Effects of Shallow Gas Development on Relative Abundances of Grassland Songbirds in a Mixed-grass Prairie

by

Jennifer Anne Rodgers

A Thesis submitted to The Faculty of Graduate Studies of
The University of Manitoba
In Partial Fulfillment of the Requirements for the Degree of

Master of Natural Resources Management

Natural Resources Institute
Clayton H. Riddell Faculty of Environment, Earth, and Resources
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FACULTY OF GRADUATE STUDIES

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ABSTRACT

Grassland bird species have declined more than birds of any other region in North America, and industrial development may exert additional pressure on these species. I evaluated the effects of natural gas infrastructure on the relative abundances of grassland songbirds in southeastern Alberta, Canada using point counts at sites with well densities ranging from 0 to 20 per 1×1 mile. Generalized Linear Mixed Models were used to evaluate effects of infrastructure on birds, and parsimonious models were selected using Akaike's Information Criterion. Vegetation near infrastructure was shorter and sparser than locations farther away, but was unlikely to have driven responses to infrastructure by birds. Gas wells may have acted as "artificial shrubs" attracting species such as vesper sparrow (*Pooecetes gramineus*) and western meadowlark (*Sturnella neglecta*) that use vegetation for perching, while other species, such as Sprague's pipit (*Anthus spragueii*) and chestnut-collared longspur (*Calcarius ornatus*), had higher abundances farther from wells.

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CHAPTER 1: PURPOSE OF RESEARCH

1.1 Introduction

In North America, grassland habitats have been reduced by 70 % (Samson et al. 2004) from their historical extents due to land-use conversion (Herkert 1994). With these large decreases in grassland habitats, declines of bird species in these regions have been higher than in any other group of birds in North America (Herkert 1994, 1995; Herkert et al. 2003). Between 1966 and 1993 alone, more than 50 % of grassland bird species in midland North America experienced significant declines (Herkert 1995) and in Canada, 73 % of grassland bird populations have been declining since 1970 (Collins and Downes 2009). These population declines may be exacerbated by other human developments that further reduce and alter grassland habitats. For example, the natural gas industry is prevalent in the prairies and uses shallow gas wells, pipelines, access roads and other related infrastructure for resource extraction. These developments are a source of anthropogenic disturbance, which can have widespread impacts on wildlife (Frost et al. 1998; Walker et al. 2007; Watkins et al. 2007) and exert additional pressure on grassland birds that are already in decline (Dale et al. 2009; Hamilton et al. 2011; Kalyn-Bogard 2011).

Natural gas industry development also alters vegetation structure and habitat composition (Hamilton 2010; Kalyn-Bogard 2011), potentially impacting grassland songbirds that are sensitive to these changes (Sutter and Brigham 1998; Davis and Duncan 1999; Davis 2004). Increases in habitat edge are caused by the construction of roads used to access gas wells and through the mowing of vegetation surrounding active wells. These habitat edges may contribute to an increase or decrease in predation and cause further changes to vegetation structure, which may benefit some bird species but negatively affect others (Davis et al. 2006; Koper et al. 2007; Koper et al. 2009). Non-native vegetation may also be introduced along access roads (Gelbard and Harrison 2003; Von der Lippe and Kowarik 2007) and in areas re-seeded after new gas wells have been drilled (Berquist et al. 2007). In particular, the exotic grass species crested wheatgrass (*Agropyron cristatum*) has been associated with natural gas development (Dale et al. 2009) and has a structure that varies from native grasses (Sutter and Brigham 1998; Henderson 2005). Many grassland bird species are sensitive to vegetation structure and may be impacted by these changes (Vickery et al. 2001; Fisher and Davis 2011*a*; Fisher and Davis 2011*b*).

As the natural gas industry continues to grow in Canada (Government of Alberta 2011), it is important to identify any impacts that associated infrastructure are having on grassland songbird species. Allowable densities of natural gas wells are currently being questioned by researchers due to their negative impacts on many species (Holloran 2005; Walker et al. 2007; Harju et al. 2010; Wyoming Game and Fish Department 2010) and it is important that these biological consequences are understood when policy, management and operations guidelines are considered (Askins et al. 2007). In this study, I sought to identify the effects of natural gas wells and associated trails and roads on the relative abundances of grassland songbirds in southeastern Alberta.

The first section of this thesis provides an outline of the objectives and purpose of this research. Chapter 2.0 provides a literature review associated with the research. Chapter 3.0 is organized as a stand-alone paper and Chapter 4.0 discusses the management implications of this research.

1.2 Problem Statement

As prairie habitats continue to decline and increasing pressures are placed on grassland birds, it is important to understand anthropogenic developments that may be negatively impacting these species. My research aimed to assess the effects of the natural gas industry on the relative abundances of grassland songbirds in southeastern Alberta. Further, I examined the impact of infrastructure associated with the industry, such as gas wells and access routes, on vegetation structure and cover, which may have further implications for birds. This may allow for the identification of mechanisms driving the responses of birds to natural gas development, assisting managers in the management of grassland habitats and allowing for the increased conservation of these species.

1.3 Objectives

My goal was to identify the impact of gas well infrastructure on the relative abundance of grassland songbirds in southeastern Alberta. Specific objectives included:

1. Evaluate the impact of shallow gas well density on the relative abundance of grassland songbird species
2. Determine the influence of proximity to wells on the relative abundance of grassland songbirds
3. Investigate whether the effects of gas well infrastructure on grassland songbird relative abundance are caused by the impact of this infrastructure on vegetation structure and cover

1.4 Research Hypotheses

I predicted that if the effects of natural gas well density were driven by edge effects associated with habitat fragmentation caused by shallow gas well infrastructure, then area-sensitive grassland songbird species would be negatively affected by increasing infrastructure density, and those species that respond negatively to distance to infrastructure would also respond negatively to infrastructure density. However, if infrastructure was surrounded by exotic vegetation introduced during re-vegetation or by vehicle activity, then vegetation structure likely differed from the surrounding native prairie, and bird species that avoid exotic vegetation would be the same species that have lower densities near infrastructure. Also, these species would only avoid infrastructure that had exotic vegetation adjacent to it, and not necessarily sites with higher well densities.

Patch sizes may be reduced by linear features associated with the natural gas industry and additional edge habitat is created by mowing vegetation surrounding gas wells to minimize fire risk. Due to their area sensitivity, it was predicted that Sprague's pipit (*Anthus spragueii*; Herkert 1994; Bolger et al. 1997; Davis 2004), chestnut-collared longspur (*Calcarius ornatus*; Davis 2004; Skinner 2004; Davis et al. 2006) and Baird's sparrow (*Ammodramus bairdii*; Johnson and Igl 2001; Davis 2004) would be negatively correlated with gas wells. In contrast, brown-headed cowbird (*Molothrus ater*) may respond positively to a reduction in patch size, (Johnson and Igl 2001; Horn et al. 2002) and therefore were predicted to increase with proximity to wells and at higher well densities. Horned lark (*Eremophila alpestris*), Savannah sparrow (*Passerculus sandwichensis*), and western meadowlark (*Sturnella neglecta*) may be insensitive to patch size (Davis 2004), though other studies have indicated that they are area sensitive (Herkert 1994; Vickery et al. 1994; Bollinger 1995), which would cause natural gas industry development to have less of an impact on these bird species.

Past research has shown that natural gas activities can greatly influence vegetation (Leu et al. 2008), which is an important habitat and nest site selection criteria for grassland songbirds (Fisher and Davis 2011*a*). However, different species of grassland songbirds demonstrate a range of preferences for vegetation characteristics and some species are tolerant of exotic vegetation and others are not. I predicted that gas wells and access routes would be correlated with an increase in the amount of crested wheatgrass and bare ground and a decrease in litter depth and vegetation. Due to these predicted changes in vegetation community structure, decreases in Sprague's pipit, Savannah sparrow, Baird's sparrow, chestnut-collared longspur, and western meadowlark close to wells and at sites with higher well densities were predicted.

1.5 Limitations

Well densities vary greatly in different areas of the prairies and results achieved in this study may not necessarily be extended to natural gas well operations in other regions with higher infrastructure levels, other forms of infrastructure or additional types of energy development. Also, other types of energy infrastructure may require higher visitation to well sites, which may have a greater impact on songbirds and their habitat.

Point count data provide a measure of relative abundance (Johnson 2008), but may not provide a complete understanding of anthropogenic effects on birds. For example, additional sampling that investigates nesting would be advantageous for determining how industrial development is influencing breeding birds and their nesting success. This is especially important in prairie habitats as grassland bird densities may be unrelated to nest success (Zimmerman 1971; Vickery et al. 1992; Winter and Faaborg 1999). Debate surrounds the use of point count data as an indication of habitat quality (Van Horne 1983; Bock and Jones 2004) and habitat quality assessments should be completed in addition to point counts. Disturbance by humans and competition from conspecifics in optimal habitat may cause individuals to instead use suboptimal habitat (Bock and Jones 2004). Therefore, relative abundance of birds may not indicate the quality of habitat or reproductive success; however, in a review of the available literature, Bock and Jones (2004) found that in most cases point counts could be used to assess habitat quality.

Bird species sing at different times of day and since point counts were initiated at sunrise and completed within 4 hours, not all species may be equally accounted for (Beason 1995). The horned lark, for example, will sing before dawn until 15 minutes after sunrise (Beason 1995) and its flight song may be heard most commonly around noon (Pickwell 1931). Given these singing times, horned lark may be underrepresented in point count data collected in this study. Savannah sparrow may also be underrepresented (Wheelwright and Rising 2008). It is not anticipated that chestnut-collared longspur (Hill and Gould 1997), clay-colored sparrow (*Spizella pallida*) (Knapton 1994), vesper sparrow (*Pooecetes gramineus*; Jones and Cornely 2002), Sprague's pipit (Robbins and Dale 1999) or western meadowlark (Davis and Lanyon 2008) would be underrepresented in point count data due to their daily patterns of singing. Daily singing patterns of Baird's sparrow are unknown (Green et al. 2002). To ensure that daily vocalization patterns did not confound my results, all point count surveys were completed during the same period of time each day.

Birds may also move away from the point count observer as they enter the plot, thereby making point count data less representative (Leuders et al. 2006). This error, however, is likely to be constant among bird species as they behave similarly in the presence of humans, and should not cause errors in analyses based on relative abundances.

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CHAPTER 2: LITERATURE REVIEW

2.1 Degradation of Mixed-grass Prairie

Grasslands across North America have experienced extensive conversion by humans, becoming severely functionally degraded and fragmented remnants of their previous extent (Herkert 1994). The Great Plains is the largest vegetative province found in North America and includes tall-grass, short-grass and mixed-grass prairie. Historically, mixed-grass prairie extended from central Canada to eastern North Dakota and south to Texas (Samson and Knopf 1994). Protection of this ecoregion has been limited (Samson and Knopf 1994; Hoekstra et al. 2005), which has allowed greater than 50 % of the historical extent of temperate grasslands and savannas to be lost. Many remnant prairies continue to be at risk of land-use conversion and other anthropogenic uses such as livestock grazing (Hoekstra et al. 2005) and industrial development.

The term *habitat loss* refers to changes in habitat amount on the landscape (Fahrig 2003). In the mixed-grass prairies, habitat loss has occurred primarily due to land-use conversion (Herkert 1994). Historically, losses of prairie habitat have been largely concentrated in the tall-grass prairie, with lower amounts of land-use conversion occurring in the short-grass and mixed-grass prairie (Ogg 2006). This is primarily due to more fertile soils found in tall-grass prairie. In more recent years, however, conversion of land for agriculture has increased in mixed-grass prairie and has been assisted by government subsidies. Agricultural land-uses have not only caused a decrease in habitat for grassland songbirds and other species, but have also restricted the natural disturbance cycles that alter native vegetation structure and composition.

Historically, prairies would have been influenced by prairie dog (*Cynomys* spp.) colonies and bison (*Bison bison*) grazing (Fahnestock and Detling 2002). Prairie dog colonies reduced biomass and increased prairie vegetation diversity, while bison altered nutrient cycling through their grazing intensity and selection of vegetation. Today, cattle (*Bos taurus*) grazing occurs throughout the prairies (Plumb and Dodd 1993), including on the study sites for this research. Both bison and cattle are thought to be generalist grazers; however, cattle are more selective in their foraging at smaller scales, but at a larger patch scale bison are more selective (Damhoureyeh and Hartnett 1997, Hartnett et al. 1997). Overall, cattle may be beneficial grazers in a landscape that is devoid of its previous bison population, but this change in disturbance to the vegetation may have implications for other species, such as songbirds, that are sensitive to vegetation structure (Vickery et al. 2001; Fisher and Davis 2011*a*; Fisher and Davis 2011*b*). Changes in vegetation structure caused by cattle grazing may be compounded with land-use changes and industrial development, such as by the natural gas industry, which also have implications for vegetation structure and composition.

Natural gas development often includes the construction of gas wells and access roads and trails. The footprint of these developments reduces the amount of native prairie habitat and may also affect its quality (Leu et al. 2008). Areas surrounding newly drilled oil or gas wells and installed roads are seeded after construction and following decommissioning, but non-native seeds may be used for re-vegetation (Simmers and Galatowitsch 2010). Since the mid-1990s it has been suggested that native seeds be used during re-seeding (EUB IL92-12 1992, Government of Alberta) and in 2003 this became a requirement in Alberta (R&R/03-5, Alberta Environment). However, some studies have found that non-native species may still be present in the seed mixes used (Simmers and Galatowitsch 2010). This means that the drilling of gas wells, construction of roads and the decommissioning of these industrial developments continues to reduce the amount of native mixed-grass prairie.

Anthropogenic development of grasslands has caused an increase in fragmentation, which increases edge effects in addition to reducing patch sizes, (Fahrig 2003) and increasing their isolation (Saunders et al. 1991, Fahrig 2003). Natural gas development may increase edge effects through the construction of roads, trails and well pads, which become matrix habitats and contribute to habitat loss. Unlike habitat loss, fragmentation may cause an increase or a decrease in biodiversity and may benefit some species over others (Fahrig 2003). For example, fragmentation has been identified as limiting to Savannah sparrow, grasshopper sparrow (*Ammodramus savannarum*) and red-winged blackbird (*Agelaius phoeniceus*), but has no impact on dickcissel (*Spiza americana*; Herkert 1994). Further, Huffaker (1958) suggested that fragmentation can sometimes stabilize predator-prey relationships and other studies have indicated that it may stabilize competition (Levin 1974; Slatkin 1974; Atkinson and Shorrocks 1981; Shmida and Ellner 1984).

2.2 Grassland Bird Population Declines

Grassland bird species have experienced greater declines than birds of any other habitat type in North America (Herkert 1994, 1995; Herkert et al. 2003; Sauer et al. 2008). Between 1966 and 1996 populations of 13 North American grassland bird species exhibited significant declines, while only 2 populations increased (Sauer et al. 2008). Of these 13 grassland bird species, more than 50 % experienced cumulative population declines of greater than 50 %, with a mean annual decline of approximately 2.6 % (Herkert 1995).

Land-use alteration and habitat loss are the most commonly proposed reasons for declines in grassland bird populations. Native grasslands have been replaced by rangelands, hayfields and row-crop agriculture, decreasing the overall habitat amount available for prairie songbirds and reducing biodiversity (Herkert 1994, 1995; Herkert et al. 2003; Sauer et al. 2008). The anthropogenic fragmentation associated with these developments can have a negative effect on species when patch sizes have been reduced to an extent that they will not support a local population or individual territory (Fahrig 2003). Smaller fragments support a lower diversity of breeding bird species and fewer breeding pairs (Herkert 1994). Studies by Herkert (1994) in Illinois between 1987 and 1989 demonstrated that some species, including grasshopper sparrow and Savannah sparrow, were more likely to occur in larger patches. In a Saskatchewan study, it was found that patch size did not strongly influence the nesting success of Sprague's pipit or clay-colored sparrow, although Sprague's pipit numbers decreased with reductions in pasture sizes (Davis et al. 2004). As well, nest survival of Savannah sparrow increased with patch size (Davis et al. 2006).

Fragmentation may also increase the amount of habitat edge, which can reduce breeding success in grassland birds and increase the success of predator species (Johnson and Temple 1990; Herkert et al. 2003; Fletcher et al. 2006). Competitive exclusion can also result from fragmentation. Habitat patches may become more suitable to some predator species making the patches not available or inaccessible to prey species, such as grassland songbirds. Nest predators such as snakes (Squamata) and mice (Muridae), however, do not benefit at the same scale of fragmentation as other predators such as coyotes (*Canis latrans*), crows (*Corvus* spp.) and hawks (Herkert et al. 2003). The presence of edges can decrease nest density and increase depredation of Savannah sparrow, grasshopper sparrow and meadowlark (*Sturnella* spp.) nests (Renfrew et al. 2005). Another study concluded that a decrease in patch size negatively influenced the nesting success of Savannah sparrow (Davis et al. 2006). Further, edge habitat may serve as an ecological trap or population sink if it attracts both prey and predators (Suarez et al. 1997; Hamer et al. 2006). Distance to edge has also been shown to impact the relative abundance of Sprague's pipit (Linnen 2006). Lower abundances of the songbird may extend to at least a distance of 250 m from oil wells and access roads. Breeding success can further be hampered in smaller fragments by an increase in brood parasitism (Suarez et al. 1997).

Other key factors contributing to wildlife population declines include reduced habitat connectivity (Donald and Evans 2006), changes in vegetation structure (Herkert 1994, Davis 2004), land-use of surrounding matrix habitat (Dunford and Freemark 2004), patch sizes and amount of edge (Herkert 1994, Winter et al. 2006) and habitat arrangement (Flather and Bevers 2002). The matrix can influence the persistence of populations within patches (Fahrig 2003), the ability of species to disperse and use habitats across the landscape (Ricketts 2001) and the quality of patches adjacent to the matrix (Saunders et al. 1991). If species are unable to cross the matrix habitat, then they may be confined to patches that are too small to support a population or territory, reducing the probability of species persistence (Fahrig 2003). This means that the quality of matrix habitat may dictate dispersal and patch colonization rates (Bender and Fahrig

2005) and the effective isolation of patches (Ricketts 2001, Carroll et al. 2004). When habitat fragments are small species may be forced to cross other habitat types to reach another suitable habitat and dispersal mortality may occur (Fletcher et al. 2006). This is increasingly likely in landscapes that have been heavily altered by human development. In this study, the construction of roads, trails and well pads by the natural gas industry not only contributes to the fragmentation of the grassland landscape, but also increases the amount of edge and matrix habitat present. Matrix habitat may be used by predator species as corridors, which can influence breeding success and mortality rates of prey species both within the matrix and in adjacent patches of habitat. As well, the matrix may serve as a source for the introduction of invasive or edge species (Saunders et al. 1991). The genetic diversity of songbird populations may decrease faster in anthropogenically fragmented habitats versus naturally fragmented habitats (MacDougall-Shackleton et al. 2011). This loss in genetic diversity can have implications for bird fitness and population persistence.

Studies have examined the effects of breeding ground habitat loss, fragmentation and edge effects on grassland birds, but few studies have evaluated the impacts of changes occurring at their wintering grounds (Vickery and Herkert 2001). Future research in these regions is required to better understand how changes occurring where species over-winter may be contributing to population declines that cannot be accounted for in studies occurring in their breeding grounds.

2.3 Effects of Energy Development on Wildlife

Energy development is widespread across North America, as natural gas, crude oil, wind energy and other natural resources are harvested. With the reliance of our society on these resources, energy development continues and it becomes increasingly important to identify the impacts of the industry on wildlife and their habitats (Arnett et al. 2007; Habib et al. 2007; Riley et al. 2012).

Crude oil production in Canada occurs from conventional oil deposits as well as non-conventional sources such as in the oil sands. The province of Alberta alone accounts for the largest producing area of oil in North America (Government of Alberta 2010). Across North America, the fossil fuel industry directly and indirectly influences wildlife. Many species of ungulates migrate seasonally and demonstrate strong habitat fidelity (Garrott et al. 1987), but with the construction of infrastructure used by the energy industry, these habitats are being converted and fragmented (Wisdom and Cook 2000; Toweill and Thomas 2002; O'Gara 2004; Watkins et al. 2007) and native palatable vegetation species are being reduced in favour of unpalatable exotics such as cheatgrass (*Bromus tectorum* L.; DiTomaso 2000, Schaffer et al. 2003). Surface disturbances, such as those caused by the fossil fuel industry, allow exotic species to spread (Bradford and Lauenroth 2006). Drilling of new oil wells is a source of disturbance to pronghorn (*Antilocapra americana*) with animals avoiding drill sites within their winter ranges (Easterly and Guenzel 1992), but to date no population-level impacts have been identified (Riley et al. 2012).

The greater sage-grouse (*Centrocercus urophasianus*) is endemic to semiarid sagebrush (*Artemisia* spp.) habitats across North America (Schroeder et al. 1999) and has suffered population losses of 1.8 to 11.8 % annually for the last four decades (Garton et al. 2011). Greater sage-grouse have been extirpated from approximately half of their historic range (Schroeder et al. 2004) and remaining populations are of concern as they coincide with areas of substantial energy industry development (Riley et al. 2012). Common oil well densities of 8 pads per 2.6 km^2 (1×1 mile section) have been shown to strongly impact greater sage-grouse breeding populations (Holloran 2005, Walker et al. 2007) with lower male lek attendance adjacent to oil development (Harju et al. 2010) and at higher well densities. A study completed at the Manyberries Oil Field in Alberta (Aldridge and Boyce 2007) found that chick survival decreased with an increase in proximity to oil and gas wells.

Waterfowl are also impacted by crude oil industry development in North America. Before drilling even occurs waterfowl are impacted by the exploratory seismic lines that fragment the landscape and reduce wetland habitat (Riley et al. 2012). The creation of oil sands also negatively impacts waterfowl, as fresh water is diverted from lakes, wetlands and rivers. Tailings produced during oil extraction are held in large ponds, which also pose a threat to waterfowl that may land on their surface and become coated in oil and other toxic substances (Trail 2006). For example, in 2009, more than 500 ducks (Anatidae) died after landing on a tailings pond in the Alberta tar sands (Riley et al. 2012).

Songbirds have also been greatly impacted by crude oil industry development in North America. In addition to having negative effects on waterfowl, waste fluids such as produced water also influence songbirds (Trail 2006). Haying or the removal of shrubs surrounding wells and linear features to reduce fire risk, increase visibility and limit snow accumulation (Riley et al. 2012) may negatively influence songbirds (Bollinger et al. 1990). Haying may affect grassland songbirds by destroying nests, eggs and young during the breeding season and the removal of vegetation can increase abandonment and predation. Direct habitat loss caused by infrastructure development also negatively impacts songbirds, contributing to their population losses (Bayne et al. 2008). Exotic vegetation may also be introduced or spread when crude oil wells are drilled or decommissioned (Tyser and Worley 1992; Larson et al. 2001; Gelbard and Belnap 2003; Gelbard and Harrison 2003). In the short-term, birds may move to avoid oil well drilling locations (Riley et al. 2012). Long-term avoidance of these areas may then occur due to repeated visitation to well sites by humans for maintenance, which can create acoustic, physical and visual disruptions to birds. Anthropogenic noise created by wells, related infrastructure and maintenance equipment also effectively eliminates habitat for birds that acoustically communicate (Bayne et al. 2008). Boreal songbird habitat loss caused by the creation of seismic lines is often long-term as the regeneration of ground vegetation species is slow (Lee and Boutin 2006). Many seismic lines are replaced by roads, pipelines or buildings causing long-term habitat loss (Lee and Boutin 2006).

Solar energy has emerged as a popular renewable source of energy in North America and is beginning to be applied on a large scale. Unfortunately, the impacts of these large-scale solar developments on wildlife are generally unknown and research to date has been limited (Lovich and Ennen 2011). Many of the landscapes that are ideal for solar industrial development also support a high biodiversity and sensitive ecosystems, such as in the Mojave desert (Randall et al. 2010). The construction and decommissioning phases of solar farms have the potential for large impacts on a variety of wildlife species. Large surface disturbances are required for solar energy facilities and are even larger when dry-cooling systems are used. The alternative to dry-cooling systems are wet-cooling systems; however, these have a large water requirement that often cannot be satisfied (Randall et al. 2010). Road construction and vegetation removal are also common during the construction of solar facilities, which increase the amount of ambient dust in the area (Munson et al. 2011). This dust can reduce solar panel productivity, so dust suppressants are often used. These suppressants have been found to harm vegetation (Goodrich et al. 2008) and reduce primary productivity in the surrounding habitat (White and Broadly 2001). Habitat fragmentation caused by the industry has further implications for large mammals such as bighorn sheep (*Ovis canadensis*) and deer (Cervidae), as well as other species such as desert tortoises (*Gopherus morafkai*). Noise, electromagnetic field generation, pollutants from spills such as at wet-cooled facilities, increased fire risk and light pollution are also of concern for wildlife located near solar development (Lovich and Ennen 2011). Some of these issues, such as road construction, vegetation removal and habitat fragmentation are also a concern with oil and natural gas development in grasslands and could become cumulative issues if alternative energy production such as solar power is pursued in the region.

Wind energy is also becoming a popular form of renewable energy in North America and large-scale facilities are being constructed across the continent. These developments directly reduce wildlife habitat, fragment habitat through the construction of linear features and cause avoidance of turbines in some species. Further, turbines can result in bird (Erickson et al. 2002; Johnson et al. 2002, 2003; Smallwood and Thelander 2004) and bat (Chiroptera; Kerns and Kerlinger 2004; Arnett 2005) mortalities due to collision with the blades, towers, support structures and power lines. In fact, bat mortality has been so high in some recorded instances, that population-level impacts are of a concern (Fieldler 2004; Kerns and Kerlinger 2004; Arnett 2005; Arnett et al. 2007).

Bat collisions are higher with turbines than other infrastructure of similar heights, suggesting that the turbines are a possible source of attraction to the species, may cause sensory failure or alter the density or distribution of bat prey (Arnett 2005; Kunz et al. 2007). Raptor (Falconiformes) habitats often overlap with planned or current wind developments, which is why the most extensive research has been completed on impacts of the industry on these species. Research has found that collisions of raptors with wind turbine blades are variable by species and the style of turbine in use (Arnett et al. 2007). Generally, newer generation turbines have been associated with fewer raptor collisions (Arnett et al. 2007). Studies examining the impact of wind turbines on passerines have also been completed, but have not found population-level impacts (Nelson and Curry 1995; Osborn et al. 2000; Erickson et al. 2001). Habitat loss or degradation caused by wind turbines also have negative implications for ungulates (Arnett et al. 2007), as well as other species such as the California ground squirrel (*Spermophilus beecheyi*) (Rabin et al. 2006). Negative implications have also been discovered for wildlife in areas with offshore wind turbines (Arnett et al. 2007). These impacts may be cumulative in addition to the introduction of exotic vegetation, habitat loss, fragmentation and edge effects caused or facilitated by roads, trails and wells that are constructed by the natural gas industry.

2.3.1 Natural Gas Development

Natural gas is a common source of energy used by society in North America. To satisfy our society's growing demand for energy resources increasing numbers of permits and leases are being assigned for natural gas across the continent, allowing the industry and domestic energy production to grow (Shore 2004). However, the increase in natural gas industrial development is of concern to many wildlife biologists, managers, interest groups and the public, as many of the effects of this industry on habitat and wildlife species are not well understood. Further, the growth of the natural gas industry may be considered cumulative in addition to other anthropogenic developments, including those for other energy sectors such as crude oil, wind and solar. Often the resulting landscape is bisected by various access roads, trails, pipelines, transmission lines as well as other infrastructure, all which have possible negative implications for wildlife (Riley et al. 2012). Though this research does not address cumulative impacts of the energy sector, it will help fill the knowledge gap that exists surrounding the impacts of the natural gas industry on grassland songbirds.

Natural gas industrial development often requires the construction of access roads, trails and pipelines in addition to shallow gas wells. Compressor stations that are used to optimize the efficiency of gas extraction from wells and to pressurize the gas pipelines for transportation of the extracted resource (LaGory et al. 2001) are also constructed by the natural gas industry. Additional infrastructure varies by company and their methods for extraction and transportation of the natural gas. For example, coal-bed methane gas wells are common in certain regions of North America and involve the removal of water in the formation so that natural gas in coal seams will move towards areas where wells will be able to extract it (Riley et al. 2012). This formation water is also referred to as produced water, which in some cases is stored in impoundments with surface areas as large as several hectares. Forty-six of the 308 natural gas wells located at my study sites are coal-bed methane wells. Shallow gas well surface infrastructure typically consists of a series of pipes emerging upright from the ground surrounded by low metal fencing.

These gas wells vary in size and may also include large tanks. On average, the footprint of wells located at my sites was 23.1 m^2 with a height of 1.44 m^2. It has been estimated that at a well density of 41 wells per km^2 (16 per 1×1 mile section; hereafter "site") in grassland habitats, the footprint of development can be 3.1 to 12 % of the landscape (Government of Canada 2008).

Natural gas development occurs in a variety of habitat types including shrub-dominated basins that are seasonally important to many ungulates and possess some of the largest natural gas reserves (Sawyer et al. 2009). Many ungulate species travel between seasonal ranges due to changes in their food requirements and weather patterns (Wallmo et al. 1977; Toweill and Thomas 2002; O'Gara and Yoakum 2004). Natural gas developments in these important seasonal ranges, as well as on migration routes, are a concern for ungulate populations in North America. As with crude oil and other energy developments, the construction of infrastructure such as roads and trails in addition to natural gas wells results in a direct loss of habitat for ungulate species (Watkins et al. 2007). Surface disturbances associated with the construction of this infrastructure may further cause the introduction and spread of unpalatable exotic vegetation (Bradford and Lauenroth 2006). Compressor stations used by the natural gas industry produce noise at levels between 75 and 90 decibels at the source, which is similar to a traffic volume of 50,000 cars per day (Riley et al. 2012) and pronghorn have exhibited avoidance of areas with noise levels of greater than 55 decibels (Landon et al. 2003). Further, the cumulative impact of natural gas and other anthropogenic developments is predicted to increase competition between ungulate species (Stewart et al. 2002; Watkins et al. 2007). Oil and natural gas development is likely to change the movement patterns of elk (*Cervus* *canadensis*), forcing them to share habitat with mule deer (*Odocoileus hemionus*) and thereby increasing forage competition (Watkins et al. 2007). The Wyoming Fish and Game Department (2010) suggested that 4 wells or 24.3 ha of disturbance per 259 ha in elk winter ranges reduced herd productivity and survival. Elk were particularly sensitive to both oil and gas developments with any density of wells greater than 4 per 259 ha and 24.3 ha of disturbance causing stress, avoidance and habitat impairment (The Wyoming Fish and Game Department 2010).

Greater sage-grouse, which are sensitive to anthropogenic disturbances, are of concern in regions where their habitats overlap areas of natural gas industry development. Male attendance to leks is lower in areas near natural gas wells (Harju et al. 2010) and lek losses in areas surrounded by oil and gas development are common (Kaiser 2006). Walker et al. (2007) found that only 38 % of leks with new natural gas development remained active 7 and 8 years later, compared with 84 % of leks with no development present. The presence of at least one gas well within a 0.4 km radius reduced male lek attendance by 35 to 91 % in comparison with lek sites devoid of wells (Harju et al. 2010). Harju et al. (2010) also found that a well density of 3.1 per km^2 decreased lek attendance by 77 to 79 % in comparison with leks farther than 8.5 km from wells. In Alberta, greater-sage grouse avoided winter habitats within a 1.9 km radius of energy development (Carpenter et al. 2010). Population-level declines have been found when leks are avoided for one or more seasons (Doherty et al. 2008; Carpenter et al. 2010). Energy development has not only caused a shift in the habitat available to greater sage-grouse, but also a decrease in the distribution of the species (Walker et al. 2007). Other studies have detected decreased male lek attendance within 5 km of active drilling rigs or

3 km of a producing natural gas well (Holloran 2005). Ponds used to hold produced water from coal-bed methane extraction can increase late-summer mortality caused by West Nile virus in greater sage-grouse (Walker et al. 2004; Zou et al. 2006; Walker et al. 2007).

The largest threat from natural gas development to waterfowl is the produced water that results from coal-bed methane extraction (Riley et al. 2012). Produced water can influence waterfowl in a variety of ways depending on the quantities and constituents present in the produced water and can affect the metabolism, fat content, reproductive state and feeding behaviour of the bird (Frost et al. 1998). Waste fluids can also negatively impact songbirds. Mortalities in more than 172 species of birds, mostly ground-foraging songbirds, have been related to energy industry waste fluids (Trail 2006). It is estimated that between 500,000 and 1 million birds are killed each year in energy extraction waste waters in the United States alone (Trail 2006).

Natural gas development can have both direct and indirect impacts on songbirds through habitat loss, avoidance, noise, vegetation structure and composition changes, creation of edge, fragmentation and reduced breeding success (Riley et al. 2012). Despite the numerous potential effects of the natural gas industry, little research has been completed on the impacts to songbirds. In boreal Alberta, 3,000 dead songbirds from at least 26 different species were found within 75 m of a natural gas flare stack 100 m in height that is used to burn off gases such as hydrogen sulfide (Bjorge 1987). Some of these mortalities were caused due to collisions with the stack and others due to pulmonary congestion caused by stack emissions. The height of such structures increases the chances of collisions (Mabey and Paul 2007), as with wind turbines. Similarly to bird collisions with wind turbines, night migrations and weather conditions such as heavy cloud cover result in the most stack-related mortalities. Songbird collisions with other natural gas infrastructure such as towers, power poles and power lines are also possible, but less likely due to their shorter heights (Riley et al. 2012).

Direct loss of habitat due to natural gas development is another concern for songbird species. Research completed in the boreal forest found that ovenbirds (*Seiurus aurocapilla*) were never detected at point counts located on pipelines, power lines, roads or in small clearings of 0.5 to 2 ha, such as are created for small well pads (Bayne et al. 2008). As well, early-successional habitats that are created by the natural gas industry and replace mature forest are not suitable for and are limiting to the ovenbird. After wells are drilled, pesticides are often used to control the spread of exotic vegetation surrounding the wells. These chemicals can cause lower nest success rates (Blus and Henry 1997; Hart et al. 2006) and increase mortality (Mineau 2000).

Noise created during crude oil and natural gas drilling and from compressor stations is another issue. Drilling noise levels are 70 decibels at 50 m from wells and maintenance noise levels can reach 72 decibels (EnCana 2007). At 1.5 km from well sites drilling noise levels still reach greater than 25 decibels. Anthropogenic noise can disrupt acoustic communication between individuals and can reduce habitat quality for birds (Riley et al. 2012). Over time, if anthropogenic noise persists, suitable habitat may be avoided (Bayne et al. 2008). In the boreal, bird densities were 1.5 times higher in forests with no anthropogenic noise in comparison with forests near a compressor station. Abundance of a third of the songbirds declined within 300 m of a compressor station (Bayne et al. 2008). Male ovenbirds near compressor stations are less likely to attract mates than those in quieter areas (Habib et al. 2007). Spotted towhee (*Pipilo maculatus*) declined when compressor stations were built, were observed farther from the source of noise (LaGory et al. 2001) and their nesting sites were found farther from the source of noise (Francis et al. 2009). Though many songbird species are negatively impacted by high noise levels, some generalist species may actually benefit. Francis et al. (2009) found that nesting success was increased in the presence of noise due to a disruption of predator-prey interactions. LaGory et al. (2001) also found that relative abundance of house finches (*Carpodacus mexicanus*) and juniper titmice (*Baeolophus griseus*) were significantly higher close to compressor stations and compared to control sites with no anthropogenic noise, which was explained by reduced competition due to the absence of other species in this area.

To date, a limited amount of literature is available that has evaluated the influence of natural gas development on grassland songbird communities (Dale et al. 2009), and the information that is available sometimes conflicts. A study completed on the Canadian Forces Base Suffield National Wildlife Area suggested that the occurrence of Baird's sparrow and Sprague's pipit decreased as natural gas well densities increased (Dale et al. 2009). Habitat near wells was also avoided by Sprague's pipit (Dale et al. 2009; Kalyn-Bogard 2011), which were never found within 50 m of wells (Kalyn-Bogard 2011). Another study found that both the footprint of natural gas development and the density of natural gas wells had significant negative implications for Sprague's pipit (Hamilton et al. 2011). Other studies have also found that Baird's sparrow increased in numbers at greater distances from natural gas wells (Great Sandhills Advisory Committee 2007). Noise created during pipeline construction overlaps with the sound frequencies produced by Sprague's pipit, which has caused reduced territory sizes for the species during this period (Skiffington and Pittaway 2010). Another study found an increase in Savannah sparrow at greater gas well densities (Dale et al. 2009). In contrast, other research has indicated that there is little influence of natural gas development on grassland songbirds and that in some cases songbirds may respond positively to energy development. For example, Linnen (2006) completed a study in Saskatchewan where chestnut-collared longspur, Sprague's pipit and Baird's sparrow did not demonstrate a significant pattern of avoidance surrounding minimal disturbance gas wells. Overall, it appears that there may be a negative impact of natural gas development on grassland songbirds, but the impacts and their extent are not yet clear due to conflicting results from studies and limited research completed to date.

2.3.2 Linear Features

Linear features associated with crude oil and natural gas development, such as trails and roads, seismic lines and pipelines may also impact birds. For example, Ŝálek et al. (2010) found that seismic lines caused local population declines in ovenbirds and avoidance of the lines was observed as long as 30 years after their use. Similarly, Fleming and Schmiegelow (2003) found that point counts that were located on pipelines greater than or equal to 15 m in width only rarely detected forest specialists. However, generalist species that prefer early-successional habitats, such as American robin (*Turdus migratorius*), were more common near energy development (Fleming and Schmiegelow 2003). In my study area, the natural gas industry does not currently have seismic lines or above-ground pipelines, but does use trails and roads to access gas wells for maintenance activities and yearly checks. Research has indicated that bird densities (Reijnen et al.

1995; Reijnen and Foppen 1995; Ortega and Capen 2002) and breeding activity (Reijnen and Foppen 1994; Foppen and Reijnen 1994; Miller et al. 1998) generally decrease as proximity to roads or trails increases and noise, high traffic volume and edge effects may cause avoidance of roads and trails by songbirds (Ŝálek et al. 2010). In Illinois, horned lark densities increased with distance from roads (Clark and Karr 1979) and research in Alberta on Sprague's pipit found that their territories rarely cross trails (Dale et al. 2009; Hamilton 2010) and they demonstrate avoidance of non-native vegetation such as crested wheatgrass, which may be introduced along these linear features (Dale et al. 2009). However, data collected in Saskatchewan have indicated that the relative abundances of Sprague's pipit, western meadowlark, chestnut-collared longspur, Baird's sparrow, Savannah sparrow, horned lark, grasshopper sparrow, vesper sparrow and clay-colored sparrow did not significantly decrease in the presence of natural gas wells or associated trails (Linnen 2006). Narrow, low-traffic access trails were avoided by Brewer's sparrow (*Spizella brewerii*), with lower abundances of the species found within 100 m of the trail (Ingelfinger and Anderson 2004). Even walking paths can cause a reduction in bird abundances and nests (Miller et al. 1998).

Collisions with vehicles are a high source of mortality to songbirds during both the breeding and wintering season (Forman and Alexander 1998, Higgins et al. 2007, Lloyd et al. 2009). However, fewer avian mortalities have been recorded on Alberta roads with lower traffic volumes and speed limits (Clevenger et al. 2003), such as those found within my study area. Lower traffic volumes and speed were also associated with fewer avian deaths in a Saskatchewan study (Fortney 2010). Ramp et al. (2006), however, suggest that lower traffic volumes and speed are only significant in reducing wildlife collisions if the organism is visible to the driver at a distance of at least 25 m. Also, though maintenance activities are infrequent in my study area, and therefore traffic noise is minimal, short-term avoidance of habitat is possible (Riley et al. 2012). Most negative impacts of linear features have been associated with paved access roads, with positive effects sometimes associated with pipelines, power lines or gravel roads (Riley et al. 2012). No paved roads were directly adjacent to my study sites. Trails and dirt roads, which were located adjacent to or within sites in this study, have less of an impact on vegetation than paved roads (Sutter et al. 2000). However, trails and roads have been associated with decreased numbers of nesting grassland birds (Miller et al. 1998; Barton and Holmes 2007).

Native prairie that is lost through the construction of access roads and trails and the exotic plants that they introduce also impact grassland songbirds through a change in vegetation structure. In my study area, roads and trails associated with the natural gas industry have been known to increase the abundance of the exotic species crested wheatgrass in surrounding areas. Once crested wheatgrass has been introduced it can spread as much as 1-2 m a year (Henderson and Naeth 2005) and out-compete native grasses (Schuman et al. 1982; Henderson and Naeth 2005). Also, the structure and structural diversity provided by non-native vegetation can vary widely from that of native species causing these areas to not be selected as territories by native birds (Fleishman et al. 2003; Fisher and Davis 2011*a*). Exotic vegetation can cause a reduction in habitat heterogeneity, which is not suitable habitat for grassland songbird species such as Sprague's pipit (Fisher and Davis 2011*a*). In particular, crested wheatgrass has a lower density of standing vegetation within 10 cm of the ground, a relatively small contribution to the litter layer and exposes more bare ground than native prairie grass species (Sutter and Brigham 1998). Overall, crested wheatgrass is taller and has a greater amount of standing dead vegetation than native grasses. Crested wheatgrass reduces native cover and diversity (Christian and Wilson 1999; Heidinga and Wilson 2002; Henderson and Naeth 2005) and is associated with a lower diversity of arthropods (McIntyre and Thompson 2003; Flanders et al. 2006) and a decreased abundance of grassland songbirds (Sutter and Brigham 1998). The diversity of grassland birds may also shift in areas with high amounts of crested wheatgrass cover (Chapman et al. 2004) and some species experience decreased nesting success (Lloyd and Martin 2005).

Energy companies may remove vegetation surrounding gas wells, roads and trails to mitigate the risk of fire, increase visibility and limit the accumulation of snow (Riley et al. 2012). The process of removing vegetation during the breeding season can destroy the nests, eggs and young of grassland songbirds and can cause an increase in abandonment and depredation (Bollinger et al. 1990). When vegetation is removed through haying or mowing almost all grassland nests are destroyed (Riley et al. 2012). Removal of vegetation may also impact songbirds by altering vegetation structure.

Vegetation structure and composition can influence habitat selection and bird abundances as well as breeding success. Litter depth, amount of bare ground, vegetation height and density (Herkert 1994; Delisle and Savidge 1997; Davis 2004), and proportions of mosses (Delisle and Savidge 1997; Davis 2004), shrubs, grasses and forbs (Herkert 1994; Delisle and Savidge 1997; Davis 2004) can significantly alter songbird distributions (Herkert 1994). Dense vegetation provides concealment of nests from possible predators (Johnson and Temple 1990), but small mammalian predators such as certain species of mice may be more common in dense vegetation (Litt and Steidl 2011). Savannah sparrow may also select sites based on dominance of live vegetation cover (Herkert 1994). Vegetation structure can be a limiting factor to area-sensitive species in small fragmented patches and may allow for increased nest predation (Renfrew et al. 2005) and brood parasitism. Both Sprague's pipit (Dale et al. 2009; Hamilton 2010) and Baird's sparrow (Dale et al. 2009) prefer habitats dominated by native vegetation, and occur in lower numbers in non-native dominated habitats. In non-native cover, chestnut-collared longspur nesting success is reduced and chicks are smaller compared with nests with native cover (Lloyd and Martin 2005). In this study, it is important to recognize that linear features used by the natural gas industry may be introducing or assisting the spread of exotic species such as crested wheatgrass, which provide a different vegetation structure than native grass, and that this can cause a shift in the territories and nest sites that are selected by grassland songbirds.

2.4 Natural History of Grassland Songbirds

The natural history of 5 focal grassland songbird species in this study is detailed below.

2.4.1 Sprague's Pipit (*Anthus spragueii*)

Sprague's pipit is a migratory songbird endemic to North American grasslands and is known for its unique circular, aerial territorial flight displays that last from 30 minutes to over 3 hours (Robbins and Dale 1999). Their breeding range extends from the northern Great Plains of southeast Alberta, through south Saskatchewan, southwest Manitoba, north and central Montana and throughout North Dakota. Sprague's pipit prefer breeding habitat in well-drained open areas of grassland that are relatively devoid of shrubs, even at low densities. The species selects habitats with grasses of intermediate height and density, as well as moderate litter depths (Owens and Myres 1973). Selection for moderate litter depths may occur because the species walks or runs to forage and escape predators (Robbins and Dale 1999). Typical nest sites occur in tall, dense vegetation and a relatively deep litter layer (Dieni and Jones 2003). Sprague's pipit also prefer habitats with native grasses such as blue grama (*Bouteloua gracilis*; Robbins and Dale 1999) over areas with exotics such as smooth brome (*Bromus inermis*) and crested wheatgrass (Wilson and Belcher 1989). Foraging tends to take place in shorter vegetation, with arthropods as the main food source (Robbins and Dale 1999).

The species has suffered significant population declines since its first recorded discovery in 1843 (Robbins and Dale 1999) due primarily to habitat loss. Widespread losses of prairie habitat due to cultivation, overgrazing and increases of exotic species have contributed to population declines of Sprague's pipit. In April of 1999, Sprague's pipit was classified as 'threatened' by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC). The species continues to be listed as threatened due to significant population declines since the 1960s, as well as predicted continued population losses and fragmentation of habitat (COSEWIC 2010*b*). The species had an estimated loss of 4.1 % per annum from 1970 to 2009 across the continent and of 3.3 % in Alberta (Breeding Bird Survey 2009). Canadian preservation of the species is particularly important for the conservation of this species, as 80 % of global breeding populations occur within the country's borders (COSEWIC 2010*b*).

2.4.2 Chestnut-collared Longspur (*Calcarius ornatus*)

The chestnut-collared longspur is a native grassland species that typically selects breeding grounds influenced by bison grazing or fire disturbance (Hill and Gould 1997). In Canada, the breeding range of the species is restricted to the short-grass and mixed-grass prairies of the Canadian prairie provinces. Ideal habitats are native short or mixed-grass prairie that has been recently mowed or grazed, has a vegetation height of less than 20 to 30 cm (Owens and Myres 1973) and a minimal litter layer (Robbins and Dale 1999). Breeding populations may also be found in east Montana, North Dakota and South Dakota, but ranges have been declining with land-use conversion and habitat loss. In Alberta, vegetation species such as blue grama, needle-and-thread (*Hesperostipa comata*), club moss (*Selaginella densa*), pasture sage (*Artemisia frigida*) and cactus (*Opuntia* spp.) are common in chestnut-collared longspur habitats. The species has also been found to nest in areas with exotic vegetation, such as crested wheatgrass. Chestnut-collared longspur do not select croplands as habitat (Owens and Myres 1973). In Alberta, territories are typically 1 ha and often breeding sites are re-visited each year (Robbins and Dale 1999).

Chestnut-collared longspur is a native prairie specialist, which due to habitat loss has disappeared from many parts of its historical breeding range (Robbins and Dale 1999). Significant population declines have occurred since the 1960s (COSEWIC 2010*a*). In 2009, the species was listed as ‘threatened’ by COSEWIC. Reasons for the listing include habitat loss and fragmentation caused by road developments in the energy sector (COSEWIC 2010*a*).

2.4.3 Savannah Sparrow (*Passerculus sandwichensis*)

Savannah sparrow is a common grassland songbird that is abundant throughout its North American range (Wheelwright and Rising 2008). Their breeding range extends from the north at the Arctic Archipelago, west towards the Aleutian Islands, south to West Virginia, eastern Kentucky and Tennessee and north to Georgia and south Ohio. Local breeding populations are also found in Colorado, Utah, Nevada, Arizona, east California, south to central Mexico and west Guatemala (Wheelwright and Rising 2008). Savannah sparrows typically arrive at their Canadian breeding habitats in the spring between late March and early May. In Alberta, these breeding habitats consist of grassy meadows, cultivated fields, lightly grazed pastures and roadsides (Wheelwright and Rising 2008). The species tends to favour dense ground vegetation, particularly grasses (Wiens 1969). Savannah sparrows also prefer nesting sites with a deep, dense litter layer and little bare ground (Dieni and Jones 2003). Estimates of territory sizes have varied, but average approximately 0.30 ha (Potter 1972; Wiens 1973; Welsh 1975; Wheelwright and Rising 2008). In habitat with sparse vegetation cover territories are larger, up to 1.25 ha (Stobo and McLaren 1975). Territory boundaries may shift to incorporate new nest sites or mates as the breeding season progresses (Wiens 1969, 1973; Welsh 1975). The main prey of Savannah sparrow during the summer months are insects and other arthropods (Wheelwright and Rising 2008). Foraging occurs on the ground where microhabitats include short vegetation in pastures. The annual mortality of adults is approximately 50 %, which is common with passerines (Wheelwright and Rising 2008). The adults typically return to the same breeding sites each year, which over time has caused reproductive isolation among populations and a high degree of geographic variation (Wheelwright and Rising 2008).

Studies from 1966 through 2005 have indicated significant population declines in eastern Canadian Savannah sparrow populations (Wheelwright and Rising 2008). Increases in agriculture, shifting of crops from alfalfa towards corn, wheat and soybean, as well as declines in dairy farming are cited as causes for Savannah sparrow declines (Jobin et al. 1996). In western Canada, population sizes have remained consistent as human activities that provide crop and lightly grazed land continue (Wheelwright and Rising 2008). In Alberta, birds have shown a preference towards minimum tillage lands (Martin and Forsyth 2003). Preservation of prairie habitats remains a conservation priority for the Savannah sparrow (Wheelwright and Rising 2008).

2.4.4 Baird's Sparrow (*Ammodramus bairdii*)

Baird's sparrow is a native prairie specialist that was first discovered in 1844 by Audubon and named after a prominent 19th century ornithologist, Spencer Fullerton Baird (Green et al. 2002). The breeding range of Baird's sparrow extends from south Alberta, south Saskatchewan and south Manitoba to south and central Montana, North Dakota, and northwest and central South Dakota, with populations possibly in west Minnesota. The species arrives in Alberta during the third week of May (Green et al. 2002). Habitat typically consists of mixed-grass or fescue prairie with vegetation species such as sedge (*Carex obtusata*), club moss (Owens and Myres 1973), needle-and-thread grass, pasture sage (Kantrud and Kologiski 1982) and blue grama grass (Davis et al. 1999). These areas are generally native ungrazed to moderately grazed prairie with low shrub cover (Owens and Myres 1973; Kantrud and Kologiski 1983). As well, studies have indicated that Baird's sparrow are area sensitive (Johnson and Igl 2001).

Habitat loss resulting from conversion of prairie, invasion of exotics, increases in shrub cover due to fire suppression and poor range management have caused a decrease in Baird's sparrow population numbers (Owens and Myres 1973; Goossen et al. 1993). In 1989, the species was listed as 'threatened' by COSEWIC, but was removed from the listing in 1996 due to increased population estimates in Saskatchewan (Green et al. 2002).

2.4.5 Western Meadowlark (*Sturnella neglecta*)

Western meadowlark is a common grassland songbird species found across the northern Great Plains and towards the Pacific Ocean (Davis and Lanyon 2008). The species is most commonly found in native grassland habitats and in areas that have been converted from cropland to perennial grassland cover (McMaster and Davis 2001; Haroldson et al. 2006). The species selects habitats with vegetation of an intermediate height and density (Madden et al. 2000). In comparison to other grassland passerines, western meadowlark have large territories, but area-sensitivity has generally not been detected (Davis 2004; Johnson and Igl 2001).

The conversion of native prairie to cropland has negatively influenced western meadowlark populations (McMaster and Davis 2001). Prescribed burning of grasslands may improve habitat quality for the species and may additionally reduce the depredation of nests (Johnson and Temple 1990).

2.5 Detectability

Point count data are indices and detectability concerns surround their use for estimating population sizes accurately. Indices reflect only the portion of the population that has been counted, a method that suffers from bias and variation (Thompson et al. 1998; Thompson 2002; Johnson 2008). For example, birds may fail to be observed due to a lack of visibility, audible cue or observer error. Biases also include the ability of the observer to detect the bird when it is available for observation. Availability and perceptibility vary with conditions, observers and bird species. Methods to increase perceptibility, such as multiple-observer methods, still are unable to account for birds that did not cue the observer during the point count period (Johnson 2008). Quantitative methods such as distance sampling, multiple-observer surveys and time-of-detection have been developed to mitigate these potential biases (Johnson 2008).

To improve the detection of birds recorded during point counts distance sampling may be used, but there are difficulties in applying this method to field work situations (Johnson 2008). The result is an estimation based on how many birds were observed of the total number of individuals present in the area. Distance sampling assumes that all birds at a distance of zero from the observer will be recorded and all birds moving farther away from the observer will be increasingly more difficult to detect (Johnson 2008; Efford and Dawson 2009). This method is also dependent on the idea that birds do not move in response to the presence of the observer, that distance estimates are accurate and birds are distributed independently of the plot area. If distances are not accurately recorded by observers, detectability estimates will be altered. This is important to note, as the ability of observers to accurately identify distances to singing birds is questionable

(Alldredge et al. 2007*b*). Alldredge et al. (2007*b*) found that the ability of observers to correctly perceive distances to birds decreased with distance, particularly after 100 m. Further, several point counts completed in the same locations, such as in multiple rounds, may cause an excess of observations of birds at one distance and location (Hutto and Young 2002). This could be caused due to a feature such as a shrub that is used as a perch by birds. Distance sampling requires a large sample size to estimate detectability curves, generally with 60 to 100 observations of a single species (Buckland et al. 2001, Rosenstock et al. 2002). Often this limits the use of distance-sampling to only the most common species in a study. Observations from multiple species may be combined so that a greater sample size is available, but pooling species is often based on the need for a larger sample size and not similar detectability among species, and therefore is not recommended (Johnson 2008). Efford and Dawson (2009) found that using the distance method to estimate detection probability created confidence intervals that were approximately twice of those for unadjusted counts. Another issue with distance sampling is that detectability is influenced by many factors and their interactions (Johnson 2008). Both identifying all of the influences and their effects and then creating detectability functions is not plausible. For these reasons, distance sampling and detectability curves were not used in this study, and based on the observations by Alldredge et al. (2007*b*) analyses were restricted to birds detected within 100 m of the observer.

Multiple-observer methods have also been developed in an attempt to reduce point count detectability biases. This method requires the use of 2 or more observers in the field, with one person acting as the primary observer and the other as a secondary observer (Johnson 2008). These roles alternate between observers from one point to another. After point counts are completed, birds recorded by the multiple observers are compared and matching birds are considered to have a first and second capture. Observers must have the ability to record birds without an indication from the other observer that they detected the same bird. This method requires the use of a short point count period so that a closed population can be assumed. The multiple-observer method further assumes that observers are able to accurately match bird observations (Alldredge et al. 2006; Kissling and Garton 2006), the detection probability for each species by observers is constant and that no bird moving in and out of the plot radius is undetected (Johnson 2008). These assumptions may be difficult to achieve in the field. Responses by birds to the presence of observers may be higher with multiple persons present. This method does not taken into account distance biases and only accounts for perceptibility biases (McCallum 2005; Diefenbach et al. 2007). A large disadvantage to the multiple-observer method is that if 2 people are completing point counts together only half the number of plots may be visited versus point counts completed separately. The loss of data from this reduced sample size decreases power, which may outweigh the benefit of having multiple observers. Due to these concerns the multiple-observer method was not used in this study.

Time-of-detection methods are also used to reduce biases in point counts. Point count intervals can be split into periods that are each treated as a trapping occasion, allowing for closed-population mark-recapture methods to be used (Johnson 2008). Farnsworth et al. (2002) proposed that once a bird has been detected and recorded no further information is noted as the bird is considered removed from the population available for detection. Alldredge et al. (2007*a*), however, continued to record information on birds after their initial detection to reduce the likelihood of double-counting individuals. Estimators may be used that divide birds by high and low detectability, or one estimator may be used that assumes the same detection among species (Farnsworth et al. 2002). This method requires long point count periods of approximately 10 minutes and assumes that all birds in the population can be detected during this time. This is problematic as birds often will sing irregularly over time (McCallum 2005). When species are wide-ranging and when many species and individuals are present, observers must be uniformly attentive during all intervals (Farnsworth et al. 2002; Alldredge et al. 2007*a*).

Double-sampling is a method that uses two different types of surveys, one which is more extensive and expensive and the other which is less accurate, but cheaper (Johnson 2008). Double-sampling may be used to calibrate point count indices, but this requires knowledge of the true population size. However, for calibration, this method requires knowledge of a true population size based on point counts, which is also the reason why calibration is needed (Lancia et al. 1994). As well, because the two surveys may be very different from each other, it can be difficult to estimate their relationship and identify the factors influencing detectability. This method is very labour-intensive (Farnsworth et al. 2005) and was not used in this study.

Despite the development of quantitative methods to account for issues with detectability in point counts indices much work is still required to perfect their use. Johnson (2008) noted that many of these methods require extensive effort and persons for limited improvement to results and that no adjustment method is effective for large-scale multi-species surveys. Adjustments may further require pooling and result in larger confidence intervals and decreased power. For these reasons, quantitative methods to adjust for detectability were not used in this study. Issues with detectability due to different landscape characteristics were minimized in this study as sites were selected for similar vegetation composition and topography. Variability was further reduced by completing point counts during a consistent period of time and year.

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CHAPTER 3: THE IMPACT OF NATURAL GAS SHALLOW WELL DENSITY AND PROXIMITY ON GRASSLAND SONGBIRDS IN MIXED-GRASS PRAIRIES

Abstract

Prairie habitats across North America have become severely degraded and fragmented, causing large declines in grassland songbird populations. Further, industry development may be exerting additional pressure on bird species. To determine the impact of natural gas industry development in mixed-grass prairie on the relative abundance of grassland songbirds, point counts were completed in southeastern Alberta. Data were collected at 34 sites in 2010 and 40 sites in 2011 with well densities ranging from 0 to 20 per 1×1 mile area. Because infrastructure such as gas wells and access routes may cause changes in vegetation structure and cover, vegetation sampling was completed at point count locations and along transects perpendicular wells and associated access trails and roads. Generalized Linear Mixed Models were used to analyze effects of gas well infrastructure on birds and vegetation. Changes in vegetation, such as an increase in bare ground, were observed near gas wells and linear features in comparison to native prairie located farther away. In general, approximately equal numbers of bird species had higher relative abundances near and farther from wells. In contrast to past research, however, it did not appear that this effect was driven by changes in vegetation. Instead, gas wells may have been selected as perches by vesper sparrow and western meadowlark, driving increases in relative abundances of these species near the infrastructure. In contrast, species that do not tend to use perches declined near the infrastructure, such as Sprague's pipit and chestnut-collared longspur. Research should continue to identify responses of birds to natural gas development to assist management of grassland habitats.

3.1 Introduction

Historically, the Great Plains of North America extended to more than 3 million km^2 (Samson et al. 2004), but today it continues to be influenced by land-use conversion (Herkert 1994) that has reduced its size by 70 % (Samson et al. 2004). As the decline of grassland habitat continues, the species that rely on these regions are placed under increasing pressure. Grassland birds have experienced larger declines in population size than birds from any other habitat type in North America (Herkert 1994, 1995; Herkert et al. 2003); populations of more than 50 % of grassland bird species declined by more than 50 % over a recent period of less than 30 years (Herkert 1995). In Canada, 73 % of grassland bird species populations have been in decline since 1970 (Collins and Downes 2009).

As land-use conversion continues across the grassland landscape, humans are exerting additional pressures through industrial development. The natural gas industry is widespread in both Canadian and American grassland habitats. Natural gas extraction requires anthropogenic features such as shallow gas wells, pipelines and access roads, all of which may have negative impacts on grassland songbirds. For example, densities of Baird's sparrow (Dale et al. 2009) and Sprague's pipit (Dale et al. 2009; Hamilton et al. 2011) may decrease with an increase in well density and avoid habitat near wells (Dale et al. 2009; Kalyn-Bogard 2011). In contrast, Savannah sparrow abundance may increase at greater natural gas well densities (Dale et al. 2009).

Maintenance activities such as mowing, and linear features such as access roads and trails, can alter vegetation structure and composition in comparison with the surrounding native grassland. Mowing around natural gas wells is a common management activity for reducing the risk of accidental fires started by maintenance crew vehicles. Mowing is often completed during the songbird breeding season and consequently may destroy nests, eggs and young, and may increase rates of abandonment and depredation of nests (Bollinger et al. 1990). In addition, linear features such as roads and trails increase the amount of edge between grassland and other habitats. The creation of habitat edges can positively or negatively influence the densities and diversities of grassland songbirds (Davis et al. 2006; Koper et al. 2007; Koper et al. 2009) and can cause an increase in risks of depredation. Further, habitat edges can cause a change in vegetation community structure (Linnen 2006; Koper et al. 2009), which may mean that habitat suitability near edges may differ from that of core habitat (Fleishman et al. 2003; Fisher and Davis 2011).

Songbirds may be further impacted by non-native vegetation introduced through access roads (Gelbard and Harrison 2003) or in seed mixes used for the re-seeding of well sites. Crested wheatgrass, which is an exotic and invasive grass species, has a vertical structure that varies from native grasses (Henderson 2005). Crested wheatgrass has lower density of standing vegetation within 10 cm of the ground, contributes less to the litter layer, and causes more bare ground to be exposed, compared with grasses that are native to the northern Great Plains (Sutter and Brigham 1998). Increased traffic for well maintenance and establishment may increase the introduction of exotic vegetation (Von der Lippe and Kowarik 2007), leading to a greater abundance of non-native cover close to natural gas well pads, pipelines and access roads (Berquist et al. 2007). Birds such as Sprague's pipit and Baird's sparrow that are sensitive to vegetation structure and prefer habitat dominated by native grasses (Davis et al. 2013) may avoid these areas.

These changes may also negatively impact the abundance of insect prey that are influenced by microhabitat (DeBano 2006; Hartley et al. 2007).

Ten thousand to 15,000 new oil and natural gas wells are drilled each year in Alberta (Government of Alberta 2011), and with expected future growth, it is important to gain a greater understanding of the impacts of this development on grassland songbirds. High densities of natural gas wells have been identified as a threat to wildlife and allowable well densities are now being called into question by researchers (Holloran 2005; Walker et al. 2007; Harju et al. 2010; Wyoming Game and Fish Department 2010). It is important to understand the impact of natural gas development on grassland songbirds so that biological consequences are understood and can be considered when policy (Askins et al. 2007), management and operations guidelines are reviewed and created.

The objectives of this study were to: (1) evaluate the impact of shallow gas well density on the relative abundance of grassland songbird species, (2) determine the influence of proximity to wells on the relative abundance of grassland songbirds, and (3) investigate whether the effects of gas well infrastructure on grassland songbird relative abundance are caused by the impact of this infrastructure on vegetation structure and cover.

3.2 Methods

3.2.1 Study Area

Research was completed in southeastern Alberta, approximately 50 km west of Medicine Hat (latitude: 50° 03’ to 50° 35’ N, longitude: 110° 40’ to 111° 53’ W). Study sites were located in Cypress, Newell, Taber and Vulcan counties. All sites were situated in mixed-grass prairie habitat and were dominated by native plant species. Grasses common to the region consist of needle-and-thread, blue grama, junegrass (*Koeleria macrantha*) and western wheatgrass (*Pascopyrum smithii*). Forbs such as prairie sage (*Artemisia ludoviciana*) and shrubs such as silver sage (*Artemisia frigida*) and wild rose (*Rosa acicularis*) are also present. Study sites were predominantly covered by native species, but also had varying amounts of exotic species, such as goatsbeard (*Tragopogon dubius*) and crested wheatgrass.

Forty sites were selected in 2010 based on legal land sections that are approximately 258 ha in area (1×1 mile section) (Table 1). Sites were at least 1 mile apart and had flat or gently sloping topography. Sites had varying shallow gas well densities, from control sites that had no wells present, to those sites with a high amount of development and up to 20 natural gas wells. Gas well densities were determined using aerial photographs and GIS records (Cenovus 2011, personal communication; Appendix I). Wells that shared the same surface Universal Transverse Mercator Geographic Co-ordinate System (UTM) co-ordinates were located on the same well pad and thus were counted as one well when quantifying well densities.

During the 2010 field season, 3 study sites were eliminated due to topography that was comparatively too variable or had too much wetland habitat present. One site used in 2010 could not be reached in 2011 due to high rainfall. In 2011, these 4 sites were replaced with new sites, including 2 control sites. These 4 new sites were selected using the same criteria and methods as in 2010. Point count data in 2010 collected by one observer was not used in any analysis, due to concerns with its accuracy. This meant that

2 additional sites did not have 2 rounds of data for all plots in 2010 and were excluded from analysis. Therefore, 34 sites from 2010 are included for analysis and 40 from 2011.

3.2.2 Field Methods

Six-minute, 100-m point counts were used in 2010 and 2011 to record all birds seen or heard by observers. In both years, point counts were completed at 10 plots at each study site, except when plots were inaccessible due to factors such as flooding. Plot locations were determined using a grid that was placed over an aerial photograph of each 1×1 mile study site. A random number table was used to determine which portion of the grid the plot would fall within, and UTM co-ordinates for the point count centre were then randomly selected. All point counts were located at least 300 m from other point count plot edges. Where necessary, plots were moved to avoid wetlands or streams, or to minimum distances from infrastructure. Safety guidelines provided by Cenovus required all field technicians to maintain at least a 7 m distance between themselves and shallow gas wells. However, a minimum distance of 50 m from infrastructure was used when selecting point count locations to ensure that avoidance of the observer by birds would not be interpreted as avoidance of the wells. Distances from point count centres to the nearest well ranged to a maximum of 2000 m.

Point counts were completed from dawn until 10 am between May 21st and July 7th. Observers stood at the point count centre and recorded the distance and direction to all birds relative to their location. Observers recorded the date, time, cloud cover and wind speeds at the beginning of every point count. On days with high temperatures (>20° C), point counts ceased by 9 am, due to declines in song intensity with warmer temperatures. Point counts were not completed in rainy or foggy weather, or if wind speeds were above

20 km/hr. Each point count plot was surveyed at least twice in each year. A third round was attempted in each year, but was not completed due to high rainfall and the requirement that all point counts be finished by the beginning of July. Where possible, each round was conducted by a different observer, to control for observer biases.

Vegetation sampling was completed within point count plots, after point counts had been finished, starting July 2nd in 2010 and June 29th in 2011, and were completed by August 13th. At each point count location, a 1-m^2 quadrat was placed north and south of the point count centre, at a distance determined using a random number table. Vegetation quadrat placement ranged from 0 m to 100 m from the point count centre, so that they fell within the area observed during point count sampling and within grassland habitat. In 2011, high rainfall in June and July meant that vegetation quadrats could not be completed at 5 point count plots because they were no longer accessible.

Quadrats were formed using crossed metre sticks pointing in each cardinal direction. Densities of vegetation were recorded in each cardinal direction, at the end of the metre stick and at the centre of the vegetation quadrat using a Wiens pole (Wiens 1969). Numbers of live, dead and crested wheatgrass stems touching the pole were recorded. Litter depth and maximum live grass height were also determined using the Wiens pole. Estimated distances from the vegetation quadrat to the nearest shrub were recorded and percentages of cover within each section of the quadrat (NW, NE, SE, and SW) were observed. Fisher and Davis (2009) suggested that in addition to vegetation height, litter depth and number of stems, certain cover classes may also be important when considering the quality of grassland bird habitat. Cover classes recorded in this study included bare ground, live grass, dead grass and forb.

Vegetation was also surveyed along transects perpendicular to gas wells, trails and roads, to determine if vegetation structure changed with distance to disturbances on a smaller spatial scale than could be evaluated among quadrats at point count plots. In 2010, vegetation transects were completed at 20 sites and in 2011 at all sites except controls. Transects began at the edge of trails or roads and at 7 m from shallow gas wells, due to safety regulations. At each site, one transect was conducted that radiated away from a well and one was placed perpendicular to its associated trail or road. Gas wells were selected using a random number table and aerial images. Each 1×1 mile study site is divided into 4 quarter-sections, each of which is then divided into another 4 legal land sections. This means that each study site can be split into 16 smaller sections. The random number table included integers from 1 to 16, and the gas well located closest to the centre of that legal land section was selected for the gas well transect. Road transect locations started at a minimum distance of 20 m from the selected well. If no road or trail was found at the selected shallow gas well, the nearest road or trail was used. Vegetation quadrats were placed at distances of 1, 2, 3, 4, 5, 10, 15 and 20 m from roads and the regulated distance from shallow gas wells. Sample methods used at each quadrat were the same as for quadrats completed at point count plots.

3.2.3 Statistical Analysis

Prior to analysis, vegetation data from quadrats located north and south of point count centres were averaged, leaving one value for each vegetation category at every point count location. Point count values were summed across rounds to allow for the use of Poisson and negative binomial distributions. Data from only 2 rounds were used for analysis, to ensure that a greater number of rounds completed did not translate into a higher number of birds recorded. Unadjusted point count data were used to assess relative abundances of birds because statistical methods used to account for variable detectability among birds have a large added expense and effort, but result in limited improvement to the data (Johnson 2008). I used these data to determine the effects of shallow gas well density and distance to wells on the relative abundance of 9 grassland songbird species that were found in > 15 % of all point counts over the course of the study: Baird's sparrow, brown-headed cowbird, chestnut-collared longspur, clay-colored sparrow, horned lark, Savannah sparrow, Sprague's pipit, vesper sparrow and western meadowlark. Similar numbers of each bird species were observed in both field seasons (Table 2).

Data were analyzed in SAS 9.2 (SAS Institute Inc. 2008). Distributions of the model residuals for each species were tested for their fit to a normal distribution using Q-Q plots in PROC UNIVARIATE, and for their fit to Poisson or negative binomial distributions using the deviance/ degrees of freedom ratio within Generalized Linear Models (GLMs) in PROC GENMOD. Distributions of residuals for all bird species best fit either a Poisson or negative binomial distribution.

Generalized Linear Mixed Models (GLMMs) were developed in PROC GLIMMIX with a log link function to model relationships between gas well infrastructure, vegetation structure and cover and relative abundances of birds. GLMMs allowed me to take into account spatial clustering through their use of a random effect. The Laplace approximation was used in SAS for maximum likelihood estimation in all models other than Sprague's pipit, where quadratic estimation was used due to convergence issues. Initially, both plot and site were included as nested random effects; however, models with both random variables did not converge, because the estimate of the variance of the plot effect was 0, which caused the G matrix to not be positive definite (Littell et al. 2006). This suggested that the random plot variable did not explain any overdispersion in addition to the variation explained by the random site variable, and therefore plot was removed as a random effect. All models used for analysis included site as the only random effect, since it explained more random variation than plot. Six vegetation structure, 5 vegetation cover and 2 natural gas infrastructure variables were included in models (Table 3). An alpha value of 0.1 and 90 % confidence levels were used to reduce the risk of a Type II error.

Models were developed for each bird species using a 2-step process. Akaike's Information Criteria (AIC; Akaike 1974) was used to rank and select best-fitting models. The model with the lowest AIC score and ΔAIC and the highest AIC weight (w_i) was selected as the model that best fit the data (Burnham and Anderson 2002). In the first step, parameters were divided into the categories vegetation structure, vegetation cover and infrastructure, and then linear and quadratic models for each independent parameter were run individually in PROC GLIMMIX (APPENDIX II), to determine if relationships between dependent and independent variables were nonlinear. Quadratic terms were only selected for subsequent models in Step 2, instead of linear terms, if they achieved a lower AIC score and ΔAIC and the highest AIC weight (w_i). The parameter year and an interaction between year and infrastructure terms, were included in infrastructure models, to determine if birds responded differently to infrastructure over time due to possible differences in management among years. Year was not included in models with vegetation parameters in this first step, because it was considered unlikely that birds would respond differently to vegetation in one year versus another.

In Step 2 (APPENDIX II), the null model and a model including only year were compared to models including year plus, (1) vegetation structure variables, (2) vegetation cover variables, (3) infrastructure variables (management), (4), selected vegetation structure variables + selected vegetation cover variables, (5) selected vegetation cover variables + selected infrastructure variables, (6) selected vegetation structure variables +selected infrastructure variables, (7) the global model, which included all selected vegetation cover and structure and infrastructure variables. The model with the lowest AIC score and ΔAIC and the highest AIC weight (w_i) was considered the most parsimonious model for the species (Table 4), and was selected as the top model. However, models that are less complex and are within 2 ΔAIC of the top model may be considered competitive (Burnham and Anderson 2002, Arnold 2010; hereafter, "competitive" models) and should also be considered. Competitive models were found for chestnut-collared longspur and Savannah sparrow. The competitive model was considered the most parsimonious model in the case of Savannah sparrow, because it was less complex than the model with the lowest AIC value; however, because the competitive chestnut-collared longspur model was more complex than the best-fitting model, it was not considered an improvement over the best-fitting model (Arnold 2010). Parameters where the confidence limits did not include zero were considered influential (Arnold 2010).

Vegetation data gathered at quadrats along transects were used to examine the influence of proximity to infrastructure on vegetation structure and cover at a small scale.

Vegetation was surveyed along transects radiating away from gas wells, two-track trails, low-impact roads and higher-impact roads. Low-impact roads were dirt or gravel and wide enough for only one vehicle and higher-impact roads were gravel, but slightly raised and wide enough for two vehicles. Distributions of the model residuals for all vegetation variables were tested for their fit to a normal distribution using Q-Q plots in PROC UNIVARIATE and for their fit to a Poisson or negative binomial distribution using the deviance/ degrees of freedom ratio in PROC GENMOD. GLMMs in PROC GLIMMIX were then used to examine the effect of distance from well, road and trails on vegetation structure and cover. Where normal, Poisson or negative binomial distributions did not fit the data, or models with these distributions did not converge, a binomial distribution was used. Site was included as a random effect.

I also completed a larger-scale vegetation analysis to evaluate if the effects of natural gas infrastructure on birds were driven by vegetation changes associated with the infrastructure. Vegetation data collected at point count plot locations was used for this analysis. Distributions that best fit the model residuals for each vegetation variable were determined using Q-Q plots in PROC UNIVARIATE and the deviance/ degrees of freedom value in PROC GENMOD. A poor fit was found for the density and percentage of crested wheatgrass variables with all distributions, so data were converted to presence/ absence and a binomial distribution was used. All other vegetation variables best fit a negative binomial distribution. GLMMs in PROC GLIMMIX were used for this with plot location included as the random effect.

Larger-scale vegetation models were developed using a 3-step model selection process (APPENDIX III). First, it was determined whether relationships between response variables and well density and distance to the nearest well were linear or quadratic. Then, in step 2, the null model was compared to each infrastructure term, the infrastructure term and year, and the interaction between each infrastructure term and year, in separate models, to evaluate whether effects of infrastructure varied by year. In step 3, the null model was compared to year and the combination of the well density and distance to the nearest well models selected in step 2. The most parsimonious model was then selected based on the same AIC criteria described above (Table 5). Competitive models within 2 ΔAIC of the top model percentage of dead grass and forbs were selected because they were less complex in both instances than the top models with the highest AIC score (Arnold 2010).

3.3 Results

3.3.1 Infrastructure

Infrastructure parameters were included in the most parsimonious AIC-selected models for 4 of the 9 songbird species analyzed (Table 4). These species were horned lark, Sprague's pipit, vesper sparrow and western meadowlark. Infrastructure parameters were also included in the competitive model for chestnut-collared longspur; however, there was weak evidence that the infrastructure parameters improved model fit, because this competitive model was not less complex than the model with the lowest AIC score and ΔAIC, and the highest AIC weight (w_i). The model with the lowest AIC score and ΔAIC, and the highest AIC weight (w_i) for Savannah sparrow also included infrastructure parameters. However, again, these results suggest that there is only weak evidence that these variables contributed to model fit, as there was a competitive model within 2 ΔAIC that was less complex that did not include infrastructure variables (Arnold 2010).

All selected models that included well density also contained the variable as an interaction with year, suggesting that responses of birds to infrastructure density varied over time (Table 4). Well density influenced horned lark more in the 2011 field season than in 2010 (Table 6; Figure 1d). Well density and its interaction with year was also in the top two AIC models for chestnut-collared longspur (Table 7; Figure 2a) and Savannah sparrow (Table 8; Figure 3); however, simpler models were competitive with models that included management variables for both species. Year alone impacted clay-colored sparrow relative abundances (Table 9).

Distance from the point count center to the nearest well influenced the relative abundances of Sprague's pipit (Table 10), vesper sparrow (Table 11) and western meadowlark (Table 12). Relative abundances of Sprague's pipit increased at greater distances from gas wells (Figure 4). In contrast, the relative abundances of vesper sparrow (Figure 5c) and western meadowlark (Figure 6) declined farther from gas wells. Distance to the nearest well was included, and was influential, as both a linear and quadratic term in the competitive model for chestnut-collared longspur (Table 7) and suggested that their abundance is relatively stable, with a slight increase at distances up to 2 km from gas wells (Figure 2b). At farther distances from wells chestnut-collared longspur abundance declined.

3.3.2 Smaller-scale (0-20 m) Impact of Distance to Well, Trail and Road on Vegetation

Vegetation structure changed in many ways with distance from the infrastructure in this study. As distance from gas wells increased, the density of dead grass, maximum height of live grass, litter depth, percentage of dead grass and forbs increased (Table 13; Figure 7). The distance to the nearest shrub, percentage of bare ground and occurrence of crested wheatgrass decreased with an increase in distance from gas wells. Changes in vegetation structure and cover were also observed at transects running away from trails and roads associated with natural gas wells. As the distance from trails increased, so did the maximum height of live grass, litter depth, percentage of dead grass and occurrence of crested wheatgrass (Table 14; Figure 8). In contrast, occurrence of bare ground was negatively correlated with distance to trail. Litter depth increased farther from low-impact roads, whereas occurrence of bare ground decreased as distance from the road increased (Table 15; Figure 9). Higher-impact roads were associated with a greater occurrence of bare ground than areas farther away (Table 16; Figure 10).

3.3.3 Larger-scale (7-2000 m) Impact of Vegetation Structure and Cover

Impacts of natural gas wells on vegetation structure and cover were also examined at a larger scale using vegetation data collected at point count plot locations (Table 5). Large differences in the density of live grass between 2010 and 2011 were observed, although this may have been due to differences in how blades were counted among years (Table 17). The maximum height of live grass, litter depth and percentage of bare ground were all impacted by infrastructure and had confidence limits that did not include 0. The maximum height of live grass increased farther from gas wells and this effect was stronger close to wells (Table 18; Figure 11). Litter depth decreased with well density, particularly in 2011 (Table 19; Figure 12). Greater amounts of bare ground were found within approximately 1 km of gas wells and at distances greater than 3.5 km from the infrastructure (Table 20; Figure 13). Consistent with the smaller-scale transect results, the larger-scale vegetation analysis indicated that there was an increase in percentage of bare ground closer to natural gas wells and an increase in the maximum height of live grass farther from wells (Tables 19-20). Higher densities of wells were associated with an increase in percentage of dead grass (Table 21). These data also indicated that vegetation structure and cover varied annually (Tables 19, 21-29).

3.3.4 Relationships between Infrastructure, Vegetation and Bird Relative Abundances

Vegetation structure influenced the relative abundances of many bird species in this study. At higher densities of live grass, there was an increase in the predicted number of brown-headed cowbird (Table 28). Higher densities of dead grass were associated with larger numbers of brown-headed cowbird (Table 28). At higher maximum heights of live grass, brown-headed cowbird (Table 28) and vesper sparrow (Table 11; Figure 5a) declined and this effect increased as the height of grass increased. Savannah sparrow demonstrated a preference for a deeper litter layer (Table 8; Figure 14), whereas vesper sparrow preferred less litter (Figure 5b). In addition, the relative abundance of brown-headed cowbird was negatively correlated with distance to the nearest shrub (Table 28).

Vegetation cover impacted 5 grassland bird species in this study. Higher amounts of bare ground were associated with a decline in Baird's sparrow at low values of bare ground, but an increase at high values of bare ground (Table 29; Figure 15a), a decline in chestnut-collared longspur (Table 7; Figure 16a). This effect was strong for Baird's sparrow, but the positive increase at higher bare ground cover may have been driven by only 3 data points (Figure 15a). At higher percentages of live grass, there was a decline in relative abundances of chestnut-collared longspur and horned lark (Tables 6, 7; Figures 1, 16b), but an increase in relative abundances of brown-headed cowbird (Table 28).

Percentage of dead grass was negatively correlated with relative abundances of chestnut-collared longspur (Table 7; Figure 16c), but positively correlated with Baird's sparrow abundances (Table 29; Figure 15b). Higher abundances of forbs were associated with a decline in horned lark relative abundances (Table 6; Figure 1b). With an increase in the percentage of crested wheatgrass, horned lark increased, particularly at lower amounts of the grass (Table 6; Figure 1c).

Though changes in vegetation structure and cover near and at higher densities of gas well infrastructure were observed in this study (Tables 5, 13), it is unlikely that these variations drove the responses of most species of birds to infrastructure. For example, Baird's sparrow, brown-headed cowbird and clay-colored sparrow were all insensitive to the presence of gas wells, but models indicated that these bird species were all highly sensitive to changes in vegetation (Table 4). GLMM models also indicated that Sprague's pipit and western meadowlark relative abundances were impacted by infrastructure, but not to vegetation structure or cover. In addition, the competitive chestnut-collared longspur model suggested that abundances of the species decreased closer to wells, despite their indicated preference for shorter vegetation (Table 7; Figure 2b). In contrast to the results for other species, the response of vesper sparrows to infrastructure might have been driven by vegetation structure. The abundance of vesper sparrows was higher closer to wells and the species preferred sites with less litter, which is found near to wells (Table 11; Figure 5b).

3.4 Discussion

Infrastructure used by the natural gas industry for resource extraction in southeastern Alberta had mixed impacts on the grassland songbird species examined in this study. Some bird species were not affected by natural gas industrial development, while other species were either positively or negatively influenced by natural gas well density or proximity. Further, the impact of well density differed among years for a few bird species. Gas well infrastructure and associated access roads and trails were correlated with a change in vegetation structure and cover when compared with habitats located farther away. However, in contrast to past research, in most cases it did not appear that the response of grassland birds to infrastructure and linear features in this study was driven by changes in vegetation near these features. In many cases, the presence of gas wells may have acted as "artificial shrubs", attracting species that typically use the vegetation for perching, while species that typically avoid shrubs were found farther from wells.

Well density per 1×1 mile site did not consistently impact any bird species in this study, but effects did differ over time. Horned lark were affected more by well density in 2011 over 2010, and in contrast chestnut-collared longspur were influenced more by well density in 2010 versus 2011. These changes over time may have occurred due to differences in activity around wells between years, the drilling of new oil or gas wells nearby, or the effect might be spurious. Regardless, our results suggest that effects of well density, up to 20 wells per site, are relatively small. Other studies have found a greater impact of well density on birds (Dale et al. 2009; Hamilton et al. 2011), but this may have been due to differences in well footprint sizes and the amount of the surrounding area disturbed in each of the study locations. In my study area, the surface area affected by most wells (measurement is based on the fencing surrounding wellheads) was 23.1 m^2 and the largest measured well was 42.3 m^2; in contrast, Kalyn-Bogard

(2011) recorded well sites up to 276 m^2. The size of mowed areas surrounding wells may have also differed among regions, meaning that the area disturbed could vary regionally for sites with the same well density.

Though well density *per se* did not influence any of the grassland songbird species in this study, relative abundances of vesper sparrow and western meadowlark increased closer to gas wells, while Sprague's pipit and chestnut-collared longspur decreased, indicating that proximity to gas wells impacted some species of grassland songbirds. Past research has indicated a strong relationship between vegetation and the presence of grassland songbirds (Davis et al. 1999; Sutter et al. 2000; Dale et al. 2009), as well as a correlation between bird species abundances and natural gas industry infrastructure (Dale et al. 2009; Hamilton et al. 2011; Kalyn-Bogard 2011). In this study, however, 9 songbird species were analyzed but vesper sparrow was the only species whose response to infrastructure might have been driven by changes in vegetation surrounding gas well infrastructure. Habitat near wells consisted of short and sparse vegetation and an increase in the number of shrubs, which is consistent with the habitat preferences of vesper sparrow (Jones and Cornely 2002; Dechant et al. 2002). Other research has also noted a strong correlation between vesper sparrow abundances and habitat preferences of the species (Jones and Cornely 2002; Dechant et al. 2003) and in many cases these variables have been further used to explain the relationship between vesper sparrow abundances and human developments (Davis and Duncan 1999; Sutter et al. 2000). Past research has also found a strong association between vegetation and the abundances of other grassland species in this study (Dale et al. 2009; Kalyn-Bogard 2011). Conversely, my results indicated that aside from vesper sparrow, avoidance or attraction to wells cannot be explained by vegetation preferences. Sprague's pipit are sensitive to edge (Koper et al. 2009) and chestnut-collared longspur are area-sensitive (Davis 2004), factors which could be exacerbated by energy developments, possibly causing the lower abundances of these species observed near gas wells in this study. Other research has also indicated that Sprague's pipits avoid habitat near wells, which is consistent with my results (Dale et al. 2009; Kalyn-Bogard 2011). In contrast to Hamilton et al. (2011), I found evidence that chestnut-collared longspur abundances declined closer to gas well infrastructure. This may have been because chestnut-collared longspur are ground foragers and do not display from shrubs or other perch sites, such as well infrastructure (Hill and Gould 1997). Interestingly, both chestnut-collared longspur and Sprague's pipits also select for sites with relatively few shrubs (Grant et al. 2004, Bleho 2009), and consistent with this, avoided well sites. In contrast, vesper sparrow (Best and Rodenhouse 1984; Jones and Cornely 2002) and western meadowlark (Lawson et al. 2011) display from shrubs and may have been attracted to gas wells as perching sites for singing.

Previous research has demonstrated that natural gas activities can impact habitat quality (Leu et al. 2008) and activities such as grazing, haying or mowing around active wells can further alter vegetation structure and composition in these areas. Larger-scale vegetation analyses indicated that increased well densities were correlated with a decrease in litter depth and an increase in dead grass. Natural gas wells were also associated with a decrease in vegetation heights and an increase in bare ground in comparison to habitat located farther from the infrastructure. This change in vegetation may have been due to focused cattle (*Bos taurus*) grazing surrounding gas wells versus habitat located farther from the infrastructure (Molloy and Koper, unpublished data).

Smaller-scale transect vegetation analysis indicated that habitat near gas wells had shorter and sparser vegetation with an increase in shrubs and crested wheatgrass in comparison to habitat located farther away from the infrastructure. In addition, habitat near access roads and trails was correlated with an increase in bare ground and habitat surrounding trails was shorter and less dense than native prairie. Past research would indicate that these changes in vegetation surrounding gas wells and access routes may have implications for grassland songbird habitat selection (Davis et al. 1999), breeding success (Herkert 1994) and relative abundances (Sutter et al. 2000; Dale et al. 2009); however, surprisingly, vegetation structure could not explain most of the results in this study (see further discussion below). Changes in vegetation caused by mowing could also cause habitat edges, which may cause an increase or decrease in predation (Koper et al. 2009), impacting grassland songbirds (Davis et al. 2006; Koper et al. 2007; Koper et al. 2009). Further research would be needed to determine if this is occurring in the region, as it was outside of the scope of this study. My results indicate that the effects of infrastructure on habitat selection by bird species may be overriding the impact of vegetation.

Gas wells in this study were correlated with an increase in the presence and density of crested wheatgrass, as hypothesized. However, in contrast to my predictions, a significant increase in crested wheatgrass was not observed near roads or trails. Other studies have indicated that increased amounts of crested wheatgrass are correlated with a lower density of dead vegetation within 10 cm of the ground, a relatively small contribution to the litter layer and more exposed bare ground than in native prairie (Sutter and Brigham 1998). These changes can cause a reduction in habitat heterogeneity over time if crested wheatgrass invades and creates a monoculture (Christian and Wilson

1999; Heidinga and Wilson 2002; Henderson and Naeth 2005) and reduce selection for these areas by native bird species (Fleishman et al. 2003; Fisher and Davis 2011). Further, an increase in crested wheatgrass can result in a decreased number of arthropods (DeBano 2006; Hartley et al. 2007), which are the prey species of multiple grassland songbirds. However, it does not appear that these changes in vegetation near gas wells drove the responses of bird species in this study, with the possible exception of vesper sparrow, which prefers the habitat characteristics found close to gas wells. Sprague's pipit are sensitive to vegetation structure (Davis et al. 2013) and were predicted to respond negatively to an increase in amounts of crested wheatgrass (Fisher and Davis 2011*a*), but models did not indicate an impact of vegetation structure or cover on the relative abundance of this species.

Much of the current scientific literature indicates a relationship between grassland bird abundances and vegetation structure and cover. Research by Dale et al. (2009) in Alberta demonstrated an avoidance of non-native vegetation, which is more common near wells, by horned lark. Additional research has indicated that Baird's sparrow respond negatively to disturbance (Sutter et al. 1995; Dechant et al. 2002; Sutter et al. 2000) and may avoid infrastructure (Linnen 2006), possibly due to a preference for larger amounts of grass cover and heights of vegetation (Madden et al. 2000; Green et al. 2002; Davis 2004), which tend to be found farther from wells. Baird's sparrows have also been known to decrease with increases in well densities (Dale et al. 2009; Kalyn-Bogard 2011) and avoid non-native vegetation surrounding wells (Dale et al. 2009). In this study, changes in vegetation at multiple scales were correlated with well density and proximity to gas wells and access routes, but it is unlikely that these differences drove the responses of birds to infrastructure in this study. For example, Baird's sparrow, brown-headed cowbird and clay-colored sparrow were insensitive to gas well density and proximity, but these bird species were highly sensitive to changes in vegetation. Conversely, Sprague's pipit and western meadowlark were sensitive to the presence of gas wells, but did not respond to vegetation structure or cover. These results strongly suggest that changes in vegetation occurring at higher well densities, near gas wells and associated access routes did not drive the response of bird species. Instead, natural gas wells may have been perceived as perches by birds, attracting species such as vesper sparrow (Jones and Cornely 2002) and western meadowlark (Lawson et al. 2011) that vocalize and display from perches. Bird species that do not tend to use perches, such as Sprague's pipit (Robbins and Dale 1999), horned lark (Beason 1995) and chestnut-collared longspur (Hill and Gould 1997) were found in higher numbers farther from the infrastructure. As the species that select for sites near wells tend to also select habitats with shrubs that can be used as perch sites, and as the species that avoid wells tend to select habitats with few shrubs, this may suggest that wells act as "artificial shrubs" from the perspective of grassland songbirds.

Not all bird species in this study were impacted by natural gas wells or their associated roads and trails. Effects on birds were species-specific, with some birds favouring habitat with or near infrastructure, and other species preferring habitat with limited alteration by the natural gas industry. Overall, 4 of the 9 bird species analyzed had infrastructure variables included in their most parsimonious GLMM. Of these 4 species, 2 were positively associated with gas wells, while the other 2 were negatively impacted by the infrastructure. I also found that vegetation structure and cover was impacted by well density and proximity to wells, roads and trails. However, in contrast to past research, it did not appear that the diversity and abundances of grassland birds in relation to infrastructure and linear features was driven by changes in vegetation cover near natural gas development. Gas wells may have acted as "artificial shrubs", attracting species such as western meadowlark and vesper sparrow that typically use vegetation for perching. Further research into the mechanisms driving responses of birds to natural gas development is required to assist managers in the management of grassland habitats as natural gas development continues in the region.

3.5 Management Implications and Conclusions

None of the bird species examined in this study were directly and consistently impacted by well density *per se*, however, relative abundances of vesper sparrow and western meadowlark increased near gas wells and abundances of Sprague's pipit and chestnut-collared longspur declined. Changes in the abundances of Sprague's pipit and chestnut-collared longspur may be a concern because both species are currently listed as threatened by COSEWIC (COSEWIC 2010). In contrast to past research, it did not appear that most bird species were responding to changes in vegetation surrounding gas well infrastructure. Instead, gas wells may have acted as "artificial shrubs" attracting species that perch. Vesper sparrow was the only species that may have responded to changes in habitat near wells in this study. This may indicate that the current re-seeding practices used by industry are not having a direct impact on the relative abundances of most grassland songbirds in the area despite observed changes in vegetation structure and cover surrounding gas wells and their associated linear features. This would also indicate that gas well densities are not yet so high in the region that they are excluding species that do not perch. Research and monitoring in the region should continue so that well density thresholds can be identified as natural gas industrial development persists.

Future research is required to examine the impacts of natural gas development on survival, reproduction and territory selection of grassland songbirds. The impacts of natural gas well drilling should also be examined as it may have a strong impact on songbirds due to factors such as increased traffic and noise associated with construction. Well densities and the construction of linear features should also be monitored so that thresholds may be identified and impacts to species, in particular chestnut-collared longspur and Sprague's pipit, are known.

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Table 1. Sites (1×1 mile) located in southeastern Alberta used for point count and vegetation sampling in May-August of 2010 and 2011, and their corresponding well densities.

Site	Well Density
01-16-13	7
02s-18-16/ 35n-17-16	9
03-19-11	12
05-14-12	0
05-18-15	8
06-13-11*	0
06-19-11	14
08-13-10*	0
10-17-14	8
10-18-18†	5
10-23-17	11
12-18-17	7
13-18-16	8
14n 23s-18-12	18
15-15-12	9
15-17-18	4
16-15-17	1
17-14-12	0
19-13-10*	0
19-15-11	9
20-15-12	6
20-23-17	4
22-17-18	4
23-15-12	7
23-17-14	19
24-19-12	13
26w 27e-17-18	0
28-16-11	11
28-17-18	4
32-16-11	11
33-17-18	6
35-14-15	1
35-16-17*	1
36-19-11	15
36-20-13	20
4n 9s-15-16	1

4n 9s-17-11	18
5n 8s-21-17	8
ACR	9
KIPP	10
Tilley	10

* Only surveyed in 2011. † Only surveyed in 2010

Table 2. The sum and standard deviation (SD) of bird species detected at 100-m fixed-radius point count plots over 2 rounds in both 2010 and 2011 from May to July in southeastern Alberta (*n*=720). All species occurred in ≥ 15 % of all point counts.

Species	2010		2011	
	Mean	SD	Mean	SD
Baird's sparrow	2.64	2.19	2.64	2.41
Brown-headed cowbird	0.68	1.68	0.34	0.78
Chestnut-collared longspur	4.37	3.39	4.08	4.41
Clay-colored sparrow	0.25	0.66	0.53	1.36
Horned lark	0.69	1.01	0.75	1.18
Savannah sparrow	4.87	2.98	5.76	3.48
Sprague's pipit	3.29	1.93	1.78	1.52
Vesper sparrow	0.50	0.87	0.43	0.96
Western meadowlark	2.78	1.73	2.03	1.66

Table 3. Variables used to model effects of vegetation structure, and shallow gas well density and proximity, on grassland songbirds in southeastern Alberta, in 2010 and 2011.

Parameter	Acronym
Year	YEAR
Vegetation structure	
Density of live grass	DLG
Density of dead grass	DDG
Density of crested wheatgrass	DCWG
Maximum height of live grass	HGT
Litter depth	LIT
Distance to the nearest shrub	SHB
Vegetation cover	
Percentage of bare ground	PBG
Percentage of live grass	PLG
Percentage of dead grass	PDG
Percentage of forbs	PF
Percentage of crested wheatgrass	PCWG
Infrastructure	
Shallow gas well density	WDENS
Distance to the nearest well	MINDIST

Table 4. Top models describing effects of shallow gas wells and vegetation structure and cover on focal grassland birds found in ≥ 15 % of all point counts in southeastern Alberta from May to July of 2010 and 2011 (*n*=720). ΔAIC greater than 4 are not shown, as they are less likely to be the best model. A ΔAIC of 0.00 indicates the most parsimonious model.

Model	Combination	K	AIC score	ΔAIC	*Wi*
Baird's sparrow (n=720)					
YEAR-PBG+PBG^2+PLG+PDG+PF-PF^2-PCWG	Year + Cover	11	2450.81	0.00	0.6447
YEAR-PBG+PBG^2+PLG+PDG+PF-PF^2-PCWG+WDENS-WDENS*YEAR+MINDIST	Year + Structure + Management	14	2452.23	1.42	0.3170
NULL	Null	3	2462.59	11.78	0.0018
Brown-headed cowbird (n=720)					
YEAR+DLG-DLG^2+DDG-DCWG-HGT+HGT^2-LIT-SHB+PBG+PLG-PLG^2+PDG-PDG^2-PCWG	Year + Cover + Structure	17	1077.22	0.00	0.6447
YEAR+DLG-DLG^2+DDG-DCWG-HGT+HGT^2-LIT-SHB+PBG+PLG-PLG^2-PDG+PDG^2-PCWG+WDENS-WDENS*YEAR-MINDIST	Year + Cover + Structure + Management	20	1079.56	2.34	0.2001
YEAR+DLG-DLG^2+DDG-DCWG-HGT+HGT^2-LIT-SHB+WDENS-WDENS*YEAR-MINDIST	Year + Cover + Management	14	1080.37	3.15	0.1335
NULL	Null	2	1112.33	35.11	0.0000
Chestnut-collared longspur (n=720)					
YEAR-PBG-PLG-PDG+PF-PF^2-PCWG	Year + Cover	10	2563.56	0.00	0.3448
YEAR-WDENS+WDENS*YEAR+MINDIST-MINDIST^2	Year + Management	8	2565.14	1.58	0.1565
NULL	Null	3	2565.65	2.09	0.1212
YEAR	Year	4	2566.20	2.64	0.0921
YEAR-PBG-PLG-PDG+PF-PF^2+PCWG+DLG-DDG-DCWG+DCWG^2-HGT-LIT+SHB	Year + Cover + Structure	17	2566.21	2.65	0.0916
YEAR+DLG-DDG-DCWG+DCWG^2-HGT-LIT+SHB-WDENS+WDENS*YEAR+MINDIST-MINDIST^2	Year + Structure + Management	15	2566.59	3.03	0.0758
YEAR+DLG-DDG-DCWG+DCWG^2-HGT-LIT+SHB	Year + Structure	11	2566.94	3.38	0.0636

Clay-colored sparrow (n=720)					
YEAR	Year	3	702.32	0.00	0.5917
YEAR-WDENS-MINDIST-MINDIST*YEAR	Year + Management	6	703.37	1.05	0.3501
NULL	Null	2	734.19	31.87	0.0000
Horned lark (n=720)					
YEAR+PBG-PLG-PDG-PF+PCWG-PCWG^2-WDENS-WDENS*YEAR+MINDIST	Year + Cover + Management	12	1394.00	0.00	0.8452
NULL	Null	2	1405.34	11.34	0.0029
Savannah sparrow (n=720)					
YEAR-DLG+DDG+DCWG-HGT+LIT-LIT^2+SHB+WDENS-WDENS*YEAR+MINDIST-MINDIST^2+MINDIST^2*YEAR	Year + Structure + Management	16	2897.81	0.00	0.4235
YEAR-DLG+DDG+DCWG-HGT+LIT-LIT^2+SHB	Year + Structure	11	2898.58	0.77	0.2881
YEAR+PBG+PLG+PDG-PF+PCWG-DLG+DDG+DCWG-HGT+LIT-LIT^2+SHB+WDENS-WDENS*YEAR+MINDIST-MINDIST^2*YEAR	Year + Cover + Structure + Management	21	2900.06	2.25	0.1375
YEAR-PBG+PLG+PDG-PF+PCWG-DLG+DDG+DCWG-HGT+LIT-LIT^2+SHB	Year + Cover + Structure	16	2901.35	3.54	0.0721
NULL	Null	3	2921.60	23.79	0.0000
Sprague's pipit (n=720)					
YEAR-WDENS+WDENS*YEAR+MINDIST	Year + Management	7	2122.39	0.00	0.9023
NULL	Null	3	2238.45	116.06	0.0000
Vesper sparrow (n=720)					
YEAR+DLG+DDG+DCWG-HGT+HGT^2-LIT-SHB-WDENS-WDENS*YEAR -MINDIST+YEAR*MINDIST+MINDIST^2-YEAR*MINDIST^2	Year + Structure + Management	16	1003.72	0.00	0.72
YEAR+WDENS-WDENS*YEAR-MINDIST+YEAR*MINDIST+MINDIST^2-YEAR*MINDIST^2	Year + Management	9	1005.71	1.99	0.2660
NULL	Null	2	1024.00	23.24	0.0000

Western meadowlark (n=720)					
YEAR+WDENS-WDENS*YEAR-MINDIST+MINDIST*YEAR	Year + Management	8	2193.87	0.00	0.8866
NULL	Null	3	2227.64	33.77	0.0000

Table 5. Top models describing effects of shallow gas well infrastructure on vegetation structure and cover in southeastern Alberta from June to August of 2010 and 2011 (spatial scale: 7-2000 m; *n*=720). ΔAIC greater than 4 are not shown, as they have low predictive power. A ΔAIC of 0.00 indicates the best model fit.

Model	K	AIC score	ΔAIC	*Wi*
<u>*Density live grass*</u>				
YEAR	4	3226.23	0.00	0.6781
YEAR-WDENS+WDENS^2+MINDIST	7	3227.72	1.49	0.3219
NULL	3	4031.04	804.81	0.0000
<u>*Density dead grass*</u>				
YEAR+WDENS+WDENS^2-MINDIST	7	3216.85	0.00	0.9885
NULL	3	3839.30	622.45	0.0000
<u>*Density crested wheatgrass*</u>				
YEAR	3	16.49	0.00	0.8495
NULL	2	20.02	3.53	0.1454
<u>*Maximum height of live grass*</u>				
MINDIST-MINDIST^2	5	4446.10	0.00	0.8035
NULL	3	4449.57	3.47	0.1417
<u>*Litter depth*</u>				
YEAR+WDENS-WDENS*YEAR-MINDIST+MINDIST*YEAR	8	2061.99	0.00	0.9920
NULL	3	2153.83	91.84	0.0000
<u>*Percentage bare ground*</u>				
MINDIST+MINDIST^2	5	2114.19	0.00	0.9374
NULL	3	2120.23	6.04	0.0457
<u>*Percentage live grass*</u>				
YEAR-WDENS-WDENS^2+MINDIST-MINDIST^2	8	5158.96	0.00	0.9961
NULL	3	5233.92	74.96	0.0000
<u>*Percentage dead grass*</u>				
YEAR+WDENS-MINDIST	6	5164.31	0.00	0.7251
YEAR	4	5166.25	1.94	0.2749
NULL	3	5192.35	28.04	0.0000
<u>*Percentage forbs*</u>				
YEAR-WDENS-WDENS*YEAR-MINDIST+MINDIST^2	8	4056.90	0.00	0.5744
YEAR	4	4057.50	0.60	0.4256
NULL	3	4085.85	28.95	0.0000

Percentage crested wheatgrass				
YEAR	3	13.31	0.00	0.6359
WDENS-YEAR	4	15.34	2.03	0.2305
NULL	2	16.43	3.12	0.1336

Table 6. The most parsimonious GLMM AIC-selected model parameters relative to horned lark (n=720) relative abundance in southeastern Alberta over 2010 and 2011. Values were summed across rounds to meet assumptions of the distribution. Models that achieved a ΔAIC greater than 2 are not shown, as they have low predictive power and are not considered parsimonious. Confidence limits not including 0 are indicated with grey shading.

Model	β	SE	*p*-value	90% Lower Confidence Limits	90% Upper Confidence Limits
YEAR+PBG-PLG-PDG-PF+PCWG-PCWG^2-WDENS-WDENS*YEAR+MINDIST					
Year	0.5643	0.2136	0.0135	0.20060	0.92810
Percentage of bare ground	0.0034	0.0056	0.5422	-0.00586	0.01275
Percentage of live grass	-0.0070	0.0035	0.0480	-0.01284	-0.00118
Percentage of dead grass	-0.0031	0.0038	0.4183	-0.00935	0.00319
Percentage of forbs	-0.0171	0.0070	0.0144	-0.02854	-0.00562
Percentage of crested wheatgrass	0.0992	0.0552	0.0728	0.00827	0.19010
Percentage of crested wheatgrass*Percentage of crested wheatgrass	-0.0046	0.0028	0.0984	-0.00919	-0.00002
Shallow gas well density	-0.0164	0.0252	0.5198	-0.05895	0.02615
Shallow gas well density*Year	-0.0750	0.0234	0.0014	-0.11360	-0.03642
Distance to the nearest well	0.0374	0.1651	0.8207	-0.23460	0.30940

Table 7. The most parsimonious GLMM AIC-selected model parameters relative to chestnut-collared longspur (*n*=720) relative abundance in southeastern Alberta over 2010 and 2011. Values were summed across rounds to meet assumptions of the distribution. Models that achieved a ΔAIC greater than 2 are not shown, as they have low predictive power and are not considered parsimonious. Confidence limits not including 0 are indicated with grey shading.

Model	β	SE	*p*-value	90% Lower Confidence Limits	90% Upper Confidence Limits
YEAR-PBG-PLG-PDG+PF-PF^2-PCWG (ΔAIC=0.00)					
Year	0.0377	0.0624	0.5514	-0.06865	0.14400
Percentage of bare ground	-0.0095	0.0039	0.0144	-0.01585	-0.00312
Percentage of live grass	-0.0054	0.0020	0.0089	-0.00870	-0.00199
Percentage of dead grass	-0.0048	0.0021	0.0240	-0.00821	-0.00129
Percentage of forbs	0.0101	0.0093	0.2735	-0.00510	0.02539
Percentage of forbs*Percentage of forb	-0.0004	0.0002	0.1132	-0.00076	0.00001
Percentage of crested wheatgrass	-0.0118	0.0121	0.3303	-0.03175	0.00815
YEAR-WDENS+WDENS*YEAR+MINDIST-MINDIST^2 (ΔAIC=1.42)					
Year	-0.0814	0.1017	0.4309	-0.25460	0.09194
Shallow gas well density	-0.0647	0.0412	0.1248	-0.13420	0.00479
Shallow gas well density*Year	0.0189	0.0110	0.0858	0.00081	0.03704
Distance to the nearest well	0.3303	0.1859	0.0761	0.02405	0.63650
Distance to the nearest well*Distance to the nearest well	-0.0925	0.0531	0.0818	-0.18000	-0.00508

Table 8. The most parsimonious GLMM AIC-selected model parameters relative to Savannah sparrow (*n*=720) relative abundance in southeastern Alberta over 2010 and 2011. Values were summed across rounds to meet assumptions of the distribution. Models that achieved a ΔAIC greater than 2 are not shown, as they have low predictive power and are not considered parsimonious. Confidence limits not including 0 are indicated with grey shading.

Model	β	SE	*p*-value	90% Lower Confidence Limits	90% Upper Confidence Limits
YEAR-DLG+DDG+DCWG-HGT+LIT-LIT^2+SHB+ WDENS-WDENS*YEAR+MINDIST-MINDIST^2+ MINDIST^2*YEAR (ΔAIC=0.00)					
Year	-0.0856	0.1265	0.5044	-0.30110	0.12990
Density of live grass	-0.0052	0.0041	0.2068	-0.01198	0.00158
Density of dead grass	0.0056	0.0041	0.1753	-0.00119	0.01230
Density of crested wheatgrass	0.0090	0.0307	0.7702	-0.04165	0.05962
Maximum height of live grass	-0.0005	0.0022	0.8312	-0.00411	0.00317
Litter depth	0.0964	0.0281	0.0006	0.05011	0.14270
Litter depth*Litter depth	-0.0081	0.0027	0.0029	-0.01250	-0.00363
Distance to the nearest shrub	0.1447	0.1800	0.4217	-0.15180	0.44130
Shallow gas well density	0.0120	0.0119	0.3182	-0.00800	0.03200
Shallow gas well density*Year	-0.0200	0.0088	0.0226	-0.03448	-0.00560
Distance to the nearest well	0.1220	0.1502	0.4171	-0.12550	0.36960
Distance to the nearest well*Distance to the nearest well	-0.0810	0.0482	0.1935	-0.16050	-0.00158
Distance to the nearest well*Distance to the nearest well*Year	0.0025	0.0049	0.0460	-0.00550	0.01056
YEAR-DLG+DDG+DCWG-HGT+LIT-LIT^2+SHB (ΔAIC=0.77)					
Year	-0.2619	0.1009	0.0151	-0.43380	-0.09004
Density of live grass	-0.0060	0.0042	0.1509	-0.01285	0.00087
Density of dead grass	0.0060	0.0041	0.1462	-0.00079	0.01280
Density of crested wheatgrass	0.0085	0.0310	0.7840	-0.04252	0.05951

Maximum height of live grass	-0.0010	0.0022	0.6511	-0.00464	0.00264
Litter depth	0.1042	0.0283	0.0003	0.05758	0.15080
Litter depth*Litter depth	-0.0084	0.0027	0.0021	-0.01292	-0.00395
Distance to the nearest shrub	0.0958	0.1778	0.5902	-0.19710	0.38870

Table 9. The most parsimonious GLMM AIC-selected model parameters relative to clay-colored sparrow (n=720) relative abundance in southeastern Alberta over 2010 and 2011. Values were summed across rounds to meet assumptions of the distribution. Models that achieved a ΔAIC greater than 2 are not shown, as they have low predictive power and are not considered parsimonious. Confidence limits not including 0 are indicated with grey shading.

Model	β	SE	*p*-value	90% Lower Confidence Limits	90% Upper Confidence Limits
YEAR					
Year	-0.9925	0.1813	<0.0001	-1.30130	-0.68360

Table 10. The most parsimonious GLMM AIC-selected model parameters relative to Sprague's pipit (n=720) relative abundance in southeastern Alberta over 2010 and 2011. Values were summed across rounds to meet assumptions of the distribution. Models that achieved a ΔAIC greater than 2 are not shown, as they have low predictive power and are not considered parsimonious. Confidence limits not including 0 are indicated with grey shading.

Model	β	SE	*p*-value	90% Lower Confidence Limits	90% Upper Confidence Limits
YEAR-WDENS+WDENS*YEAR+MINDIST					
Year	0.5877	0.1097	<0.0001	0.4009	0.7745
Shallow gas well density	-0.0154	0.0165	0.3564	-0.0432	0.0124
Shallow gas well density*Year	0.0117	0.0115	0.3093	-0.0073	0.0307
Distance to the nearest well	0.2319	0.1014	0.0226	0.0648	0.3990

Table 11. The most parsimonious GLMM AIC-selected model parameters relative to vesper sparrow (n=720) relative abundance in southeastern Alberta over 2010 and 2011. Values were summed across rounds to meet assumptions of the distribution. Models that achieved a ΔAIC greater than 2 are not shown, as they have low predictive power and are not considered parsimonious. Confidence limits not including 0 are indicated with grey shading.

Model	β	SE	p-value	90% Lower Confidence Limits	90% Upper Confidence Limits
YEAR+DLG+DDG+DCWG-HGT+HGT^2-LIT-SHB-WDENS-WDENS*YEAR -MINDIST+MINDIST*YEAR+ MINDIST^2-MINDIST^2*YEAR					
Year	0.7156	0.4996	0.1635	-0.13540	1.56670
Density of live grass	0.0081	0.0128	0.5291	-0.01307	0.02924
Density of dead grass	0.0192	0.0151	0.2037	-0.00566	0.04409
Density of crested wheatgrass	0.0620	0.1137	0.5859	-0.12540	0.24930
Maximum height of live grass	-0.0455	0.0141	0.0013	-0.06877	-0.02231
Maximum height of live grass*Maximum height of live grass	0.0006	0.0002	<0.0001	0.00035	0.00084
Litter depth	-0.0790	0.0427	0.0649	-0.14930	-0.00864
Distance to the nearest shrub	-0.7229	0.6569	0.2716	-1.80520	0.35940
Shallow gas well density	-0.0157	0.0350	0.6571	-0.07465	0.04334
Shallow gas well density*Year	-0.0352	0.0290	0.2252	-0.08294	0.01256
Distance to the nearest well	-3.0452	0.7726	<0.0001	-4.31810	-1.77220
Distance to the nearest well*Year	1.1804	1.0033	0.2399	-0.47260	2.83340
Distance to the nearest well*Distance to the nearest well	0.5129	0.3093	0.0979	0.00326	1.02250
Distance to the nearest well*Distance to the nearest well*Year	-0.1152	0.3508	0.7428	-0.69310	0.46280

Table 12. The most parsimonious GLMM AIC-selected model parameters relative to western meadowlark (*n*=720) relative abundance in southeastern Alberta over 2010 and 2011. Values were summed across rounds to meet assumptions of the distribution. Models that achieved a ΔAIC greater than 2 are not shown, as they have low predictive power and are not considered parsimonious. Confidence limits not including 0 are indicated with grey shading.

Model	β	SE	*p*-value	90% Lower Confidence Limits	90% Upper Confidence Limits
YEAR+WDENS-WDENS*YEAR-MINDIST+MINDIST*YEAR					
Year	0.3922	0.1439	0.0111	0.14720	0.63730
Shallow gas well density	0.0166	0.0126	0.1939	-0.00458	0.03786
Shallow gas well density*Year	-0.0183	0.0125	0.1448	-0.03888	0.00234
Distance to the nearest well	-0.1963	0.1107	0.0767	-0.37860	-0.01395
Distance to the nearest well*Year	0.1943	0.1189	0.1026	-0.00149	0.39020

Table 13. The influence of distance from the nearest natural gas well (spatial scale: 0-20 m; n=401) on vegetation variables at 1-m^2 quadrats in southeastern Alberta in 2010 and 2011. Significant p-values are indicated with grey shading.

Variable	Distribution	Estimate	p-value	90% Lower Confidence Limits	90% Upper Confidence Limits
Density live grass	negative binomial	0.0064	0.1352	-0.0006	0.0134
Density dead grass	negative binomial	0.0187	0.0003	0.0103	0.0271
Density crested wheatgrass	Poisson	-0.0237	0.1385	-0.0500	0.0026
Maximum height of live grass	negative binomial	0.0141	<0.0001	0.0084	0.0199
Litter depth	negative binomial	0.0433	<0.0001	0.0337	0.0529
Distance to the nearest shrub (presence/absence)	binomial	-0.1007	0.0246	-0.1743	-0.0272
Percentage bare ground	negative binomial	-0.0945	<0.0001	-0.1192	-0.0698
Percentage live grass	negative binomial	0.0033	0.2852	-0.0018	0.0083
Percentage dead grass	negative binomial	0.0070	0.0332	0.0016	0.0124
Percentage forbs	negative binomial	0.0198	0.0132	0.0067	0.0329
Percentage crested wheatgrass (presence/absence)	binomial	-0.3008	0.0002	-0.4317	-0.1698

Table 14. The influence of distance from the nearest natural gas associated trail on vegetation variables at 1-m^2 quadrats in southeastern Alberta in 2010 and 2011 (spatial scale: 0-20 m; *n*=193). Significant *p*-values are indicated with grey shading.

Variable	Distribution	Estimate	*p*-value	90% Lower Confidence Limits	90% Upper Confidence Limits
Density live grass	negative binomial	0.0020	0.7960	-0.0108	0.0147
Density dead grass	negative binomial	0.0152	0.0775	0.0010	0.0293
Maximum height of live grass	negative binomial	0.0088	0.0326	0.0020	0.0156
Litter depth	negative binomial	0.0276	0.0024	0.0128	0.0424
Distance to the nearest shrub	negative binomial	0.0062	0.6064	-0.0136	0.0259
Percentage bare ground (presence/absence)	binomial	-0.0716	0.0185	-0.1213	-0.0218
Percentage live grass	negative binomial	-0.0063	0.2217	-0.0147	0.0022
Percentage dead grass	negative binomial	0.0137	0.0003	0.0076	0.0199
Percentage forbs	negative binomial	0.0014	0.8819	-0.0139	0.0166
Percentage crested wheatgrass (presence/absence)	binomial	0.2139	0.0235	0.0591	0.3686

Table 15. The influence of distance from the nearest natural gas associated low impact road on vegetation variables at 1-m^2 quadrats in southeastern Alberta in 2010 and 2011 (spatial scale: 0-20 m; n=119). Significant p-values are indicated with grey shading.

Variable	Distribution	Estimate	p-value	90% Lower Confidence Limits	90% Upper Confidence Limits
Density live grass	negative binomial	0.0012	0.8690	-0.0112	0.0137
Density dead grass	negative binomial	-0.0030	0.7610	-0.0195	0.0134
Maximum height of live grass	negative binomial	-0.0036	0.5949	-0.0147	0.0075
Litter depth	negative binomial	0.0371	0.0410	0.0074	0.0669
Distance to the nearest shrub	binomial	-0.0148	0.8811	-0.1781	0.1485
Percentage bare ground (presence/absence)	binomial	-0.1258	0.0050	-0.1986	-0.0531
Percentage live grass	negative binomial	0.0088	0.1198	-0.0005	0.0181
Percentage dead grass	negative binomial	-0.0124	0.1106	-0.0253	0.0004
Percentage forbs	negative binomial	-0.0053	0.7079	-0.0288	0.0181
Percentage crested wheatgrass (presence/absence)	binomial	-0.0689	0.3899	-0.2013	0.0635

Table 16. The influence of distance from the nearest natural gas associated higher impact road on vegetation variables at 1-m^2 quadrats in southeastern Alberta in 2010 and 2011 (spatial scale: 0-20 m; *n*=89). Significant *p*-values are indicated with grey shading.

Variable	Distribution	Estimate	*p*-value	90% Lower Confidence Limits	90% Upper Confidence Limits
Density live grass	negative binomial	0.0027	0.7860	-0.0137	0.0191
Density dead grass	normal	0.0006	0.9739	-0.0274	0.0286
Density crested wheatgrass	Poisson	-0.0343	0.3079	-0.0900	0.0214
Maximum height of live grass	negative binomial	0.0076	0.3797	-0.0067	0.0218
Litter depth	negative binomial	0.0144	0.2891	-0.0080	0.0368
Distance to the nearest shrub	negative binomial	0.0042	0.7917	-0.0224	0.0309
Percentage bare ground (presence/absence)	binomial	-0.1450	0.0093	-0.2355	-0.0546
Percentage live grass	negative binomial	-0.0050	0.4615	-0.0162	0.0062
Percentage dead grass	negative binomial	0.0011	0.8523	-0.0090	0.0113
Percentage forbs	negative binomial	0.0118	0.4863	-0.0163	0.0398
Percentage crested wheatgrass (presence/absence)	binomial	-0.1987	0.0694	-0.3784	-0.0191

Table 17. Mean and standard deviation (SD) for vegetation measurements averaged over 1-m^2 quadrats surveyed within point count locations (spatial scale: 7-2000 m; *n*=720) in southeastern Alberta during 2010 and 2011.

Species	2010		2011	
	Mean	SD	Mean	SD
Density live grass (number of stems)	2.77	1.69	15.81	7.39
Density dead grass (number of stems)	2.45	1.71	13.11	7.36
Density crested wheatgrass (number of stems)	0.03	0.27	0.09	0.78
Maximum height of live grass (cm)	22.97	10.85	22.58	11.55
Litter depth (mm)	2.39	1.97	1.32	1.74
Distance to the nearest shrub (km)	0.04	0.13	0.11	0.19
Percentage bare ground (%)	2.79	6.60	3.09	8.57
Percentage live grass (%)	29.56	14.98	42.05	19.03
Percentage dead grass (%)	39.41	18.23	30.91	17.74
Percentage forbs (%)	12.90	10.24	9.28	8.42
Percentage crested wheatgrass (%)	0.31	2.19	0.45	2.87

Table 18. The most parsimonious GLMM AIC-selected model parameters describing effects of shallow gas well infrastructure on the maximum height of live grass (spatial scale: 7-2000 m; n=720) in southeastern Alberta over 2010 and 2011. Models that achieved a ΔAIC greater than 2 are not shown, as they have low predictive power and are not considered parsimonious. Confidence limits not including 0 are indicated with grey shading.

Model	β	SE	*p*-value	90% Lower Confidence Limits	90% Upper Confidence Limits
MINDIST-MINDIST^2					
Distance to the nearest well	0.2313	0.0887	0.0095	0.08507	0.37760
Distance to the nearest well*Distance to the nearest well	-0.0537	0.0257	0.0372	-0.09599	-0.01134

Table 19. The most parsimonious GLMM AIC-selected model parameters describing effects of shallow gas well infrastructure on litter depth (spatial scale: 7-2000 m; *n*=720) in southeastern Alberta over 2010 and 2011. Models that achieved a ΔAIC greater than 2 are not shown, as they have low predictive power and are not considered parsimonious. Confidence limits not including 0 are indicated with grey shading.

Model	β	SE	*p*-value	90% Lower Confidence Limits	90% Upper Confidence Limits
YEAR+WDENS-WDENS*YEAR-MINDIST+MINDIST*YEAR					
Year	0.9612	0.1699	<0.0001	0.68050	1.24200
Shallow gas well density	0.0361	0.0116	0.0020	0.01698	0.05519
Shallow gas well density*Year	-0.0414	0.0139	0.0032	-0.06430	-0.01849
Distance to the nearest well	-0.0132	0.1176	0.9109	-0.20710	0.18080
Distance to the nearest well*Year	0.0778	0.1534	0.6124	-0.17550	0.33120

Table 20. The most parsimonious GLMM AIC-selected model parameters describing effects of shallow gas well infrastructure on percentage bare ground (spatial scale: 7-2000 m; *n*=720) in southeastern Alberta over 2010 and 2011. Models that achieved a ΔAIC greater than 2 are not shown, as they have low predictive power and are not considered parsimonious. Confidence limits not including 0 are indicated with grey shading.

Model	β	SE	*p*-value	90% Lower Confidence Limits	90% Upper Confidence Limits
MINDIST+MINDIST^2					
Distance to the nearest well	-1.8552	0.5928	0.0019	-2.83250	-0.87780
Distance to the nearest well*Distance to the nearest well	0.4934	0.1649	0.0029	0.22150	0.76530

Table 21. The most parsimonious GLMM AIC-selected model parameters describing effects of shallow gas well infrastructure on percentage dead grass (spatial scale: 7-2000 m; n=720) in southeastern Alberta over 2010 and 2011. Models that achieved a ΔAIC greater than 2 are not shown, as they have low predictive power and are not considered parsimonious. Confidence limits not including 0 are indicated with grey shading.

Model	β	SE	*p*-value	90% Lower Confidence Limits	90% Upper Confidence Limits
YEAR+WDENS-MINDIST (ΔAIC=0.00)					
Year	0.2487	0.0459	<0.0001	0.17290	0.32460
Shallow gas well density	0.0081	0.0047	0.0858	0.00035	0.01587
Distance to the nearest well	-0.0258	0.0460	0.5746	-0.10160	0.04998
YEAR (ΔAIC=1.94)					
Year	0.2456	0.0457	<0.0001	0.17020	0.32100

Table 22. The most parsimonious GLMM AIC-selected model parameters describing effects of shallow gas well infrastructure on density of live grass (spatial scale: 7-2000 m; *n*=720) in southeastern Alberta over 2010 and 2011. Models that achieved a ΔAIC greater than 2 are not shown, as they have low predictive power and are not considered parsimonious. Confidence limits not including 0 are indicated with grey shading.

Model	β	SE	*p*-value	90% Lower Confidence Limits	90% Upper Confidence Limits
YEAR					
Year	-1.7264	0.0431	<0.0001	-1.79750	-1.65530

Table 23. The most parsimonious GLMM AIC-selected model parameters describing effects of shallow gas well infrastructure on density dead grass (spatial scale: 7-2000 m; *n*=720) in southeastern Alberta over 2010 and 2011. Models that achieved a ΔAIC greater than 2 are not shown, as they have low predictive power and are not considered parsimonious. Confidence limits not including 0 are indicated with grey shading.

Model	β	SE	*p*-value	90% Lower Confidence Limits	90% Upper Confidence Limits
YEAR+WDENS+WDENS^2-MINDIST					
Year	-1.6755	0.0534	<0.0001	-1.76360	-1.58730
Shallow gas well density	0.0103	0.0166	0.5370	-0.01714	0.03769
Shallow gas well density*Shallow gas well density	0.0003	0.0008	0.6945	-0.00101	0.00164
Distance to the nearest well	-0.0249	0.0543	0.6475	-0.11440	0.06470

Table 24. The most parsimonious GLMM AIC-selected model parameters describing effects of shallow gas well infrastructure on density crested wheatgrass (spatial scale: 7-2000 m; *n*=720) in southeastern Alberta over 2010 and 2011. Models that achieved a ΔAIC greater than 2 are not shown, as they have low predictive power and are not considered parsimonious. Confidence limits not including 0 are indicated with grey shading.

Model	β	SE	*p*-value	90% Lower Confidence Limits	90% Upper Confidence Limits
YEAR					
Year	14.0955	8.3002	0.0909	0.38380	27.80720

Table 25. The most parsimonious GLMM AIC-selected model parameters describing effects of shallow gas well infrastructure on percentage live grass (spatial scale: 7-2000 m; *n*=720) in southeastern Alberta over 2010 and 2011. Models that achieved a ΔAIC greater than 2 are not shown, as they have low predictive power and are not considered parsimonious. Confidence limits not including 0 are indicated with grey shading.

Model	β	SE	*p*-value	90% Lower Confidence Limits	90% Upper Confidence Limits
YEAR-WDENS-WDENS^2+MINDIST-MINDIST^2					
Year	-0.3416	0.0419	<0.0001	-0.41070	-0.27240
Shallow gas well density	-0.0073	0.0146	0.6179	-0.03143	0.01682
Shallow gas well density*Shallow gas well density	-0.0001	0.0007	0.9399	-0.00116	0.00105
Distance to the nearest well	0.1730	0.1263	0.1718	-0.03534	0.38130
Distance to the nearest well*Distance to the nearest well	-0.0267	0.0312	0.3929	-0.07822	0.02479

Table 26. The most parsimonious GLMM AIC-selected model parameters describing effects of shallow gas well infrastructure on percentage forbs (spatial scale: 7-2000 m; *n*=720) in southeastern Alberta over 2010 and 2011. Models that achieved a ΔAIC greater than 2 are not shown, as they have low predictive power and are not considered parsimonious. Confidence limits not including 0 are indicated with grey shading.

Model	β	SE	*p*-value	90% Lower Confidence Limits	90% Upper Confidence Limits
YEAR-WDENS-WDENS*YEAR-MINDIST+MINDIST^2 (ΔAIC=0.00)					
Year	0.4565	0.1103	<0.0001	0.27420	0.63870
Shallow gas well density	-0.0023	0.0097	0.8143	-0.01824	0.01369
Shallow gas well density*Year	-0.0169	0.0115	0.1437	-0.03589	0.00212
Distance to the nearest well	-0.4517	0.1958	0.0216	-0.77450	-0.12890
Distance to the nearest well*Distance to the nearest well	0.1074	0.0528	0.0426	0.02035	0.19450
YEAR (ΔAIC=0.60)					
Year	0.3419	0.0610	<0.0001	0.24120	0.44270

Table 27. The most parsimonious GLMM AIC-selected model parameters describing effects of shallow gas well infrastructure on percentage crested wheatgrass (spatial scale: 7-2000 m; *n*=720) in southeastern Alberta over 2010 and 2011. Models that achieved a ΔAIC greater than 2 are not shown, as they have low predictive power and are not considered parsimonious. Confidence limits not including 0 are indicated with grey shading.

Model	β	SE	*p*-value	90% Lower Confidence Limits	90% Upper Confidence Limits
YEAR					
Year	-13.7814	8.3347	0.2404	-27.55150	-0.01125

Table 28. The most parsimonious GLMM AIC-selected model parameters relative to brown-headed cowbird (n=720) relative abundance in southeastern Alberta over 2010 and 2011. Values were summed across rounds to meet assumptions of the distribution. Models that achieved a ΔAIC greater than 2 are not shown, as they have low predictive power and are not considered parsimonious. Confidence limits not including 0 are indicated with grey shading.

Model	β	SE	p-value	90% Lower Confidence Limits	90% Upper Confidence Limits
YEAR+DLG-DLG^2+DDG-DCWG-HGT+HGT^2-LIT-SHB+PBG+PLG-PLG^2+PDG-PDG^2-PCWG					
Year	1.3713	0.4485	0.0050	0.60740	2.13520
Density of live grass	0.0934	0.0464	0.0447	0.01690	0.16980
Density of live grass*Density of live grass	-0.0023	0.0011	0.0337	-0.00407	-0.00052
Density of dead grass	0.0282	0.0149	0.0586	0.00367	0.05263
Density of crested wheatgrass	-0.3955	0.5027	0.4317	-1.22370	0.43270
Maximum height of live grass	-0.0397	0.0142	0.0056	-0.06311	-0.01618
Maximum height of live grass*Maximum height of live grass	0.0003	0.0001	0.0072	0.00012	0.00051
Litter depth	-0.0706	0.0601	0.2408	-0.16950	0.02845
Distance to the nearest shrub	-1.0035	0.6045	0.0975	-1.99960	-0.00750
Percentage of bare ground	0.0132	0.0117	0.2597	-0.00606	0.03238
Percentage of live grass	0.0352	0.0153	0.0214	0.01007	0.06031
Percentage of live grass*Percentage of live grass	-0.0002	0.0002	0.1655	-0.00052	0.00004
Percentage of dead grass	0.0118	0.0176	0.5001	-0.01707	0.04076
Percentage of dead grass*Percentage of dead grass	-0.0002	0.0002	0.4791	-0.00052	0.00021
Percentage of crested wheatgrass	-0.0014	0.0732	0.9853	-0.12200	0.11930

Table 29. The most parsimonious GLMM AIC-selected model parameters relative to Baird's sparrow (*n*=720) relative abundance in southeastern Alberta over 2010 and 2011. Values were summed across rounds to meet assumptions of the distribution. Models that achieved a ΔAIC greater than 2 are not shown, as they have low predictive power and are not considered parsimonious. Confidence limits not including 0 are indicated with grey shading.

Model	β	SE	*p*-value	90% Lower Confidence Limits	90% Upper Confidence Limits
YEAR-PBG+PBG^2+PLG+PDG+PF-PF^2-PCWG					
Year	-0.0111	0.0795	0.8904	-0.14650	0.12440
Percentage of bare ground	-0.0245	0.0103	0.0182	-0.04149	-0.00744
Percentage of bare ground*Percentage of bare ground	0.0004	0.0002	0.0181	0.00013	0.00070
Percentage of live grass	0.0006	0.0027	0.8174	-0.00377	0.00501
Percentage of dead grass	0.0054	0.0028	0.0532	0.00080	0.00992
Percentage of forbs	0.0099	0.0120	0.4084	-0.00980	0.02958
Percentage of forbs*Percentage of forbs	-0.0006	0.0003	0.0762	-0.00106	-0.00004
Percentage of crested wheatgrass	-0.0186	0.0161	0.2493	-0.04516	0.00797

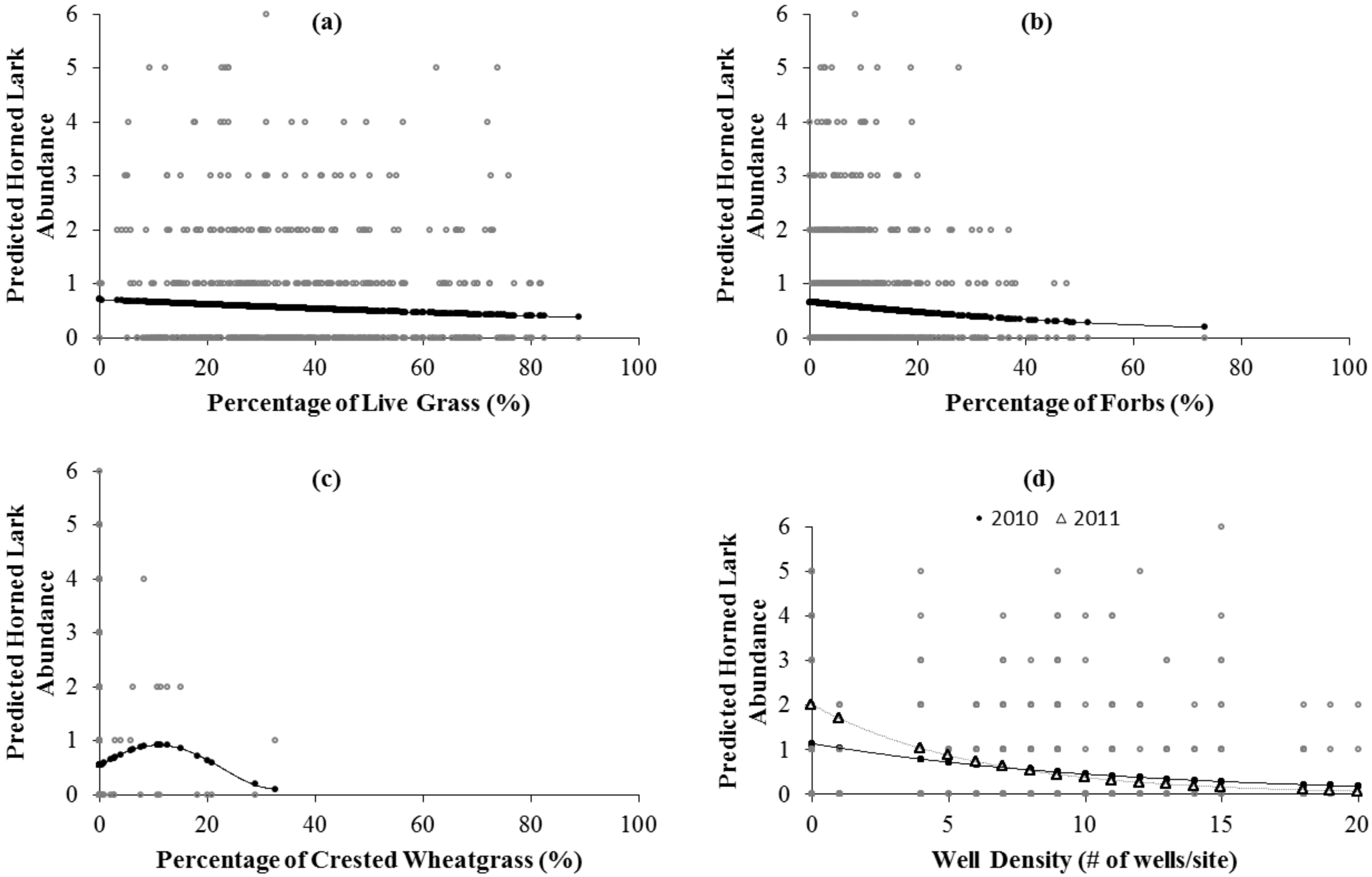


Figure 1. The effect of percentage of (a) live grass, (b) forbs, (c) crested wheatgrass, and (d) well density (# of wells/site) in 2010 and 2011 on the AIC-selected model-predicted abundance of horned lark (*n*=720). Bird abundance is based on 100-m fixed-radius point counts completed in southeastern Alberta in 2010 and 2011. Values were summed across rounds to meet assumptions of the distribution. Raw data values are shown in grey.

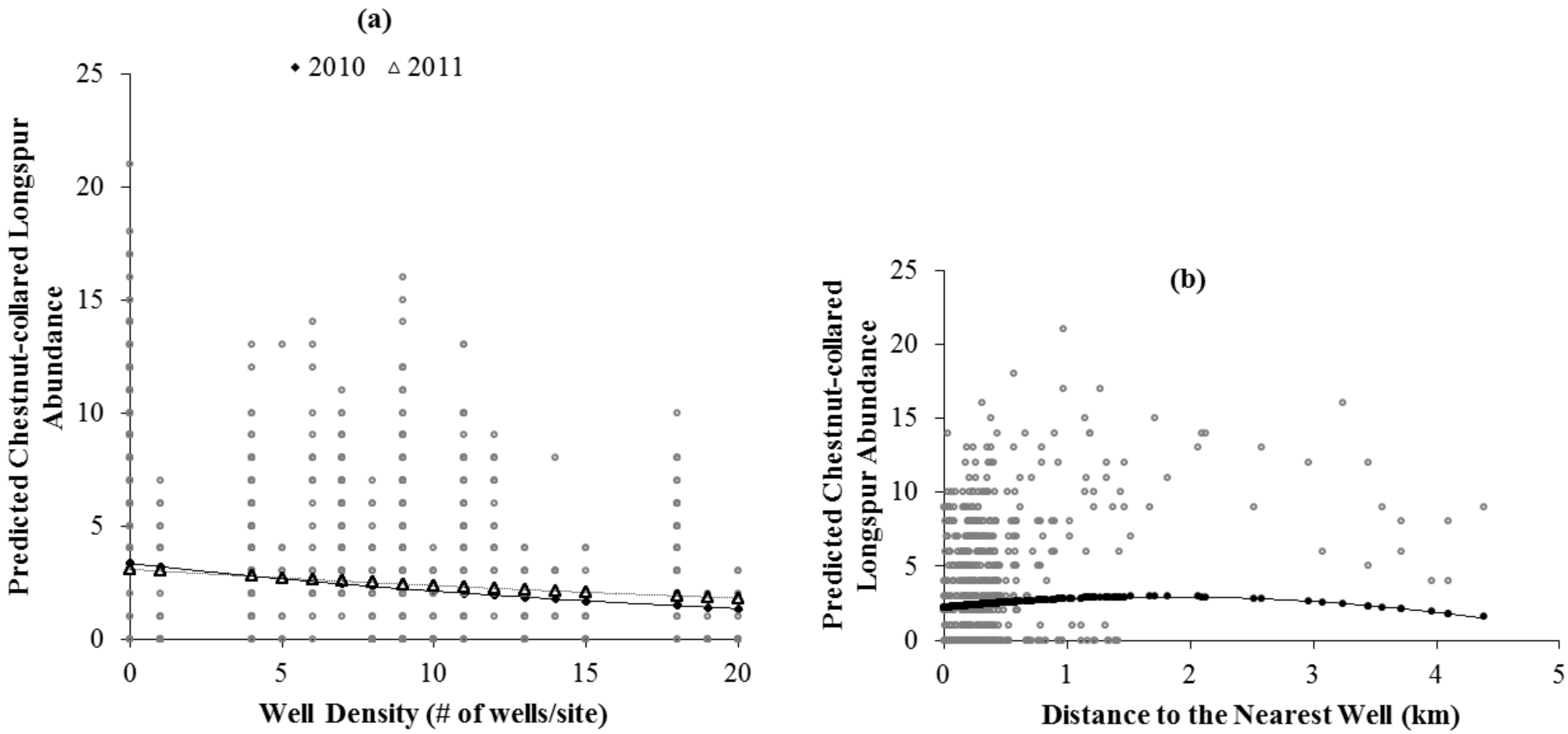


Figure 2. The effect of (a) well density(# of wells/site) in 2010 and 2011, and (b) distance to the nearest well (km) on the competitive model-predicted abundance of chestnut-collared longspur (*n*=720). Bird abundance is based on 100-m fixed-radius point counts completed in southeastern Alberta in 2010 and 2011. Values were summed across rounds to meet assumptions of the distribution. Raw data values are shown in grey.

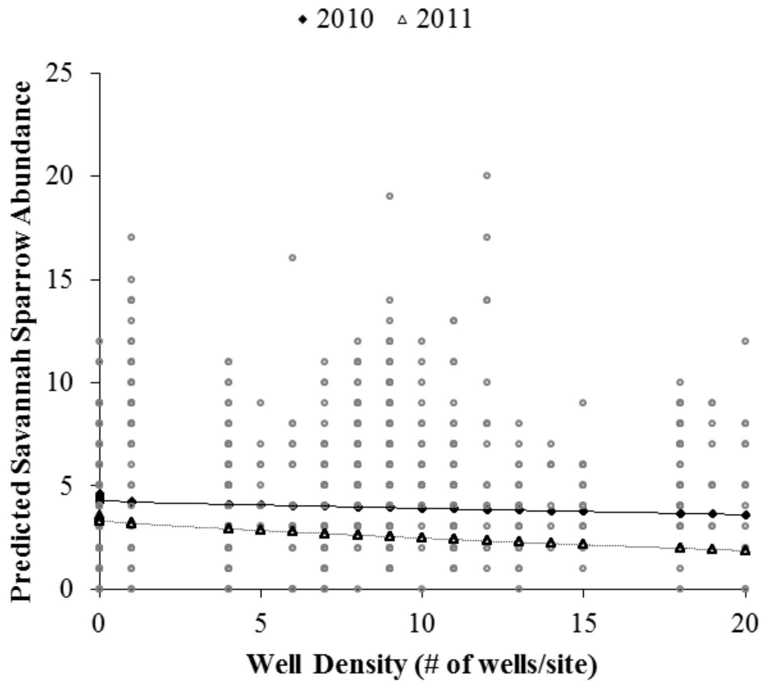


Figure 3. The effect well density (# of wells/site) in 2010 and 2011 on the competitive model-predicted abundance of Savannah sparrow (*n*=720). Bird abundance is based on 100-m fixed-radius point counts completed in southeastern Alberta in 2010 and 2011. Values were summed across rounds to meet assumptions of the distribution. Raw data values are shown in grey.

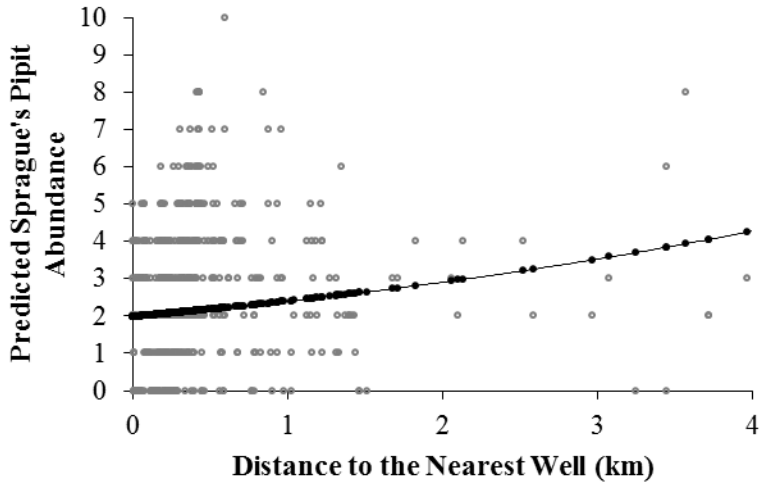


Figure 4. The effect of distance to the nearest well (km) on the AIC-selected model-predicted abundance of Sprague's pipit (*n*=720). Bird abundance is based on 100-m fixed-radius point counts completed in southeastern Alberta in 2010 and 2011. Values were summed across rounds to meet assumptions of the distribution. Raw data values are shown in grey.

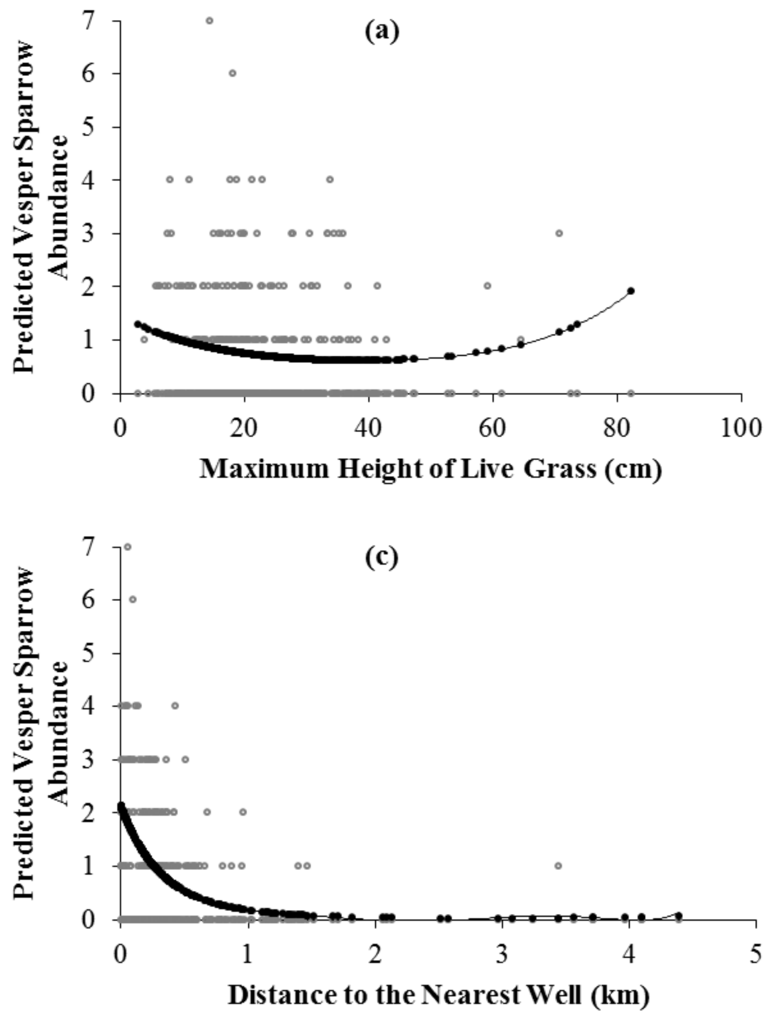


Figure 5. The effect of (a) maximum height of live grass (cm), (b) litter depth (mm), and (c) distance to the nearest well (km) on the AIC-selected model-predicted abundance of vesper sparrow (*n*=720). Bird abundance is based on 100-m fixed-radius point counts completed in southeastern Alberta in 2010 and 2011. Values were summed across rounds to meet assumptions of the distribution. Raw data values are shown in grey.

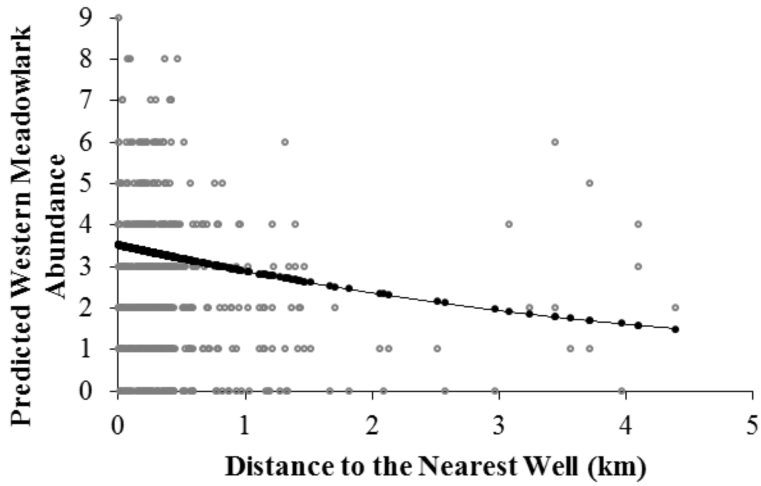
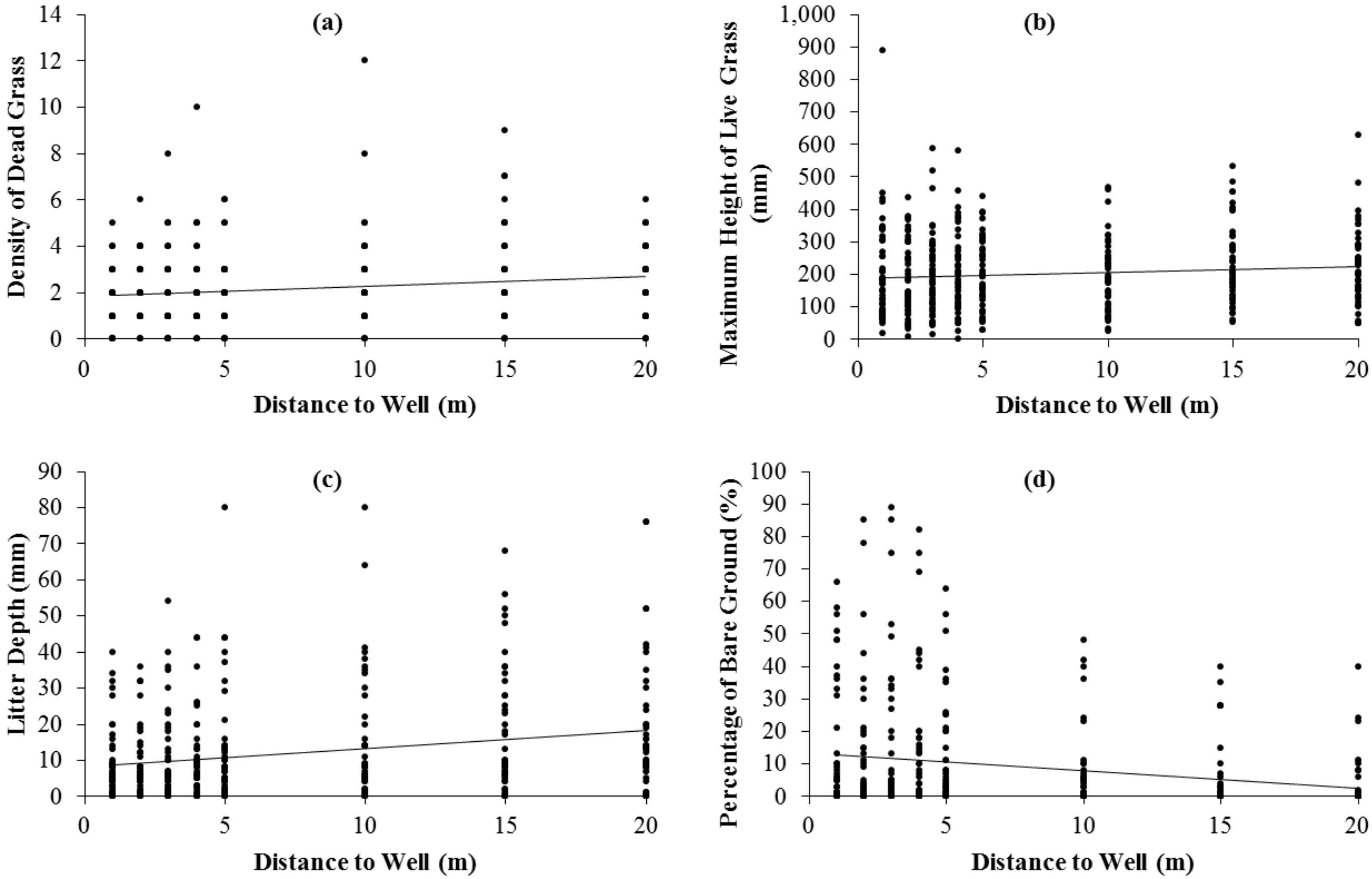


Figure 6. The effect of distance to the nearest well (km) on the AIC-selected model-predicted abundance of western meadowlark (*n*=720). Bird abundance is based on 100-m fixed-radius point counts completed in southeastern Alberta in 2010 and 2011. Values were summed across rounds to meet assumptions of the distribution. Raw data values are shown in grey.


(a)
Density of Dead Grass
Distance to Well (m)
(b)
Maximum Height of Live Grass (mm)
Distance to Well (m)
(c)
Litter Depth (mm)
Distance to Well (m)
(d)
Percentage of Bare Ground (%)
Distance to Well (m)

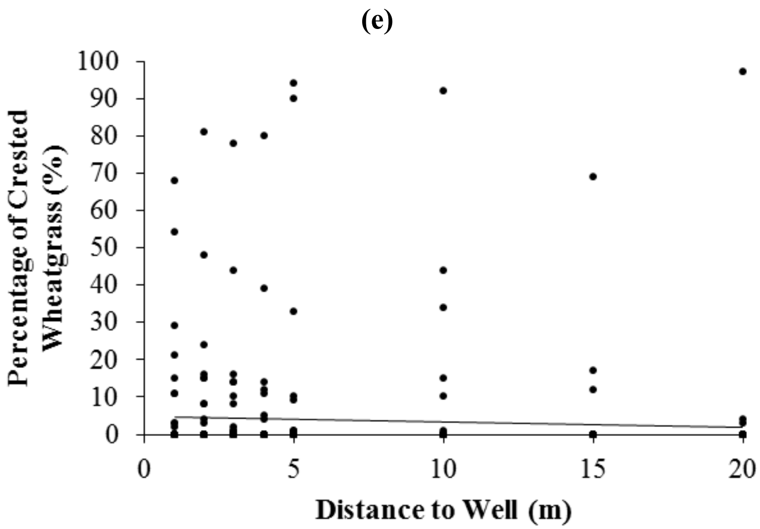


Figure 7. The change in (a) density of dead grass (number of stems), (b) maximum height of live grass (mm), (c) litter depth (mm), (d) percentage of bare ground (%), and (e) crested wheatgrass (%) with distance to natural gas well (m) based on transect vegetation data collected in southeastern Alberta in 2010 and 2011 (spatial scale: 0-20 m; *n*=401).

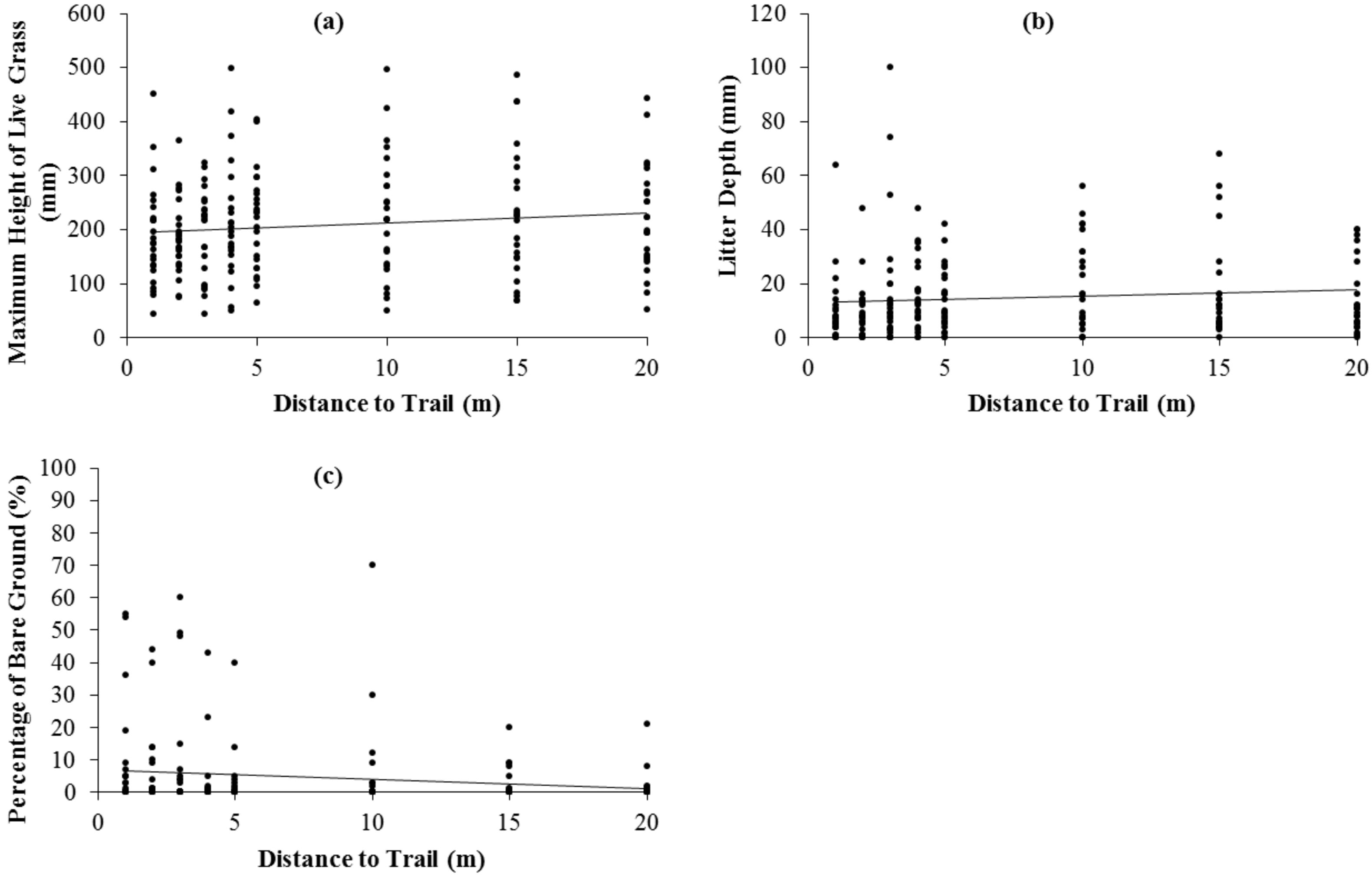


Figure 8. The change in (a) maximum height of live grass (mm), (b) litter depth (mm) and (c) percentage bare ground (%) with distance to natural gas well access trail (m) based on transect vegetation data collected in southeastern Alberta in 2010 and 2011 (spatial scale: 0-20 m; *n*=193).

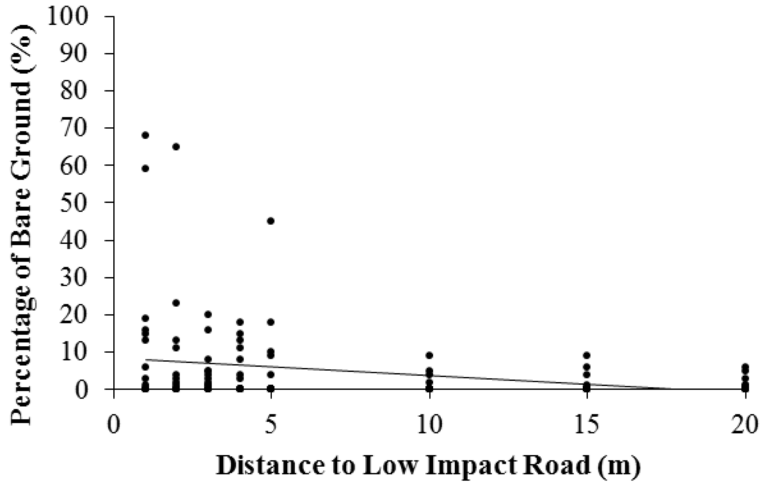


Figure 9. The change in percentage of bare ground (%) with distance to natural gas well low impact access road (m) based on transect vegetation data collected in southeastern Alberta in 2010 and 2011 (spatial scale: 0-20 m; *n*=119).

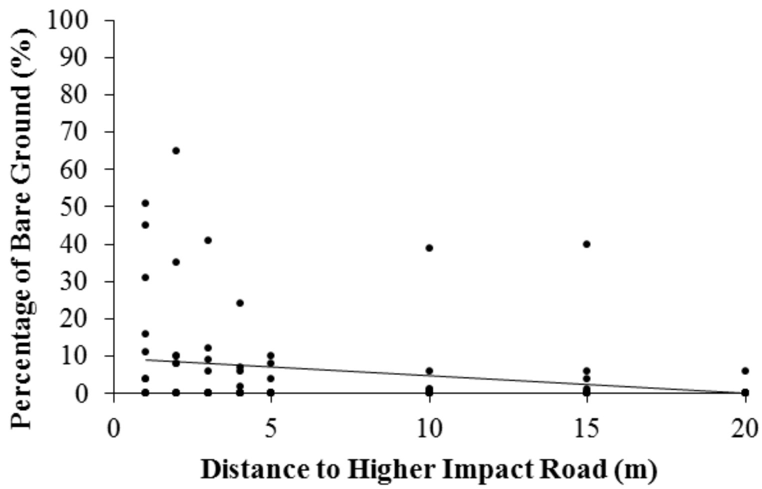


Figure 10. The change in percentage of bare ground (%) with distance to natural gas well higher impact access road (m) based on transect vegetation data collected in southeastern Alberta in 2010 and 2011 (spatial scale: 0-20 m; *n*=89).

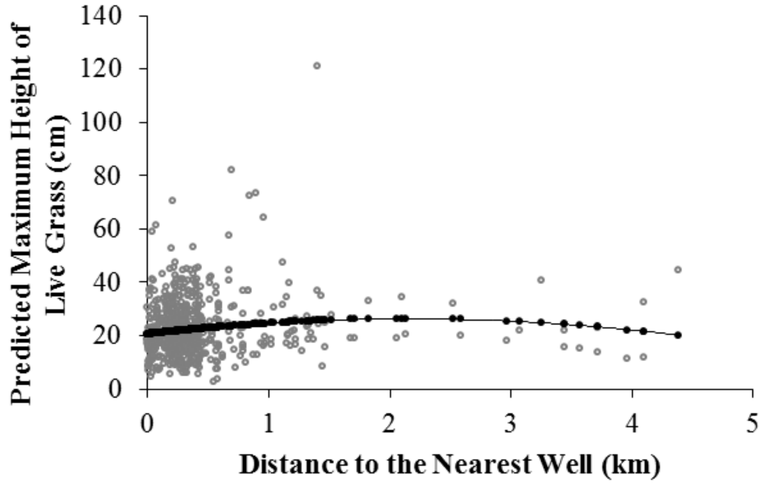


Figure 11. The effect of distance to the nearest well (km) on the AIC-selected model-predicted maximum height of live grass (cm) (spatial scale: 7-2000 m; *n*=720). The predicted maximum height of live grass is based on data collected at vegetation quadrats completed at point count locations in southeastern Alberta in 2010 and 2011.

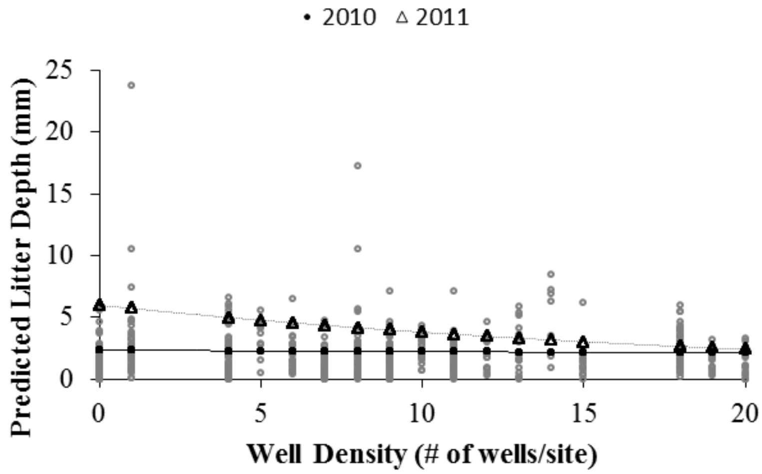


Figure 12. The effect of well density (# of wells/site) in 2010 and 2011 on the AIC-selected model-predicted litter depth (mm) (spatial scale: 7-2000 m; *n*=720). The predicted litter depth is based on data collected at vegetation quadrats completed at point count locations in southeastern Alberta in 2010 and 2011.

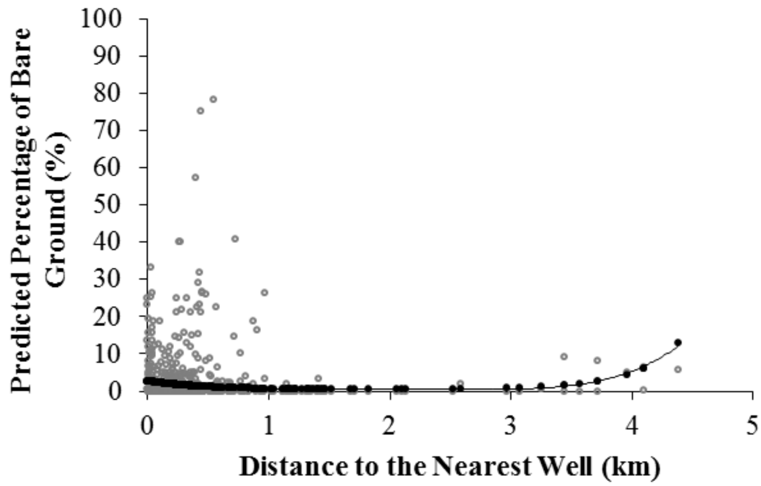


Figure 13. The effect of distance to the nearest well (km) on the AIC-selected model-predicted percentage of bare ground (%) (spatial scale: 7-2000 m; *n*=720). The predicted maximum height of live grass is based on data collected at vegetation quadrats completed at point count locations in southeastern Alberta in 2010 and 2011.

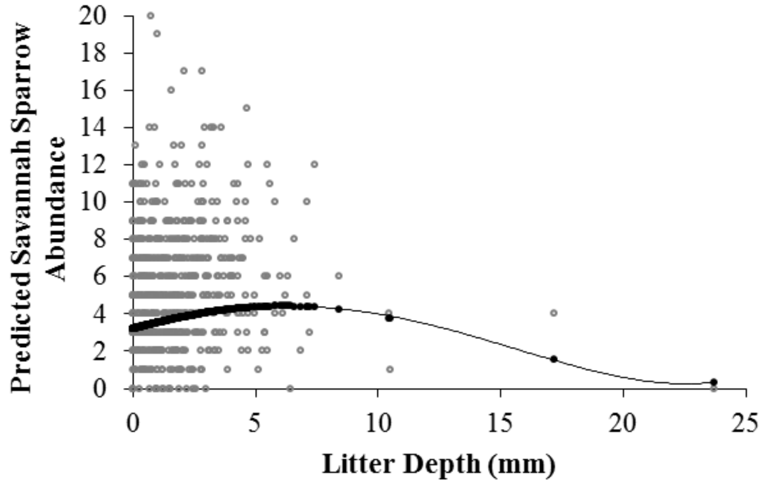


Figure 14. The effect of litter depth (mm) on the AIC-selected model-predicted abundance of Savannah sparrow (*n*=720). Bird abundance is based on 100-m fixed-radius point counts completed in southeastern Alberta in 2010 and 2011. Raw data values are shown in grey.

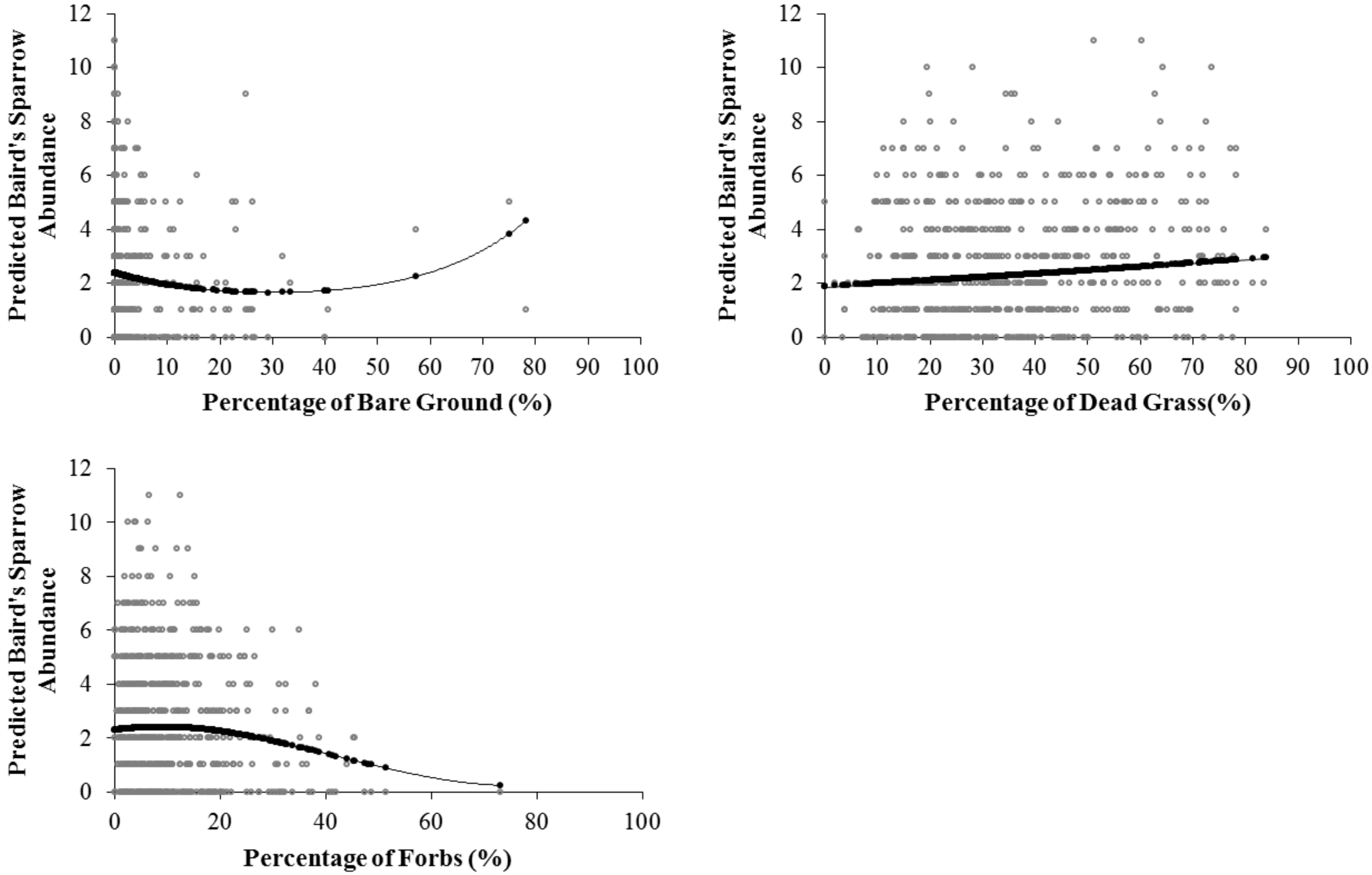


Figure 15. The effect of percentage of (a) bare ground, (b) dead grass, and (c) forbs on the AIC-selected model-predicted abundance of Baird's sparrow (*n*=720). Bird abundance is based on 100-m fixed-radius point counts completed in southeastern Alberta in 2010 and 2011. Values were summed across rounds to meet assumptions of the distribution. Raw data values are shown in grey.

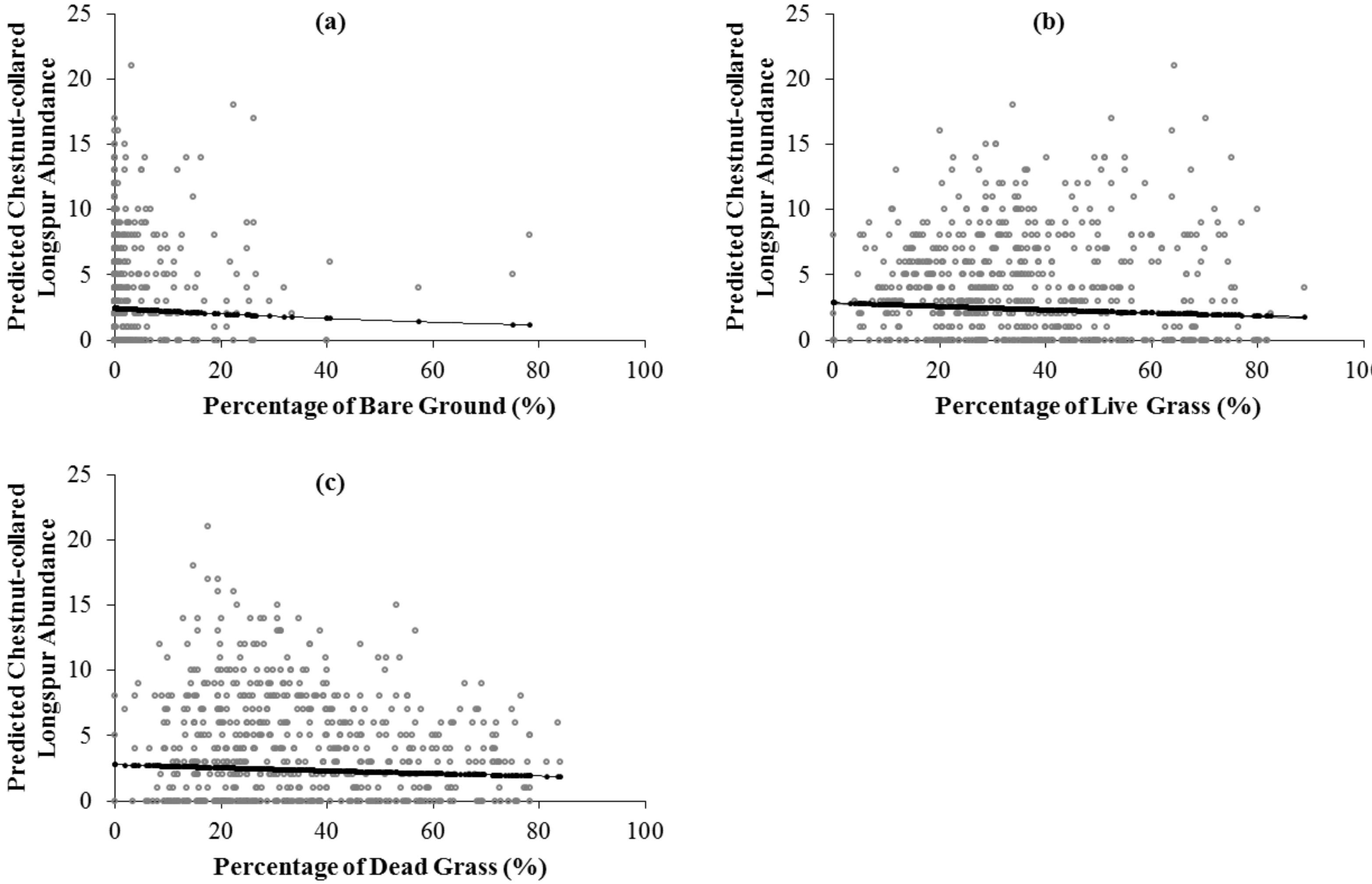


Figure 16. The effect of percentage of (a) bare ground, (b) live grass, and (c) dead grass on the AIC-selected model-predicted abundance of chestnut-collared longspur (n=720). Bird abundance is based on 100-m fixed-radius point counts completed in southeastern Alberta in 2010 and 2011. Values were summed across rounds to meet assumptions of the distribution. Raw data values are shown in grey.

CHAPTER 4: MANAGEMENT IMPLICATIONS

Energy development is occurring across North America and as industrial development continues it becomes increasingly important to identify impacts on wildlife. In addition to other human developments, the energy sector is placing pressure on grassland habitats, which have already been reduced by up to 70 % from their historical extents (Samson et al. 2004). The natural gas industry is prevalent across the prairies in both the United States and Canada, where development continues to increase (Government of Alberta 2011). Land-use conversion and other human developments remain a leading cause in the reduction of grassland habitats in North America and apply pressure on species inhabiting remaining fragments. Grassland birds are at particular risk due to higher declines of these species than in any other group of birds in North America (Herkert 1994, 1995; Herkert et al. 2003). In this study, I sought to identify the effects of natural gas wells and their associated linear features on the relative abundances and diversity of grassland songbirds found in southeastern Alberta.

Analysis using Generalized Linear Mixed Models (GLMMs) selected using Akaike's Information Criteria (AIC; Akaike 1974) indicated that both horned lark and chestnut-collared longspur were impacted differently by well density in different years. Overall, well density did not consistently impact any of the grassland songbird species in this study, but abundances of vesper sparrow and western meadowlark increased closer to gas wells, while Sprague's pipit and chestnut-collared longspur decreased. These results indicate that most grassland bird species examined were not negatively impacted by natural gas industry development; however, the two species that demonstrated a negative relationship with the infrastructure are of conservation concern. Sprague's pipit and chestnut-collared longspur have been listed as threatened by COSEWIC (Committee on the Status of Endangered Wildlife in Canada) due to their severe population declines (COSEWIC 2010*a*; *b*) and 80 % of global Sprague's pipit breeding populations are located in Canada (COSEWIC 2010*b*).

In the study area, habitat near gas wells and associated linear features differed in vegetation cover and structure in comparison to habitats located farther away. Current management practices have succeeded in reducing crested wheatgrass along trails, but the species continues to be present in greater amounts near gas wells. This may be due to the invasion of the species following a disturbance such as the drilling of a new well. This indicates that though natural gas companies are now re-seeding areas around gas wells with native seed mixes (R&R/03-5, Alberta Environment), changes in vegetation are still of concern near infrastructure. Vesper sparrow, however, was the only species analyzed that may have responded to vegetation changes surrounding infrastructure. Based on the results of this study, it is hypothesized that birds may view gas wells as "artificial shrubs" attracting bird species that perch to the infrastructure.

Gas wells may have been used as perches by some bird species, while other species that do not typically use perches were found in greater abundances farther from the infrastructure. Data showing the exact locations of birds and their selection of territories relative to gas well infrastructure was not collected. In the future, studies collecting such data would be beneficial and could assist in identifying the impacts of gas wells, trails and roads in the study area. Further, this research could identify whether it is necessary to not only limit the construction of linear features, but also if there is a need to limit their use to outside of the songbird breeding season (May-August), as has already been recommended for other wildlife (Holloran 2005; Kaiser 2006; Riley et al. 2012).

In this study, proximity to gas wells impacted some grassland songbirds, but the effect of well density was inconsistent and varied between years. This means that a well density threshold could not be identified, perhaps because it has not yet been reached in this region for most species. As natural gas industry development continues, a commitment to ongoing monitoring should be made so that the well density threshold for grassland songbirds may be identified and not exceeded, to mitigate negative impacts on species. In particular, monitoring should focus on abundances of Sprague's pipit and chestnut-collared longspur, which have already been identified as threatened (COSWEIC 2010*a*; *b*) and were negatively impacted by proximity to gas wells in this study.

Research should also be completed that examines the impacts of natural gas development on the survival and reproduction of grassland songbirds in the region. This research could investigate the impacts of drilling on songbird communities and the cumulative impacts of natural gas and crude oil development. Though roads in this study were not associated with traffic volumes high enough to provide consistent acoustic disruptions, the influence of noise produced by compressor stations and gas wells themselves on grassland songbirds is important to identify. Finally, studies examining natural gas development across the prairies would be beneficial, as behavioural responses and habitat requirements can vary across a species' range (Johnson and Igl 2001).

Overall, the results of this study indicated that most grassland songbirds in southeastern Alberta were not impacted by natural gas development in the region. Relative abundances of 2 species increased near gas wells and the abundances of 2 species declined near the infrastructure. Vegetation changes were observed near gas wells and associated trails and roads, but it is unlikely that these changes drove the responses of birds. Instead, birds may have viewed gas wells as perches, driving the responses of birds in this study. This may indicate that natural gas industry development is having a comparatively small impact on songbirds versus other forms of energy development, though further research is still required.

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Appendix I.

Well Density Calculations

Well densities were calculated based on information provided by the industrial partner for this research, and included wells from all companies operating in the study area. No new wells were spudded at study sites between 2010 and 2011, so a single well density for both years was used. If there were two or more wells with the same surface hole (same above ground infrastructure), but a different bottom hole, they were counted as 1. In most cases this occurred due to a flowing gas well and commingled well with the same surface co-ordinates. All commingled gas wells are shared with flowing gas wells. Other shared co-ordinates were:

02s-18-16/35n-17-16 had 2 wells that were counted as 1 in 4 cases

16-15-17 two wells were counted as 1

33-17-18 two wells were counted as 1

10-23-17 a suspended well and flowing gas well, counted as 1

12-18-17 a suspended well and flowing coalbed methane well, counted as 1

13-18-16 a suspended well and flowing coalbed methane well, counted as 1

14n 23s-18-12 a drilled and cased well and suspended well, counted as 1

15-15-12 a drilled and cased well and suspended well, counted as 1

15-17-18 a suspended well and flowing gas well, counted as 1

19-15-11 a flowing well and drilled as cased well, counted as 1

20-13-17 a suspended well and flowing well, counted as 1

22-17-18 a flowing well and drilled and cased well, counted as 1

23-17-14 a drilled and cased well and flowing well, counted as 1

26w 27e-17-18 a flowing well and drilled and cased well, counted as 1

28-16-11 a suspended well and drilled and cased well, counted as 1

4n 9s-17-11 two wells shared co-ordinates 4 times, and were counted as 1 in each case

5n 8s-21-17 two flowing gas wells had the same co-ordinates and were counted as 1

KIPP a flowing well and suspended well, counted as 1

"Drain", "water injector", "water disposal" and "observation" were not included in well density calculations. All "abandoned" wells that were capped and no longer had surface infrastructure were not used in to calculate well density. "Abandoned gas zone" co-ordinates and "oil" wells were also not used. "Licensed" wells were removed from estimates because it was assumed that no action had yet occurred and there was currently no surface infrastructure. "Suspended" wells were included in well density calculations because they had not yet been capped and it was assumed that the infrastructure was therefore still in place. "Flowing coalbed methane", "suspended gas" and "drilled and cased" wells were counted towards well density unless they shared a surface hole, in which case each surface hole was counted only once.

Only wells that fell within each 1×1 mile study site were counted. The farthest that any well could be from a point count, assuming that they were in the very corners of the site diagonal to each other is 1.41 mi (sqrt(1^2+1^2), or 2.27 km. The exception was split sites such as KIPP, which for example, could have points and infrastructure a max of 2.9 km apart. Split site maximum distances were calculated in Google Earth 5.2 (Google Inc. 2010) when point counts were first selected. No wells farther than these distances apart were counted towards well density, though they were used to calculate distance to the nearest well.

APPENDIX II.

Selection method for models describing effects of shallow gas wells and vegetation structure on focal grassland bird species found in ≥ 15 % of all point counts in southeastern Alberta from May to July of 2010 and 2011 (*n*=720). AICs were used to select parameters and models. A ΔAIC of 0.00 indicates the best model fit. On an individual species basis, in step 1 it was determined if parameters were linear or quadratic. In some cases, quadratic models did not converge, and are therefore not shown. In step 2, different combinations of variables describing vegetation structure, vegetation cover, and infrastructure were compared to determine which of these groupings had the greatest influence on each bird species. Quadratic terms for each variable, and the interaction between year and each infrastructure variable, were only included in step 2 models if results from step 1 suggested that they were influential.

Combination	Model	K	AIC score	ΔAIC	Wi
	<u>*Baird's Sparrow (n=720)*</u>				
	STEP 1				
	Structure				
	DLG	4	2464.58	0.00	1.0000
	DLG-DLG^2	5	2529.89	65.31	0.0000
	DDG	4	2462.11	0.00	1.0000
	DDG+DDG^2	5	2524.17	62.06	0.0000
	DCWG	4	2463.78	0.00	0.7311
	DCWG-DCWG^2	5	2465.78	2.00	0.2689
	HGT	4	2463.90	0.00	1.0000
	HGT-HGT^2	5	2527.51	63.61	0.0000
	LIT	4	2460.19	0.00	0.6106
	LIT-LIT^2	5	2461.09	0.90	0.3894

SHB	4	2464.44	0.00	0.6910
SHB+SHB^2	5	2466.05	1.61	0.3090
Cover				
PBG	4	2462.07	5.32	0.0654
PBG+PBG^2	5	2456.75	0.00	0.9346
PLG	4	2464.21	0.00	1.0000
PLG-PLG^2	5	2529.64	65.43	0.0000
PDG	4	2454.26	0.00	1.0000
PDG+PDG^2	5	2514.65	60.39	0.0000
PF	4	2454.60	0.65	0.4195
PF-PF^2	5	2453.95	0.00	0.5805
PCWG	4	2462.15	0.00	0.6559
PCWG+PCWG^2	5	2463.44	1.29	0.3441
Infrastructure				
WDENS	4	2464.20	0.00	1.0000
WDENS+WDENS^2	5	2527.89	63.69	0.0000
WDENS	4	2464.20	2.04	0.2406
WDENS+YEAR	5	2466.12	3.96	0.0921
WDENS+YEAR-WDENS*YEAR	6	2462.16	0.00	0.6673

	MINDIST	4	2464.37	0.00	0.7161
	MINDIST-MINDIST^2	5	2466.22	1.85	0.2839
	MINDIST	4	2464.37	0.00	0.6551
	MINDIST+YEAR	5	2466.29	1.92	0.2508
	MINDIST+YEAR-MINDIST*YEAR	6	2468.25	3.88	0.0941
	STEP 2				
	NULL	3	2462.59	11.78	0.0018
	YEAR	4	2464.51	13.70	0.0007
Year + Cover	YEAR+DLG+DDG-DCWG-HGT+LIT-SHB	10	2465.81	15.00	0.0004
Year + Structure	YEAR-PBG+PBG^2+PLG+PDG+PF-PF^2-PCWG	11	2450.81	0.00	0.6447
Year + Management	YEAR+WDENS-WDENS*YEAR+MINDIST	7	2463.33	12.52	0.0012
Year + Cover + Structure	YEAR+DLG+DDG-DCWG-HGT+LIT-SHB-PBG+PBG^2+PLG+PDG+PF-PF^2-PCWG	17	2457.47	6.66	0.0231
Year + Cover + Management	YEAR+DLG+DDG-DCWG-HGT+LIT-SHB+WDENS-WDENS*YEAR+MINDIST	13	2466.71	15.90	0.0002
Year + Structure + Management	YEAR-PBG+PBG^2+PLG+PDG+PF-PF^2-PCWG+WDENS-WDENS*YEAR+MINDIST	14	2452.23	1.42	0.3170
Year + Cover + Structure + Management	YEAR-DLG+DDG-DCWG-HGT+LIT-SHB-PBG+PBG^2+PLG+PDG+PF-PF^2-PCWG+WDENS-WDENS*YEAR+MINDIST	20	2458.96	8.15	0.0110
	Brown-headed cowbird (n=720)				
	STEP 1				
	Structure				
	DLG	3	1107.89	0.07	0.4913
	DLG-DLG^2	4	1107.82	0.00	0.5087
	DDG	3	1113.41	0.00	0.6995
	DDG+DDG^2	4	1115.10	1.69	0.3005

DCWG	3	1103.34	0.00	0.7037
DCWG+DCWG^2	4	1105.07	1.73	0.2963
HGT	3	1113.35	0.45	0.4440
HGT+HGT^2	4	1112.90	0.00	0.5560
LIT	3	1114.06	0.00	0.6118
LIT-LIT^2	4	1114.97	0.91	0.3882
SHB	3	1108.82	0.00	0.5212
SHB-SHB^2	4	1108.99	0.17	0.4788
Cover				
PBG	3	1114.03	0.00	0.6932
PBG-PBG^2	4	1115.66	1.63	0.3068
PLG	3	1103.41	4.60	0.0911
PLG-PLG^2	4	1098.81	0.00	0.9089
PDG	3	1111.98	4.31	0.1039
PDG-PDG^2	4	1107.67	0.00	0.8961
PCWG	3	1107.24	0.00	1.0000
Infrastructure				
WDENS	3	1113.72	0.00	0.6177
WDENS-WDENS^2	4	1114.68	0.96	0.3823

	WDENS	3	1113.72	11.99	0.0023
	WDENS+YEAR	4	1107.35	5.62	0.0567
	WDENS+YEAR-WDENS*YEAR	5	1101.73	0.00	0.9410
	MINDIST	3	1112.63	0.00	0.5987
	MINDIST+MINDIST^2	4	1113.43	0.80	0.4013
	MINDIST	3	1112.63	6.25	0.0295
	MINDIST+YEAR	4	1106.38	0.00	0.6707
	MINDIST+YEAR+MINDIST*YEAR	5	1107.99	1.61	0.2999
	STEP 2				
	NULL	2	1112.33	35.11	0.0000
	YEAR	3	1106.05	28.83	0.0000
Year + Cover	YEAR+DLG-DLG^2+DDG-DCWG-HGT+HGT^2-LIT-SHB	11	1084.18	6.96	0.0199
Year + Structure	YEAR+PBG+PLG-PLG^2+PDG-PDG^2-PCWG	9	1089.42	12.20	0.0014
Year + Management	YEAR+WDENS-WDENS*YEAR-MINDIST	6	1102.67	25.45	0.0000
Year + Cover + Structure	YEAR+DLG-DLG^2+DDG-DCWG-HGT+HGT^2-LIT-SHB+PBG+PLG-PLG^2+PDG-PDG^2-PCWG	17	1077.22	0.00	0.6447
Year + Cover + Management	YEAR+DLG-DLG^2+DDG-DCWG-HGT+HGT^2-LIT-SHB+WDENS-WDENS*YEAR-MINDIST	14	1080.37	3.15	0.1335
Year + Structure + Management	YEAR+PBG+PLG-PLG^2+PDG-PDG^2-PCWG +WDENS-WDENS*YEAR-MINDIST	12	1091.75	14.53	0.0005
Year + Cover + Structure + Management	YEAR+DLG-DLG^2+DDG-DCWG-HGT+HGT^2-LIT-SHB+PBG+PLG-PLG^2-PDG+PDG^2-PCWG+WDENS-WDENS*YEAR-MINDIST	20	1079.56	2.34	0.2001

Chestnut-collared longspur (n=720)

STEP 1

Structure				
DLG	4	2567.02	-0.54	0.9551
DDG	4	2564.49	0.00	1.0000
DCWG	4	2567.06	6.47	0.0379
DCWG+DCWG^2	5	2560.59	0.00	0.9621
HGT	4	2565.87	0.00	0.6649
HGT-HGT^2	5	2567.24	1.37	0.3351
LIT	4	2566.70	0.00	0.7311
LIT+LIT^2	5	2568.70	2.00	0.2689
SHB	4	2567.56	0.00	0.7291
SHB+SHB^2	5	2569.54	1.98	0.2709
Cover				
PBG	4	2565.14	0.00	1.0000
PLG	4	2564.86	0.00	1.0000
PDG	4	2567.37	0.00	0.5225
PDG-PDG^2	5	2567.55	0.18	0.4775
PF	4	2567.17	2.29	0.2414
PF-PF^2	5	2564.88	0.00	0.7586

	PCWG	4	2566.92	0.00	0.7311
	PCWG-PCWG^2	5	2568.92	2.00	0.2689
	Infrastructure				
	WDENS	4	2565.14	0.00	1.0000
	WDENS	4	2565.14	0.49	0.3293
	WDENS+YEAR	5	2565.69	1.04	0.2501
	WDENS-YEAR+WDENS*YEAR	6	2564.65	0.00	0.4207
	MINDIST	4	2566.73	1.28	0.3452
	MINDIST-MINDIST^2	5	2565.45	0.00	0.6548
	MINDIST-MINDIST^2	5	2565.45	0.00	0.5099
	MINDIST-MINDIST^2+YEAR	6	2566.04	0.59	0.3797
	YEAR+MINDIST-YEAR*MINDIST-MINDIST^2+YEAR*MINDIST^2	8	2568.51	3.06	0.1104
	STEP 2				
	NULL	3	2565.65	2.09	0.1212
	YEAR	4	2566.20	2.64	0.0921
Year + Cover	YEAR-PBG-PLG-PDG+PF-PF^2-PCWG	10	2563.56	0.00	0.3448
Year + Structure	YEAR+DLG-DDG-DCWG+DCWG^2-HGT-LIT+SHB	11	2566.94	3.38	0.0636
Year + Management	YEAR-WDENS+WDENS*YEAR+MINDIST-MINDIST^2	8	2565.14	1.58	0.1565
Year + Cover + Structure	YEAR-PBG-PLG-PDG+PF-PF^2+PCWG+DLG-DDG-DCWG+DCWG^2-HGT-LIT+SHB	17	2566.21	2.65	0.0916
Year + Cover + Management	YEAR-PBG-PLG-PDG+PF-PF^2-PCWG-WDENS+WDENS*YEAR+MINDIST-MINDIST^2	14	2567.88	4.32	0.0398
Year + Structure + Management	YEAR+DLG-DDG-DCWG+DCWG^2-HGT-LIT+SHB-WDENS+WDENS*YEAR+MINDIST-MINDIST^2	15	2566.59	3.03	0.0758

Year + Cover + Structure + Management	YEAR-PBG-PLG-PDG+PF-PF^2+PCWG+DLG-DDG-DCWG+DCWG^2-HGT-LIT+SHB-WDENS+WDENS*YEAR+MINDIST-MINDIST^2	21	2569.88	6.32	0.0146
	<u>*Clay-colored sparrow (n=720)*</u>				
	STEP 1				
	Structure				
	DLG	3	711.66	0.00	0.5585
	DLG-DLG^2	4	712.13	0.47	0.4415
	DDG	3	720.02	0.00	0.7311
	DDG-DDG^2	4	722.02	2.00	0.2689
	DCWG	3	735.67	0.00	0.6900
	DCWG-DCWG^2	4	737.27	1.60	0.3100
	HGT	3	729.66	0.00	1.0000
	LIT	3	733.29	0.00	0.7261
	LIT+LIT^2	4	735.24	1.95	0.2739
	SHB	3	734.86	0.00	0.6479
	SHB+SHB^2	4	736.08	1.22	0.3521
	Cover				
	PBG	3	736.19	0.00	0.7058
	PBG+PBG^2	4	737.94	1.75	0.2942
	PLG	3	734.31	0.00	1.0000

	PDG	3	735.81	0.00	1.0000
	PF	3	735.93	0.00	0.6581
	PF-PF^2	4	737.24	1.31	0.3419
	PCWG	3	736.17	0.00	0.7311
	PCWG+PCWG^2	4	738.17	2.00	0.2689
	Infrastructure				
	WDENS	3	736.19	0.00	0.7311
	WDENS-WDENS^2	4	738.19	2.00	0.2689
	WDENS	3	736.19	31.88	0.0000
	WDENS-YEAR	4	704.31	0.00	0.7211
	WDENS-YEAR-WDENS*YEAR	5	706.21	1.90	0.2789
	MINDIST	3	735.26	0.00	0.6411
	MINDIST-MINDIST^2	4	736.42	1.16	0.3589
	MINDIST	3	735.26	33.83	0.0000
	MINDIST-YEAR	4	703.21	1.78	0.2911
	MINDIST-YEAR-MINDIST*YEAR	5	701.43	0.00	0.7089
	STEP 2				
	NULL	2	734.19	31.87	0.0000
	YEAR	3	702.32	0.00	0.5917
Year + Cover	YEAR+PBG+PLG+PDG+PF+PCWG	8	710.91	8.59	0.0081
Year + Structure	YEAR+DLG+DDG+DCWG+HGT-LIT-SHB	9	708.48	6.16	0.0272
Year + Management	YEAR-WDENS-MINDIST-MINDIST*YEAR	6	703.37	1.05	0.3501

Year + Cover + Structure	YEAR+PBG+PLG+PDG+PF-PCWG+DLG+DDG+DCWG+HGT-LIT-SHB	14	716.99	14.67	0.0004
Year + Cover + Management	YEAR+PBG+PLG+PDG+PF+PCWG-WDENS-MINDIST-MINDIST*YEAR	11	712.29	9.97	0.0040
Year + Structure + Management	YEAR+DLG+DDG+DCWG+HGT+LIT-SHB-WDENS-MINDIST-MINDIST*YEAR	12	709.27	6.95	0.0183
Year + Cover + Structure + Management	YEAR+PBG+PLG+PDG+PF-PCWG+DLG-DDG+DCWG+HGT-LIT-SHB-WDENS-MINDIST-MINDIST*YEAR	17	718.52	16.20	0.0002
	Horned lark (n=720)				
	STEP 1				
	Structure				
	DLG	3	1405.83	0.00	0.7301
	DLG-DLG^2	4	1407.82	1.99	0.2699
	DDG	3	1407.32	0.00	0.7251
	DDG+DDG^2	4	1409.26	1.94	0.2749
	DCWG	3	1407.18	6.64	0.0349
	DCWG-DCWG^2	4	1400.54	0.00	0.9651
	HGT	3	1404.28	2.82	0.1962
	HGT+HGT^2	4	1401.46	0.00	0.8038
	LIT	3	1407.25	0.00	0.6693
	LIT-LIT^2	4	1408.66	1.41	0.3307
	SHB	3	1406.83	0.00	0.7191
	SHB+SHB^2	4	1408.71	1.88	0.2809

Cover				
PBG	3	1403.25	0.00	0.7211
PBG+PBG^2	4	1405.15	1.90	0.2789
PLG	3	1402.89	0.00	0.7271
PLG+PLG^2	4	1404.85	1.96	0.2729
PDG	3	1406.96	0.00	0.5769
PDG+PDG^2	4	1407.58	0.62	0.4231
PF	3	1402.25	0.00	0.6248
PF-PF^2	4	1403.27	1.02	0.3752
PCWG	3	1406.77	1.23	0.3509
PCWG-PCWG^2	4	1405.54	0.00	0.6491
Infrastructure				
WDENS	3	1403.77	0.00	0.7221
WDENS-WDENS^2	4	1405.68	1.91	0.2779
WDENS	3	1403.77	7.43	0.0236
WDENS+YEAR	4	1405.77	9.43	0.0087
WDENS+YEAR-WDENS*YEAR	5	1396.34	0.00	0.9678
MINDIST	3	1406.75	0.00	0.6434
MINDIST+MINDIST^2	4	1407.93	1.18	0.3566

	MINDIST	3	1406.75	0.00	0.6585
	MINDIST+YEAR	4	1408.74	1.99	0.2435
	MINDIST-YEAR+MINDIST*YEAR	5	1410.56	3.81	0.0980
	STEP 2				
	NULL	2	1405.34	11.34	0.0029
	YEAR	3	1407.34	13.34	0.0011
Year + Cover	YEAR+PBG-PLG-PDG-PF+PCWG-PCWG^2	9	1403.02	9.02	0.0093
Year + Structure	YEAR-DLG+DDG+DCWG-DCWG^2-HGT+HGT^2+LIT+SHB	11	1415.33	21.33	0.0000
Year + Management	YEAR-WDENS-WDENS*YEAR+MINDIST	6	1398.33	4.33	0.0970
Year + Cover + Structure	YEAR-PBG-PLG-PDG-PF+PCWG-PCWG^2-DLG+DDG+DCWG-DCWG^2-HGT+HGT^2+LIT+SHB	17	1414.24	20.24	0.0000
Year + Cover + Management	YEAR+PBG-PLG-PDG-PF+PCWG-PCWG^2-WDENS-WDENS*YEAR+MINDIST	12	1394.00	0.00	0.8452
Year + Structure + Management	YEAR-DLG+DDG+DCWG-DCWG^2-HGT+HGT^2+LIT+SHB-WDENS-WDENS*YEAR-MINDIST	14	1400.98	6.98	0.0258
Year + Cover + Structure + Management	YEAR-PBG-PLG-PDG-PF+PCWG-PCWG^2-DLG+DDG+DCWG-DCWG^2-HGT+HGT^2+LIT+SHB-WDENS-WDENS*YEAR-MINDIST	20	1401.62	7.62	0.0187
	Savannah sparrow (n=720)				
	STEP 1				
	Structure				
	DLG	4	2917.58	0.00	1.0000
	DDG	4	2901.71	0.00	0.6835
	DDG-DDG^2	5	2903.25	1.54	0.3165

DCWG	4	2923.15	0.00	0.7211
DCWG+DCWG^2	5	2925.05	1.90	0.2789
HGT	4	2923.54	0.00	1.0000
LIT	4	2923.60	3.84	0.1279
LIT-LIT^2	5	2919.76	0.00	0.8721
SHB	4	2922.93	0.00	0.7109
SHB+SHB^2	5	2924.73	1.80	0.2891
Cover				
PBG	4	2922.49	0.00	0.6846
PBG+PBG^2	5	2924.04	1.55	0.3154
PLG	4	2919.91	0.00	0.5212
PLG+PLG^2	5	2920.08	0.17	0.4788
PDG	4	2921.48	0.00	1.0000
PF	4	2917.00	0.00	1.0000
PCWG	4	2923.38	0.00	0.6318
PCWG+PCWG^2	5	2924.46	1.08	0.3682
Infrastructure				
WDENS	4	2922.45	0.00	0.6803
WDENS-WDENS^2	5	2923.96	1.51	0.3197

	WDENS	4	2922.45	19.71	0.0001
	WDENS-YEAR	5	2909.32	6.58	0.0359
	WDENS+YEAR-WDENS*YEAR	6	2902.74	0.00	0.9640
	MINDIST	4	2922.12	0.57	0.4292
	MINDIST-MINDIST^2	5	2921.55	0.00	0.5708
	MINDIST-MINDIST^2	5	2921.55	13.76	0.0005
	MINDIST-MINDIST^2-YEAR	6	2907.79	0.00	0.5160
	YEAR-MINDIST+YEAR*MINDIST-MINDIST^2-YEAR*MINDIST^2	8	2907.92	0.13	0.4835
	STEP 2				
	NULL	3	2921.60	23.79	0.0000
	YEAR	4	2908.32	10.51	0.0022
Year + Cover	YEAR-PBG+PLG+PDG-PF+PCWG	9	2905.35	7.54	0.0098
Year + Structure	YEAR-DLG+DDG+DCWG-HGT+LIT-LIT^2+SHB	11	2898.58	0.77	0.2881
Year + Management	YEAR+WDENS-WDENS*YEAR+MINDIST-MINDIST^2+MINDIST^2*YEAR	9	2905.03	7.22	0.0115
Year + Cover + Structure	YEAR-PBG+PLG+PDG-PF+PCWG-DLG+DDG+DCWG-HGT+LIT-LIT^2+SHB	16	2901.35	3.54	0.0721
Year + Cover + Management	YEAR-PBG+PLG+PDG-PF+PCWG+WDENS-WDENS*YEAR+MINDIST-MINDIST^2+MINDIST^2*YEAR	14	2901.88	4.07	0.0553
Year + Structure + Management	YEAR-DLG+DDG+DCWG-HGT+LIT-LIT^2+SHB+WDENS-WDENS*YEAR+MINDIST-MINDIST^2+MINDIST^2*YEAR	16	2897.81	0.00	0.4235
Year + Cover + Structure + Management	YEAR+PBG+PLG+PDG-PF+PCWG-DLG+DDG+DCWG-HGT+LIT-LIT^2+SHB+WDENS-WDENS*YEAR+MINDIST-MINDIST^2*YEAR	21	2900.06	2.25	0.1375

<u>*Sprague's pipit (n=720)*</u>

STEP 1

Structure				
DLG	4	2181.15	9.63	0.0080
DLG+DLG^2	5	2171.52	0.00	0.9920
DDG	4	2177.48	7.92	0.0187
DDG+DDG^2	5	2169.56	0.00	0.9813
DCWG	4	2237.80	0.00	0.7756
DCWG+DCWG^2	5	2240.28	2.48	0.2244
HGT	4	2235.31	0.68	0.4158
HGT-HGT^2	5	2234.63	0.00	0.5842
LIT	4	2213.57	0.86	0.3941
LIT-LIT^2	5	2212.71	0.00	0.6059
SHB	4	2246.78	0.00	0.6921
SHB-SHB^2	5	2248.40	1.62	0.3079
Cover				
PBG	4	2238.12	0.00	0.6803
PBG+PBG^2	5	2239.63	1.51	0.3197
PLG	4	2232.06	0.00	0.6671
PLG-PLG^2	5	2233.45	1.39	0.3329

PDG	4	2229.96	0.85	0.3953
PDG-PDG^2	5	2229.11	0.00	0.6047
PF	4	2239.62	0.00	0.5012
PF-PF^2	5	2239.63	0.01	0.4988
PCWG	4	2236.87	0.26	0.4675
PCWG+PCWG^2	5	2236.61	0.00	0.5325
Infrastructure				
WDENS	4	2238.18	0.00	0.5987
WDENS+WDENS^2	5	2238.98	0.80	0.4013
WDENS	4	2238.18	117.09	0.0000
WDENS+YEAR	5	2123.45	2.36	0.2351
WDENS+YEAR+WDENS*YEAR	6	2121.09	0.00	0.7649
MINDIST	4	2238.29	0.00	0.6715
MINDIST-MINDIST^2	5	2239.72	1.43	0.3285
MINDIST	4	2238.29	115.82	0.0000
MINDIST+YEAR	5	2122.47	0.00	0.8581
MINDIST+YEAR-MINDIST*YEAR	6	2126.07	3.60	0.1419

	STEP 2				
	NULL	3	2238.45	116.06	0.0000
	YEAR	4	2128.25	5.86	0.0482
Year + Cover	YEAR-PBG+PLG+PDG-PDG^2-PF-PCWG+PCWG^2	11	2130.42	8.03	0.0163
Year + Structure	YEAR+DLG-DLG^2+DDG-DDG^2-DCWG+HGT-HGT^2-LIT+LIT^2+SHB	14	2147.00	24.61	0.0000
Year + Management	YEAR-WDENS+WDENS*YEAR+MINDIST	7	2122.39	0.00	0.9023
Year + Cover + Structure	YEAR-PBG-PLG-PDG-PDG^2-PF-PCWG+PCWG^2+DLG-DLG^2+DDG-DDG^2+DCWG+HGT-HGT^2-LIT+LIT^2+SHB	21	2155.72	33.33	0.0000
Year + Cover + Management	YEAR-PBG+PLG-PDG-PDG^2-PF-PCWG+PCWG^2-WDENS+WDENS*YEAR+MINDIST	14	2129.05	6.66	0.0323
Year + Structure + Management	YEAR+DLG-DLG^2+DDG-DDG^2-DCWG+HGT-HGT^2-LIT+LIT^2+SHB-WDENS+WDENS*YEAR+MINDIST	17	2136.09	13.70	0.0010
Year + Cover + Structure + Management	YEAR-PBG-PLG-PDG-PDG^2-PF-PCWG+PCWG^2+DLG-DLG^2+DDG-DDG^2+DCWG+HGT-HGT^2-LIT+LIT^2+SHB-WDENS+WDENS*YEAR+MINDIST	24	2144.99	22.60	0.0000
	Vesper sparrow (n=720)				
	STEP 1				
	Structure				
	DLG	3	1021.10	0.00	0.7301
	DLG+DLG^2	4	1023.09	1.99	0.2699
	DDG	3	1025.90	0.00	1.4120
	DDG+DDG^2	4	1027.56	1.66	0.3183
	DCWG	3	1025.60	0.00	0.5854
	DCWG-DCWG^2	4	1026.29	0.69	0.4146
	HGT	3	1024.97	1.90	0.2789
	HGT+HGT^2	4	1023.07	0.00	0.7211

LIT	3	1024.34	0.00	0.5212
LIT-LIT^2	4	1024.51	0.17	0.4788
SHB	3	1019.92	0.00	0.7301
SHB+SHB^2	4	1021.91	1.99	0.2699
Cover				
PBG	3	1025.85	2.37	0.2342
PBG-PBG^2	4	1023.48	0.00	0.7658
PLG	3	1023.83	0.00	0.6878
PLG+PLG^2	4	1025.41	1.58	0.3122
PDG	3	1025.98	0.08	0.4900
PDG-PDG^2	4	1025.90	0.00	0.5100
PF	3	1025.71	0.00	0.5903
PF-PF^2	4	1026.44	0.73	0.4097
PCWG	3	1025.21	0.76	0.4061
PCWG-PCWG^2	4	1024.45	0.00	0.5939
Infrastructure				
WDENS	3	1023.42	0.00	0.6953
WDENS-WDENS^2	4	1025.07	1.65	0.3047
WDENS	3	1023.42	5.38	0.0477
WDENS+YEAR	4	1020.11	2.07	0.2496
WDENS+YEAR-WDENS*YEAR	5	1018.04	0.00	0.7027

	MINDIST	3	1008.36	2.20	0.2497
	MINDIST+MINDIST^2	4	1006.16	0.00	0.7503
	MINDIST+MINDIST^2	4	1006.16	2.56	0.1284
	MINDIST+MINDIST^2+YEAR	5	1003.84	0.24	0.4097
	YEAR-MINDIST+YEAR*MINDIST+MINDIST^2-YEAR*MINDIST^2	7	1003.60	0.00	0.4619
	STEP 2				
	NULL	2	1024.00	20.28	0.0000
	YEAR	3	1020.93	17.21	0.0001
Year + Cover	YEAR+PBG-PBG^2-PLG+PDG-PDG^2-PF+PCWG-PCWG^2	11	1027.11	23.39	0.0000
Year + Structure	YEAR+DLG+DDG+DCWG-HGT+HGT^2-LIT-SHB	10	1016.99	13.27	0.0009
Year + Management	YEAR+WDENS-WDENS*YEAR-MINDIST+YEAR*MINDIST+MINDIST^2-YEAR*MINDIST^2	9	1005.71	1.99	0.2660
Year + Cover + Structure	YEAR+PBG-PBG^2-PLG+PDG-PDG^2-PF+PCWG-PCWG^2-DLG+DDG-DCWG-HGT+HGT^2-LIT-SHB	18	1028.31	24.59	0.0000
Year + Cover + Management	YEAR+PBG-PBG^2-PLG+PDG-PDG^2-PF+PCWG-PCWG^2+WDENS-WDENS*YEAR-MINDIST+YEAR*MINDIST+MINDIST^2-YEAR*MINDIST^2	17	1013.23	9.51	0.0062
Year + Structure + Management	YEAR+DLG+DDG+DCWG-HGT+HGT^2-LIT-SHB-WDENS-WDENS*YEAR -MINDIST+YEAR*MINDIST+MINDIST^2-YEAR*MINDIST^2	16	1003.72	0.00	0.7195
Year + Cover + Structure + Management	YEAR+PBG-PBG^2-PLG+PDG-PDG^2-PF+PCWG-PCWG^2+DLG+DDG-DCWG-HGT+HGT^2-LIT-SHB+WDENS-WDENS*YEAR-MINDIST+YEAR*MINDIST+MINDIST^2-YEAR*MINDIST^2	24	1012.92	9.20	0.0072

Western Meadowlark (n=720)

STEP 1

Structure				
DLG	4	2199.11	0.00	1.0000
DDG	4	2219.31	0.00	1.0000
DCWG	4	2229.64	0.00	0.6083
DCWG-DCWG^2	5	2230.52	0.88	0.3917
HGT	4	2229.64	0.00	1.0000
LIT	4	2228.28	0.00	0.5325
LIT-LIT^2	5	2228.54	0.26	0.4675
SHB	4	2229.50	0.00	0.6759
SHB+SHB^2	5	2230.97	1.47	0.3241
Cover				
PBG	4	2229.64	0.00	1.0000
PDG	4	2225.51	0.00	0.7311
PDG+PDG^2	5	2227.51	2.00	0.2689
PF	4	2229.21	0.00	1.0000
PCWG	4	2229.55	0.00	0.5461
PCWG+PCWG^2	5	2229.92	0.37	0.4539

	Infrastructure				
	WDENS	4	2227.68	0.00	0.6900
	WDENS-WDENS^2	5	2229.28	1.60	0.3100
	WDENS	4	2227.68	33.84	0.0000
	WDENS+YEAR	5	2198.48	4.64	0.0895
	WDENS+YEAR-WDENS*YEAR	6	2193.84	0.00	0.9105
	MINDIST	4	2225.25	0.00	1.0000
	MINDIST	4	2225.25	32.71	0.0000
	MINDIST-YEAR	5	2197.52	4.98	0.0766
	MINDIST+YEAR+MINDIST*YEAR	6	2192.54	0.00	0.9234
	STEP 2				
	NULL	3	2227.64	33.77	0.0000
	YEAR	4	2198.98	5.11	0.0689
Year + Cover	YEAR+PBG+PDG-PF+PCWG	8	2206.51	12.64	0.0016
Year + Structure	YEAR-DLG+DDG+DCWG+HGT-LIT+SHB	10	2205.03	11.16	0.0033
Year + Management	YEAR+WDENS-WDENS*YEAR-MINDIST+MINDIST*YEAR	8	2193.87	0.00	0.8866
Year + Cover + Structure	YEAR-PBG+PDG-PF+PCWG-DLG+DDG-DCWG+HGT-LIT+SHB	14	2212.18	18.31	0.0001
Year + Cover + Management	YEAR+PBG+PDG-PF+PCWG+WDENS-WDENS*YEAR+MINDIST-MINDIST*YEAR	12	2201.55	7.68	0.0191
Year + Structure + Management	YEAR-DLG+DDG+DCWG+HGT-LIT+SHB+WDENS-WDENS*YEAR-MINDIST+MINDIST*YEAR	14	2201.45	7.58	0.0200
Year + Cover + Structure + Management	YEAR+PBG+PDG+PF+PCWG-DLG+DDG-DCWG+HGT-LIT+SHB+WDENS-WDENS*YEAR-MINDIST+MINDIST*YEAR	18	2209.42	15.55	0.0004

APPENDIX III.

Selection method for models describing larger-scale effects of shallow gas well infrastructure on vegetation structure and cover in southeastern Alberta from June to August of 2010 and 2011 (spatial scale: 7-2000 m; *n*=720). AICs were used to select parameters and models. A ΔAIC of 0.00 indicates the best model fit. In step 1 it was determined if infrastructure parameters were linear or quadratic. In some cases, quadratic models did not converge, and are therefore not shown. Then, in step 2, different combinations of each infrastructure parameter and the inclusion and interaction with the parameter "YEAR" were compared, to determine if effects of infrastructure might vary between years. The most parsimonious models resulting from step 1 and 2 for each infrastructure variable were then combined in step 3 and compared with the null model and a model including only the parameter "YEAR" to determine which of these models had the greatest influence on each vegetation variable.

Model	K	AIC score	ΔAIC	Wi
<u>*Density live grass*</u>				
STEP 1				
WDENS	4	4033.03	7.10	0.0279
WDENS+WDENS^2	5	4025.93	0.00	0.9721
MINDIST	4	4025.14	0.00	0.5037
MINDIST-MINDIST^2	5	4025.17	0.03	0.4963
STEP 2				
NULL	3	4031.04	804.74	0.0000
WDENS+WDENS^2	5	4025.93	799.63	0.0000
WDENS+WDENS^2-YEAR	6	3226.3	0.00	0.5523
WDENS-YEAR-WDENS*YEAR+WDENS^2+WDENS^2*YEAR	8	3226.72	0.42	0.4477
NULL	3	4031.04	806.02	0.0000
MINDIST	4	4025.14	800.12	0.0000
MINDIST-YEAR	5	3225.02	0.00	0.7120
MINDIST-YEAR-MINDIST*YEAR	6	3226.83	1.81	0.2880
STEP 3				
NULL	3	4031.04	804.81	0.0000
YEAR	4	3226.23	0.00	0.6781
YEAR-WDENS+WDENS^2+MINDIST	7	3227.72	1.49	0.3219

Density dead grass				
STEP 1				
WDENS	4	3832.35	3.83	0.1284
WDENS+WDENS^2	5	3828.52	0.00	0.8716
MINDIST	4	3841.3	0.00	0.6422
MINDIST+MINDIST^2	5	3842.47	1.17	0.3578
STEP 2				
NULL	3	3839.3	624.24	0.0000
WDENS+WDENS^2	5	3828.52	613.46	0.0000
WDENS+WDENS^2-YEAR	6	3215.06	0.00	0.8670
WDENS-YEAR+WDENS*YEAR+WDENS^2-WDENS^2*YEAR	8	3218.81	3.75	0.1330
NULL	3	3839.3	616.61	0.0000
MINDIST	4	3841.3	618.61	0.0000
MINDIST-YEAR	5	3222.69	0.00	0.6803
MINDIST-YEAR+MINDIST*YEAR	6	3224.2	1.51	0.3197
STEP 3				
NULL	3	3839.3	622.45	0.0000
YEAR	4	3225.76	8.91	0.0115
YEAR+WDENS+WDENS^2-MINDIST	7	3216.85	0.00	0.9885
Density crested wheatgrass				
STEP 1				
WDENS	3	22	0.00	0.8797
WDENS-WDENS^2	4	25.98	3.98	0.1203
MINDIST	3	22.18	0.00	0.8526
MINDIST-MINDIST^2	4	25.69	3.51	0.1474
STEP 2				
NULL	2	20.02	1.21	0.2723
WDENS	3	22	3.19	0.1012
WDENS+YEAR	4	18.81	0.00	0.4986
WDENS+YEAR+WDENS*YEAR	5	21.53	2.72	0.1280

NULL	2	20.02	0.90	0.3378
MINDIST	3	22.18	3.06	0.1147
MINDIST+YEAR	4	19.12	0.00	0.5297
MINDIST+YEAR+MINDIST*YEAR	5	25.91	6.79	0.0178
STEP 3				
NULL	2	20.02	3.53	0.1454
YEAR	3	16.49	0.00	0.8495
YEAR-WDENS-MINDIST	5	26.71	10.22	0.0051
Maximum height of live grass				
STEP 1				
WDENS	4	4450.51	0.00	0.5162
WDENS+WDENS^2	5	4450.64	0.13	0.4838
MINDIST	4	4448.4	2.30	0.2405
MINDIST-MINDIST^2	5	4446.1	0.00	0.7595
STEP 2				
NULL	3	4449.57	0.00	0.5113
WDENS	4	4450.51	0.94	0.3195
WDENS+YEAR	5	4452.43	2.86	0.1223
WDENS+YEAR-WDENS*YEAR	6	4454.35	4.78	0.0468
NULL	3	4449.57	3.47	0.1021
MINDIST-MINDIST^2	5	4446.1	0.00	0.5789
MINDIST-MINDIST^2+YEAR	6	4447.77	1.67	0.2512
MINDIST+YEAR+MINDIST*YEAR-MINDIST^2-MINDIST^2*YEAR	8	4450.39	4.29	0.0678
STEP 3				
NULL	3	4449.57	3.47	0.1417
YEAR	4	4451.47	5.37	0.0548
MINDIST-MINDIST^2	5	4446.1	0.00	0.8035
Litter depth				
STEP 1				
WDENS	4	2154.12	0.00	0.7291
WDENS+WDENS^2	5	2156.1	1.98	0.2709

MINDIST	4	2153.17	0.00	0.6011
MINDIST-MINDIST^2	5	2153.99	0.82	0.3989
STEP 2				
NULL	3	2153.83	95.50	0.0000
WDENS	4	2154.12	95.79	0.0000
WDENS+YEAR	5	2069.94	11.61	0.0030
WDENS+YEAR-WDENS*YEAR	6	2058.33	0.00	0.9970
NULL	3	2153.83	84.53	0.0000
MINDIST	4	2153.17	83.87	0.0000
MINDIST+YEAR	5	2072.47	3.17	0.1701
MINDIST+YEAR+MINDIST*YEAR	6	2069.3	0.00	0.8299
STEP 3				
NULL	3	2153.83	91.84	0.0000
YEAR	4	2071.62	9.63	0.0080
YEAR+WDENS-WDENS*YEAR-MINDIST+MINDIST*YEAR	8	2061.99	0.00	0.9920
<u>*Percentage bare ground*</u>				
STEP 1				
WDENS	4	2121.65	0.00	1.0000
MINDIST	4	2121.84	7.65	0.0214
MINDIST+MINDIST^2	5	2114.19	0.00	0.9786
STEP 2				
NULL	3	2120.23	0.00	0.5501
WDENS	4	2121.65	1.42	0.2705
WDENS-YEAR	5	2123.64	3.41	0.1000
WDENS-YEAR+WDENS*YEAR	6	2124.1	3.87	0.0794
NULL	3	2120.23	6.04	0.0295
MINDIST+MINDIST^2	5	2114.19	0.00	0.6038
MINDIST+MINDIST^2-YEAR	6	2116.08	1.89	0.2347
MINDIST+YEAR-MINDIST*YEAR+MINDIST^2+MINDIST^2*YEAR	8	2117.23	3.04	0.1321

STEP 3				
NULL	3	2120.23	6.04	0.0457
YEAR	4	2122.23	8.04	0.0168
MINDIST+MINDIST^2	5	2114.19	0.00	0.9374
Percentage live grass				
STEP 1				
WDENS	4	5223.91	1.37	0.3351
WDENS+WDENS^2	5	5222.54	0.00	0.6649
MINDIST	4	5217.65	1.77	0.2921
MINDIST-MINDIST^2	5	5215.88	0.00	0.7079
STEP 2				
NULL	3	5233.92	75.69	0.0000
WDENS+WDENS^2	5	5222.54	64.31	0.0000
WDENS+WDENS^2-YEAR	6	5158.23	0.00	0.8808
WDENS-YEAR+WDENS*YEAR+WDENS^2-WDENS^2*YEAR	8	5162.23	4.00	0.1192
NULL	3	5233.92	76.13	0.0000
MINDIST-MINDIST^2	5	5215.88	58.09	0.0000
MINDIST-MINDIST^2-YEAR	6	5157.79	0.00	0.8749
MINDIST-YEAR+MINDIST*YEAR-MINDIST^2-MINDIST^2*YEAR	8	5161.68	3.89	0.1251
STEP 3				
NULL	3	5233.92	74.96	0.0000
YEAR	4	5170.03	11.07	0.0039
YEAR-WDENS-WDENS^2+MINDIST-MINDIST^2	8	5158.96	0.00	0.9961
Percentage dead grass				
STEP 1				
WDENS	4	5190.41	0.00	0.6213
WDENS+WDENS^2	5	5191.4	0.99	0.3787
MINDIST	4	5189.68	0.00	0.7311
MINDIST-MINDIST^2	5	5191.68	2.00	0.2689

STEP 2				
NULL	3	5192.35	29.73	0.0000
WDENS	4	5190.41	27.79	0.0000
WDENS+YEAR	5	5162.62	0.00	0.5793
WDENS+YEAR-WDENS*YEAR	6	5163.26	0.64	0.4207
NULL	3	5192.35	27.00	0.0000
MINDIST	4	5189.68	24.33	0.0000
MINDIST+YEAR	5	5165.35	0.00	0.7130
MINDIST+YEAR+MINDIST*YEAR	6	5167.17	1.82	0.2870
STEP 3				
NULL	3	5192.35	28.04	0.0000
YEAR	4	5166.25	1.94	0.2749
YEAR+WDENS-MINDIST	6	5164.31	0.00	0.7251
<u>*Percentage forbs*</u>				
STEP 1				
WDENS	4	4087.84	0.00	0.6921
WDENS-WDENS^2	5	4089.46	1.62	0.3079
MINDIST	4	4084.7	1.43	0.3285
MINDIST+MINDIST^2	5	4083.27	0.00	0.6715
STEP 2				
NULL	3	4085.85	27.57	0.0000
WDENS	4	4087.84	29.56	0.0000
WDENS+YEAR	5	4059.3	1.02	0.3752
WDENS+YEAR-WDENS*YEAR	6	4058.28	0.00	0.6248
NULL	3	4085.85	29.33	0.0000
MINDIST+MINDIST^2	5	4083.27	26.75	0.0000
MINDIST+MINDIST^2+YEAR	6	4056.52	0.00	0.8299
MINDIST+YEAR+MINDIST*YEAR+ MINDIST^2-MINDIST^2*YEAR	8	4059.69	3.17	0.1701
STEP 3				
NULL	3	4085.85	28.95	0.0000
YEAR	4	4057.5	0.60	0.4256
YEAR-WDENS-WDENS*YEAR- MINDIST+MINDIST^2	8	4056.9	0.00	0.5744

Percentage crested wheatgrass

STEP 1				
WDENS	3	18.41	0.00	0.8641
WDENS-WDENS^2	4	22.11	3.70	0.1359
MINDIST	3	18.4	0.00	0.7867
MINDIST-MINDIST^2	4	21.01	2.61	0.2133
STEP 2				
NULL	2	16.43	1.09	0.2995
WDENS	3	18.41	3.07	0.1113
WDENS-YEAR	4	15.34	0.00	0.5165
WDENS+YEAR-WDENS*YEAR	5	19.26	3.92	0.0728
NULL	2	16.43	0.00	0.5349
MINDIST	3	18.4	1.97	0.1998
MINDIST-YEAR	4	18.4	1.97	0.1998
MINDIST-YEAR+MINDIST*YEAR	5	20.63	4.20	0.0655
STEP 3				
NULL	2	16.43	3.12	0.1336
YEAR	3	13.31	0.00	0.6359
WDENS-YEAR	4	15.34	2.03	0.2305