winged blackbird (*Agelaius phoeniceus*, n = 47). Other grassland species included horned lark (*Eremophila alpestris*, n = 25), upland sandpiper (*Bartramia longicauda*, n = 19), and lark bunting (*Calamospiza melanocorys*, n = 14).

On method evaluation sites, we observed no pattern in the locations of grassland birds (all species combined) in relation to the randomly designated edge of the survey area (Table 1; Fig. 2a). Similarly, the null model was the top-ranked model for 5 of 6 individually modeled species (Table 1). For Savannah sparrow, the slope model was top-ranked, but within 2 AIC units of the null and the slope parameter was

Table 1

Model comparison table (Δ AlC) for grassland bird species combined and individual species when n \geq 18 for 3 models describing potential avoidance or attraction to edges associated with oil and natural gas development (roads, single-bore well pads, and multi-bore well pads).

		Null	∆AIC Slope	Plateau
Edge type & Species	n ^a	$(k^b = 1)$	(k = 2)	(k = 3)
Method evaluation surveys				
Grassland birds combined ^c	292	0.0	0.2	7.9
Baird's sparrow	32	0.0	1.0	2.9
Bobolink	21	0.0	1.9	6.1
Chestnut-collared longspur	38	0.0	1.4	3.8
Grasshopper sparrow	106	0.0	2.0	NA ^d
Savannah sparrow	70	1.9	0.0	7.6
Sprague's pipit	18	0.0	0.7	NA
Roads				
Grassland birds combined	343	6.8	5.8	0.0
Bobolink	83	0.0	2.0	0.7
Brown-headed cowbird	27	0.0	2.0	2.9
Chestnut-collared longspur	32	0.0	2.0	3.9
Clay-colored sparrow	24	0.0	2.0	3.7
Grasshopper sparrow	156	0.0	0.5	NA
Savannah sparrow	30	0.0	1.1	2.1
Single-bore wells				
Grassland birds combined	847	13.5	4.0	0.0
Baird's sparrow	20	6.1	0.0	0.9
Bobolink	78	7.9	5.9	0.0
Brown-headed cowbird	35	0.0	1.0	1.7
Chestnut-collared longspur	121	2.1	0.0	7.3
Clay-colored sparrow	171	0.0	0.6	4.0
Grasshopper sparrow	289	3.0	0.0	0.3
Savannah sparrow	251	9.9	6.4	0.0
Sprague's pipit	18	15.5	1.5	0.0
Western meadowlark	50	0.0	2.0	2.9
Multi-bore wells				
Grassland birds combined	235	3.4	2.0	0.0
Bobolink	24	0.4	0.9	0.0
Grasshopper sparrow	121	5.5	0.0	4.0
Savannah sparrow	62	0.3	0.0	2.3

a. Number of birds included in analysis.

b. k is the number of parameters in each model.

c. Grassland birds combined included all species in this table and lark bunting, horned lark, and upland sandpiper, and excluded brown-headed cowbirds.

d. NAs occurred when the plateau model would not converge.

not significant (p = 0.08; all coefficient estimates and standard errors are located in Appendix A).

Grassland birds combined avoided habitat within 150 m of roadways (95% CI: 87–214 m; Fig. 2B); the plateau model was bestsupported and no other models were competitive (Table 1). The null model was the lowest AIC model for all individually modeled species (Table 1). Bobolink had some support for the plateau model (0.7 Δ AIC, Table 1), which predicted that bobolinks were less abundant within 150 m (95% CI: 0–469 m) of road edges (Fig. 3). The top-ranked model for Savannah sparrow was the null model, but the plateau model was nearly competitive (2.1 Δ AIC Table 1, Fig. 3). Model selection results indicated no support for road-avoidance for brown-headed cowbird, chestnut-collared longspur, clay-colored sparrow, and grasshopper sparrow (Table 1).

The mixed effect model on un-pooled data performed similarly. The mixed model converged for the null, slope, and plateau model for grassland birds combined and bobolinks. In both cases, the plateau model was also selected the minimum AIC model and returned similar breakpoint estimates for grassland birds combined (143 m, 95% CI: 50–211) and bobolink (124 m, 95% CI: 50–420; Appendix B).

For single-bore well sites, grassland birds combined and 6 of 9 individually modeled species demonstrated reduced density near well edges (Table 1). Estimated avoidance distance for grassland birds combined was 267 m (95% CI: 157–378 m; Fig. 2C). The breakpoint was estimated at 228 m for Savannah sparrow (95% CI: 96–360 m),



Fig. 2. Density of grassland birds (all species combined) by distance from edge, for different types of edges. Surveys conducted from 2012 to 2014 in western North Dakota. Circle size is proportional to area surveyed in each distance zone. The plateau model fit is shown in dashed lines and estimated breakpoints (with 95% CI) are shown along x axis, except for method evaluation surveys (3A), where the dashed line shows the fit of the null model.

250 m for bobolink (95% CI: 58–442 m), and 350 m for Sprague's pipit (95% CI: 215–485 m; Fig. 3). The slope model was top-supported for Baird's sparrow, chestnut-collared longspur, and grasshopper sparrow (Fig. 3) indicating reduced density within at least 550 m of single-bore well edges (Table 1, Table A.1). Model selection did not support avoidance patterns for western meadowlark or clay-colored sparrow (Table 1). Brown-headed cowbird was best fit by the null model, but the plateau model was competitive (Δ AIC 1.7). This was the only species where the plateau model estimated a negative slope, indicating higher density near well edges (Fig. 3, Table A.1).

With single-bore wells, the mixed effects model converged for grassland birds combined, bobolink, and grasshopper sparrow. The plateau model was the minimum AIC model for grassland birds combined (351 m, 95% CI: 250–462), bobolink (250 m, 95% CI: 173–320), and grasshopper sparrow (336 m, 95% CI: 50–444; Appendix B).

For multi-bore well sites, the plateau model had the minimum AIC value for grassland birds combined and for bobolink (Table 1). Estimated avoidance distances were 150 m for grassland birds combined (95% CI: 67–233; Fig. 2D) and 200 m for bobolink (95% CI: 0–498; Fig. 3). The top-ranked model for grasshopper sparrow was the slope model, indicating that densities did not level off within 550 m of multi-bore wells (Table 1, Fig. 3). The slope model was the minimum AIC model for Savannah sparrow, suggesting that this species was more abundant near multi-bore well pads, but the null was also competitive (Δ AIC 0.3, Table 1, Fig. 3). No other species was numerous enough for species-specific modeling in relation to multi-bore well sites.

The random effects model converged for grassland birds combined and bobolinks for multi-bore wells. The plateau model was also the minimum AIC model with similar breakpoints estimated for grassland birds combined (139 m, 95% CI: 50–211). The null model was topsupported for bobolink, but the plateau model was competitive and estimated the same breakpoint as the pooled analysis (200 m, 95% CI: 0–420; Appendix B).

4. Discussion

Avoidance of oilfield infrastructure indicates that the impact of oil development on many species of grassland birds will be much greater than projections that solely consider direct habitat loss. We found that many species of grassland birds avoid habitat near secondary roads, single-bore well pads, and multi-bore well pads, providing evidence that detrimental habitat effects extend well beyond the area occupied by infrastructure. Because negative effects extend into surrounding habitat, variation in well and road configurations can dramatically alter the amount of habitat that will remain suitable for grassland birds as oil development continues in the region.

Of our study sites, newer single-bore well pads (those built after 2005) averaged 2.2 ha in size, or approximately 150 m square. The addition of 150 m of surrounding habitat increases the area affected by a single well pad from 2.2 to 20 ha. The inclusion of 350 m of surrounding habitat increases the potential affected area to 56 ha. Secondary gravel roads commonly measured ~10 m wide and usually had an additional ~10 m of roadside habitat that differed from the interior (i.e. right-of-way or ditches) on each side of the road. The inclusion of 150 m on either side of the roadway increases the area affected 10-fold. Thus, any 1 km of secondary road can detrimentally affect up to 33 ha of habitat. Because long underground bores (currently up to 3.2 km) are used in horizontal drilling, wells can be clustered in highly developed, regularly spaced corridors at 6.4-km intervals (Fig. 4A, C). When this configuration is used, each well pad would contribute to a minimal amount of degradation. For example, 16 wells along 2 corridors each contribute about 12.5 ha of degradation per 518 ha area, beyond that already affected by roads. In a less optimally organized landscape where wells are not strictly confined to corridors, a single well pad can affect a much larger area, up to the maximum 56 ha (Fig. 4B, D). Using predictions of the plateau model, we determined that within an avoidance zone, overall bird density is reduced by about 33%, as compared to areas outside the avoidance zone. Thus, we can say that if 2% of a hypothetical, undeveloped grassland landscape is converted to roads and well pads and 25% of available grassland is within an avoidance zone, the potential carrying capacity of the site is reduced by about 10%. If the avoidance zone affects 50% of the landscape, carrying capacity is reduced, by about 19%. However, these estimates do not account for potential reductions or increases in survival or fecundity for the birds that do utilize habitat within avoidance zones (Burr, 2014).

Some species appeared largely unaffected by oil-related infrastructure, while other species avoided infrastructure, in some instances for



Fig. 3. Each row displays bird density for individual species at road (first column), single well (center), and multi-bore well sites (right). Circle size is proportional to area surveyed in each distance zone. Dashed lines show model fit of top-supported model. When plateau model was selected, the estimated breakpoint (and 95% CI) is shown along x-axis in dark gray. Species codes are Baird's sparrow (BAIS), bobolink (BOBO), brown-headed cowbird (BHCO), chestnut-collared longspur (CCLO), clay-colored sparrow (CCSP), grasshopper sparrow (GRSP), Savannah sparrow (SAVS), and Sprague's pipit (SPPI). Blank panels are instances where data were too sparse.

considerable distances. Studies of conventional oil and gas development have found similar variation in tolerance by species (Chalfoun et al., 2002; Francis et al., 2011; Kalyn Bogard and Davis, 2014). Varying tolerance of anthropogenic noise is suggested as a factor driving variation in avian avoidance of natural gas wells (Francis et al., 2011), but oil wells in our study area were considerably less noisy and thus noise is less likely to be a key driver in this system. Habitat preferences may explain some, but not all, of the species-specific variation in tolerance. For example, fences around oil well pads offer perching sites, which may attract birds like western meadowlarks that like to sing from tall perches (Payne et al., 1997). Further, fences often exclude cows from grazing strips of grassland around well pads, resulting in tall or dense vegetation that may attract species like clay-colored sparrow (Dechant et al., 1998). Nonetheless, bobolinks also often sing from perches and are known to prefer relatively lush vegetation (Herkert, 1994), but they consistently avoided roads, wells, and multi-bore wells. Many of these species have very similar life-histories (e.g. most regional grassland birds are ground-nesting), therefore mechanisms like increased nest depredation



Fig. 4. Scenarios demonstrating how well configuration can alter the amount of habitat affected, given avoidance zones of 150 m from roads and 350 m from well pads. The use of 6.4 km spacing between developed corridors allows 60% of the landscpae to remain outside of avoidance zones, even with many roads (A). When wells are not restricted to 2 corridors, a much larger proportion of the landscape is affected (B). Schematic B has the same number of wells and roads as A, but only 40% of the landscape is outside of avoidance zones. Figure elements C and D show real landscapes (both in McKenzie County, North Dakota) that exemplify these scenarios. Even in landscapes with many wells (C. 24 wells) a considerable amount of suitable habitat can remain available (75%), when optimal spacing and multi-bore well pads are utilized and few unnecessary roads are built. The landscape in D has 14 wells, but only 54% of the landscape remains outside of avoidance zones.

around roads or well pads are unlikely to be causing avoidance, because nest predators would be unlikely to target one species over another (Lahti, 2001).

We found that combined grassland birds avoided habitat near road edges. In grasslands of southern Alberta, Sprague's pipits did not appear to avoid low-traffic roads (Koper et al., 2009), but sagebrush-obligate songbirds were significantly less common in areas within 100 m of roads associated with natural gas extraction in Wyoming, USA (Ingelfinger and Anderson, 2004). It is likely that roads associated with oil and natural gas extraction experience considerably higher traffic volume than roads in most other comparable locations, and this was certainly the case in our North Dakota study area (Fershee, 2012). Thus, we conclude that reduced avian density near roads was likely a direct result of heavy traffic associated with oil development in the region.

For multi-bore wells, the distance of avoidance for grassland birds combined was less than that observed at single-bore wells. At the time of our study, multi-bore well sites were relatively uncommon in the region and therefore our sample included sites that were more variable than we would have preferred (e.g. pump-jacks temporarily inactive, surveys could not extend to 500 m, active drilling visible from site). Nonetheless, our results suggest that a multi-bore well would not adversely affect a substantially larger area than a singlebore well and that placing several wells on a multi-bore pad may be a viable method to minimize the footprint of oil development. When there is the option to build numerous single-bore well pads or combine these on to 1 multi-bore pad, the multi-bore pad could potentially reduce the amount of habitat lost and minimize the total amount of habitat that would be adversely affected.

Compared to other research, our results differed for several key species. In Saskatchewan, Canada, Sprague's pipit density was not affected by natural gas well proximity or density (Kalyn Bogard and Davis, 2014). This is unsurprising considering variability in disturbances that result from oil and natural gas development across regions. Studies of grassland birds and energy development in Canada commonly examine response to shallow gas development (Hamilton et al., 2011; Kalyn Bogard and Davis, 2014). Natural gas wells generally have less extensive above-ground infrastructure, no moving parts, a smaller well pad, and, in some developments, compressors associated with natural gas wells generate more considerable noise (Francis et al., 2009, Riley et al., 2011). Most oil well sites in our study had numerous tall structures (pumping units, storage tanks, power-lines), were surrounded by barbed wire fencing, had brightly burning natural gas flares, generated relatively minor chronic noise, and were visited frequently by large trucks (maintenance staff and tanker trucks to empty storage tanks). Further, horizontal drilling techniques combined with a relatively flat landscape and low human population density have allowed for development of well pads along linear corridors, in comparison to neural or grid patterns common in other areas (Francis et al., 2011, Brand et al., 2014). At the time of our study, horizontal well bores extended as far as 3.2 km from a well pad site, and developed corridors were often spaced in parallel rows at 3.2 km intervals. This development pattern may allow birds to more easily avoid developed areas by offering core regions between intensively developed corridors.

Some differences between our study results and the findings of other studies may also be due to the use of different field and analytical methods. Many studies of edge or disturbance effects on bird density rely on circular point count methods to examine variation in density with increasing distance from anthropogenic disturbances (e.g. Miller et al., 1998 [recreation trails], Ortega and Capen, 2002 [roads], Bayne et al., 2008 [compressor stations], Thomas et al., 2014 [conventional oil wells]). Typically, point count methods estimate bird abundance or density within 100 m of the observer, thereby combining information that spans a 200 m distance interval and potentially diminishing the ability to detect fine-scale changes in density. Point counts may also under-sample areas close to edges; point counts are often placed so that the outside of the circle is abutting the habitat edge of interest, and thus the relative amount of area surveyed near this edge would be less than areas surveyed at 100 m (i.e. the diameter of the count circle) from the edge. Detectability also declines with increasing distance from the observer, making areas within 0-50 m of the edge poorly sampled. Our rectangular mapping technique effectively allowed us to estimate the area of impact around a disturbance to the nearest 50 m interval and also minimized detection issues.

Oil development in the Williston Basin and Bakken Formations is occurring at a rapid pace (North Dakota Industrial Commission, 2012). This region broadly overlaps the breeding ranges of numerous grassland bird species of conservation concern and most grasslands in the region, even state- and federally owned grasslands with conservation goals were being actively developed for oil production. In particular, the oil-producing areas extend across much of the core U.S. breeding range of the Sprague's pipit, a species that is currently a candidate for listing under the U.S. Endangered Species Act (U.S. Fish and Wildlife Service, 2010). The species is also listed as threatened in Canada (COSEWIC, 2010). We found that, of endemic grassland birds, Sprague's pipit is one of the most sensitive to disturbances associated with oil development, raising further concern about the impact of ongoing oil development in the region.

Our results suggest that rather than placing numerous single-bore well pads throughout the landscape, the footprint of oil development may be minimized by clustering these wells along corridors and on multi-bore pads, leaving more core habitat available for grassland birds. Any situation where a well could be placed outside of developed corridors, a strategy that is occasionally used to minimize impact to wetlands, could have negative consequences for grassland bird habitat and potentially increase the negative impact of the well. Finally, highly developed corridors containing as many as 8-48 well bores along a 1.6 km stretch of road are predicted. Few intensively developed corridors were completed at the time of our study and therefore these types of sites were not available for inclusion in our study. The cumulative impact of highly developed corridors may push birds farther from edges or contribute to habitat fragmentation that ultimately renders the remaining grassland habitat unsuitable for area-sensitive species (Ribic et al., 2009).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx. doi.org/10.1016/j.biocon.2015.08.040.

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