Landscape Scale Effects of Oil and Gas Development on Grassland Passerines in Southern Alberta

By

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ABSTRACT

Agriculture and, more recently, oil and gas development have contributed to extensive degradation and loss of temperate grasslands. I investigated the landscape-scale effects of oil and gas development, and roads, on grassland birds in southern Alberta using abundance, clutch size and nesting success data collected from 2010-2014. I estimated: (i) the distance at which there are effects of edge, and effects of shallow gas well density, using piecewise regressions; (ii) the locations and extent of habitat affected by infrastructure for obligate grassland species– Baird's Sparrow (*Ammodramus bairdii*), Chestnut-collared Longspur (*Calcarius ornatus*) and Sprague's Pipit (*Anthus spragueii*); and generalist species – Clay-colored Sparrows (*Spizella pallida*), Horned Lark (*Eremophila alpestris*), Savannah Sparrow (*Passerculus sandwichensis*), Vesper Sparrow (*Pooecetes gramineus)* and Western Meadowlark (*Sturnella neglecta*), and (iii) the total area affected by wells and roads. My findings suggest that the effects of roads, overall, extended to further distances than edge effects associated with natural gas wells, obligate species had more habitat affected by infrastructure than generalist species and shallow gas wells affected more habitat than did oil wells, due to their greater density on the landscape. Additionally, obligates, on average, were negatively affected by proximity to edge where as generalists were more productivity closer to edge. Reducing fragmentation caused by roads, minimizing the spread of non-native vegetation and management of cattle around gas wells could improve habitat quality for these focal species.

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which were Chestnut-collared Longspur (*Calcarius ornatus*) and Sprague's Pipit (*Anthus spragueii*) (data collected from May 2010 to July 2014).

CHAPTER 1: INTRODUCTION

1.1 Background

Temperate grasslands are considered one of the most at-risk biomes globally, which is attributed to extensive human-induced habitat loss (Hoekstra et al. 2005). Grassland topography and soils are conducive for grain cultivation and livestock, which explains their historical destruction for agriculture (Shiyomi and Koizumi 2001). More recently, oil and gas activity has contributed to habitat degradation since many oil deposits are within native prairie (Riley et al. 2012). Consequently, there is more than a 70 % global decline in grassland birds (North American Bird Conservation Initiative Canada 2012). While there has been a 12 % decline of grassland birds in Canada since 1970, in Alberta, less than 50 % of the native are considered healthy (Thorpe and Godwin 2010). Interestingly, the activities on breeding grounds, such as Alberta, are proposed as a greater contributor to the decline of grassland birds than those on wintering grounds (Murphy 2003). Thus, studies to mitigate and minimize the effects of development in the breeding habitat of grassland birds are critical in reversing declines.

Anthropogenic habitat loss reduces the suitability of native prairie for grassland birds (Hoekstra et al. 2005). The large tracts of continuous habitat required by grassland obligates (Johnson 2001) are degraded by roads, croplands, and oil and gas infrastructure (Owens and Myres 1973; Sliwinski and Koper 2012; Kalyn Bogard and Davis 2014). The noises from oil wells and roads may disturb communication between birds (Reijnen and Foppen 1995; Riley et al. 2012), which may reduce the suitability of habitat at distances greater than 1 km from infrastructure (Habib et al. 2007). Furthermore, roads act as corridors for the spread of exotic vegetation and predators (Ingelfinger and Anderson 2004). Additionally, the mixing and exposure of soil during the installation of oil infrastructure also facilitates the spread of non-native plants (Riley et al. 2012). As a result, vegetation cover and species richness are

significantly lower at natural gas sites (Jones et al. 2014) and near roads. At disturbed sites, dominant exotic vegetation like crested wheatgrass (*Agropyron cristatum*) and smooth brome (*Bromus inermis*) alter the vegetation structure of native prairie, which many grassland birds avoid (Dale et al. 2007). Cumulatively, this means that at the landscape scale, many types of anthropogenic development reduce the amount and quality of suitable grassland patches. Although agriculture has historically been the main reason for habitat loss in grasslands (Owens and Myres 1973), expanding oil and gas development to address increased energy demands (Dorian et al. 2006) may further degrade the remaining native prairie. In Canada, oil and gas development is critical to economic growth, and a quarter of reserves are still to be extracted (Aboriginal Affairs and Northern Development 2008). Globally, Canada is ranked 5th for energy production (Canadian Association of Petroleum Producers 2014a) with Alberta producing most of its natural gas (Canadian Association of Petroleum Producers 2014b). Since Alberta provides a critical breeding habitat for grassland birds (Sauer et al. 2014), degradation of native prairie due to increased oil infrastructure is of great concern in this region. Many effects of oil and gas development on wildlife are documented (Boesch and Rabalais; Bolze and Lee 1989; Ko and Day 2004); however, there have been few studies on grassland birds. While previous studies have demonstrated effects of proximity to roads and croplands on grassland songbirds (Koper et al. 2009; Sliwinski and Koper 2012), effects of proximity to oil and gas development are yet to be determined.

1.2 Objectives

(i) To determine the distance(s) at which there is an effect of oil and gas infrastructure and roads (edge) on abundance, clutch size and nesting success of each focal species of songbird.

(ii) To create predictive maps for each focal species based on songbird abundance, clutch size, nest density and nesting success.

(iii)To determine the footprint of oil and gas wells and the proportion of habitat affected by distance to edge.

Hypotheses

The impacts of ecological edges on each species vary with the type of feature contributing to habitat fragmentation and loss. When compared to shallow gas wells, when an oil well is installed, there are higher rates of visitation for maintenance, larger amounts of habitat are removed, and greater increases in road density (Patey Le Drew 2013). Further, shallow gas wells are associated with fewer risks of hydrogen sulphide leaks and less increase in the density of low impact trails (Patey Le Drew 2013). I predicted, therefore, that oil wells would have greater edge effects than shallow gas wells for passerines sensitive to habitat alterations.

The effects of distance to edge vary among species. While Chestnut-collared Longspurs, Sprague's Pipits and Baird's Sparrows are area and edge sensitive, obligate species (Davis 2004; Koper et al. 2009; Sliwinski and Koper 2012), Savannah Sparrows, Vesper Sparrows and Western Meadowlarks are generally less sensitive to disturbances because they are facultative and not obligate grassland birds (Wheelwright and Rising 1993; Lanyon 1994; Jones and Cornely 2002). Furthermore, though Horned Larks prefer bare ground, which is not exclusive to grassland habitat (Beason 1995), Clay-colored Sparrows prefer shrubby areas (Knapton 1994) . Since generalists can thrive in disturbed and high quality habitat**,** I predicted that the area and edge sensitive (obligate) species would be more sensitive to habitat loss from roads, oil wells and shallow gas wells. In contrast, I predict that the effects on the habitat of generalist species will be lower or minimal.

Finally, while the disturbances associated with an oil well are greater than that for a shallow gas well, shallow gas wells are found at higher densities than oil wells. Thus, I predicted that the area of habitat affected by shallow gas wells would be greater than that of oil wells at the landscape scale.

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CHAPTER 2: LITERATURE REVIEW

2.1 Grassland Degradation and Loss

Natural ecological processes such as drought, grazing and fire, which maintained native prairie vegetation structure, have been loss, contributing to habitat degradation (Gamache and Payette 2004). For example, the natural processes that maintained vegetation height in short-grass prairie were strongly affected by the removal of the plains bison (*Bison bison bison*) (Gamache and Payette 2004). Grazing patterns have been altered by the introduction of cattle, which have changed the vegetation structure in native prairies (Gamache and Payette 2004). Furthermore, natural fires that restricted the spread of woody vegetation in mixed and tall-grass prairie were suppressed (Askins 1993). While temperate grasslands cover 8 % of the Earth, 70 % of native cover was lost by 1950 (Federal 2010). It is estimated that an additional 15 % were destroyed by 2003, including in the loss of 48 % of short- grass prairie, 48 % of mixed-grass prairie and 97 % of tall-grass prairie in Canada (Federal, Provincial and Territorial Governments of Canada 2010).

2.2 Habitat Loss and Habitat Fragmentation

Habitat loss reduces the amount of a habitat that is available for many species (Koper et al. 2009), which increases patch isolation (Ewers and Didham 2006) and the loss of species (Schmiegelow and Mönkkönen 2002). Significant isolation of patches affect the dynamics of metapopulations, which are interacting subpopulations, because dispersal to and from fragmented habitat becomes difficult (Ewers 2006). For example, the occurrence of northern harriers and short-eared owls in patches were influenced by the proximity to grassland/source habitat (Herkert 1994). A decline in the abundance or loss of a species can also occur when the heterogeneity within a particular habitat is degraded due to habitat loss (Schmiegelow and

Mönkkönen 2002). For instance, in forest ecosystems where old growth and post burn stands are scarce, obligate species reliant on these habitats also become rare (Schmiegelow and Mönkkönen 2002). In the same way, the extensive human-induced habitat loss in native prairie has reduced the amount of critical habitat required by prairie obligates, significantly contributing to their decline (Askins 1993).

Habitat fragmentation can reduce patch size, which influences the suitability of grassland patches (Koper et al. 2009). Habitat fragmentation, which describes the configuration of patches resulting from habitat loss at the landscape scale (Koper et al. 2007), also increases the influence of the habitat surrounding a patch (Wiens 2008). Many studies have shown that large stretches of contiguous habitat are required for area/edge-sensitive species in forests (Hobson and Bayne 2000) and grasslands (Johnson 2001; Sliwinski and Koper 2012). Area-sensitive species require a habitat that is much larger than their territory size to reproduce (Davis 2004). Thus, a study in southern Saskatchewan found that the occurrence of Sprague's Pipits (*Anthus spragueii*), Grasshopper Sparrows (*Ammodramus savannarum*), Chestnut-collared Longspurs (*Calcarius ornatus*) and Baird's Sparrows (*Ammodramus bairdii*), which are all area sensitive species, were related to size of available grassland patches (Davis 2004). Other area-sensitive species like Clay-colored Sparrows (*Spizella pallida*), Brown-headed Cowbirds (*Molothrus ater*) and Western Meadowlarks (*Sturnella neglecta*) may be absent in small patches (Davis 2004). Consequently, the abundance of area-sensitive species is negatively correlated with patch size (Davis 2004).

Another way that habitat fragmentation influences habitat suitability is by increasing the effects of edge. Edge effects occur in patches with a high perimeter to area ratio or where there is a small amount of core habitat compared to edge (Wiens 2008). The variability in abiotic and biotic processes along edges (Ewers and Didham 2006) in grasslands can result in a higher

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occurrence of nest predators (Winter et al. 2000) and changes in vegetation structure (Zanette et al. 2000). Consequently, the abundance of area-sensitive species may be low near edges (Davis et al. 2006) since the suitability of foraging and nesting habitat is reduced (Zanette et al. 2000). Furthermore, since the effects of edge are intensified when multiple edges collide (Fletcher and Koford 2002), areas where roads border oil or gas wells could be of a lower quality. Presumably, in cases when edges are artificial and not natural, habitat quality might be lower because there are increases in human activity. However, lower habitat quality closer to edge is possibly driven by habitat degradation, rather than habitat loss *per se*. In a 39-square-kilometer area, only 0.08 – 0.6 % of land was lost to roads and 0.014 – 0.03% to natural gas well pads (Yoo 2014). Therefore, habitat fragmentation due to roads and oil and gas infrastructure, and its associated edge effects, might have a larger effect on species occurrence than habitat loss *per se* (Koper et al. 2007).

2.3 Degradation from Agriculture

In western Canada, native grasslands have been disturbed for agriculture through field cultivation and livestock grazing (Owens and Myres 1973). As native prairies are converted to cropland or hayland, the resulting fields are often unsuitable nesting grounds for native grassland songbirds (Owens and Myres 1973). Consequently, grassland songbirds, with the exception of Horned Larks, are usually found at low densities absent in cultivated areas (Owens and Myres 1973). Furthermore, the construction of homes and roads that are associated with field cultivation (Bowen 2002) contribute to habitat loss and fragmentation. Disturbances caused by livestock grazing, however, can provide the vegetative heterogeneity needed to meet the habitat requirements of various songbirds (United States Geological Survey 2013). Heavy grazing removes the dense vegetation required by some grassland songbirds, but can provide the short

vegetation or bare ground required by others (Owens and Myres 1973). As such, Baird's

Sparrows, Sprague's Pipits, Clay-colored Sparrows and Grasshopper Sparrows responded

negatively to heavily grazed pastures, while Horned Larks and Chestnut-collared Longspurs

responded positively (Kantrud 1981; Dale 1983 in CEC 2013). Thus, much of the historical

decline of grassland birds in North America has been attributed to the fragmentation of habitat as

they are converted to croplands (Owens and Myres 1973).

2.4 Effects of Oil and Gas Development

The four most abundant types of petroleum infrastructure usually found in southern

Alberta include: shallow gas wells, which do not produce any noises; oil wells, including

pumpjacks and progressive pumps, which produce noise; compressor stations, which produce

noises: and pipelines, which are silent (Patey Le Drew 2013). Natural gas is removed from

subsurface sediments by shallow gas wells and transported through pipelines (Demirbas 2010).

Natural gas must be pressurized in intervals of 40 – 100 miles, which is maintained by

compressor stations (Kerr-McGee Gathering LLC 2014). Although crude oil is found below

natural gas deposits, pressure differentials usually push the oil to the surface (Patey Le Drew

2013). However, when there is low pressure within an oil deposit compared to the surface, some

form of pumping mechanism is required (Patey Le Drew 2013). Consequently, pumpjacks and

progressive pumps act as artificial lifts, pulling crude oil to the surface (Patey Le Drew 2013).

2.4.1 Noise

The effects of oil and gas drilling and the construction of energy infrastructure have been

recorded for some species. The rate that sage grouse males visited leks declined with increasing

distance to sites that were drilled (Copeland et al. 2013), which can negatively affect

reproductive rates. Beluga whales (*Delphinapterus leucas*) avoided playbacks of oil drilling

(Turl 1981) because acute noises from offshore drilling reduce their ability to identify signals and communicate (Awbrey 1983; Thomas et al. 1990). Although studies have confirmed that acute noises from oil drilling negatively impact marine mammals, fish, and Greater Sage-grouse (*Centrocercus urophasianus*) (Myrberg 1990; Copeland et al. 2013; Hardee 2013), it is expected that other sensitive birds and wildlife will also respond negatively (Robbins 2013).

The effects of chronic noise from oil and gas well sites on some species of birds have been studied. The noise associated with increased human activity when new energy infrastructure is installed can impair acoustic signalling by birds (Riley et al. 2012). Typically, low-frequency sounds, like those from compressor stations, have a lower attenuation and acoustic energy than high-frequency sounds (Barber et al. 2011). Anthropogenic ambient noises can overlap with the frequencies of bird songs and calls (Habib et al. 2007). Consequently, at compressor stations, where noises can be heard beyond 1 kilometer in boreal forests, there was a reduction in pairing success of Ovenbirds (*Seiurus aurocapilla*) (Habib et al. 2007). Additionally, a study that examined the effects of chronic noise from oil and gas development in forests found that densities of some passerines were 1.5 times greater near noiseless facilities than at noise-producing sites (Bayne et al. 2008). However, a study on wintering habitat in Texas concluded that songbird abundance is unaffected by noise since there was no significant difference in abundance at active oil wells and abandoned sites (Lawson et al. 2011). The conflicting reported responses of passerines to noise from oil infrastructure in the literature might suggest that habitat selection requirements vary with the time of year, type of habitat or if summer or wintering habitat is being used. Since there has been little work done on the effects of distance to oil wells on the breeding grounds of grassland passerines at the local or landscape scale, this study is important in reducing knowledge gaps.

2.4.2 Habitat Loss and Alteration

The installation of oil and gas wells in native prairie can degrade a songbird's habitat by altering vegetation characteristics. During drilling and the installation of oil infrastructure, soil is mixed and exposed allowing the spread of non-native plants (Riley et al. 2012) such as crested wheatgrass and smooth brome, which many songbirds avoid (Dale et al. 2007). In addition to the spread of non-native plants, vegetation structure is degraded around wells as they are visited for maintenance or as cattle grazing persists (Koper et al. 2014; Kalyn Bogard and Davis 2014). Consequently, the documented negative effects of oil and gas infrastructure can be partially attributed to vegetation changes (Kalyn Bogard and Davis 2014). Thus, Grasshopper Sparrows, Chestnut-collared Longspurs, McCown's Longspurs (*Rhynchophanes mccownii*) and Sprague's Pipits abundance were lower closer to shallow gas wells (Hamilton et al. 2011). Interestingly, on wintering grounds, Western Meadowlarks (*Sturnella neglecta*) and Eastern Meadowlarks (*Sturnella magna*) were found more frequently at active oil well sites because vegetation characteristics were more favourable (Lawson et al. 2011). On the other hand, Sprague's Pipits and Baird's Sparrows appeared to be unaffected by shallow gas well density or proximity, which could be attributed to the fact that grazing was well-managed in this study area (Kalyn Bogard and Davis 2014). Although the individual effect of exotic species that are introduced by the creation of trails and the installation of pipelines might be minimal, the cumulative effects may have landscape-scale implications (Kalyn Bogard and Davis 2014). Therefore, the footprint of an oil well or compressor station is not just dependent on the amplitude of noises it produces, but the distance at which vegetation is altered. Also, since shallow gas wells are found at higher densities, it is possible that shallow gas wells contribute to greater habit alterations than do oil wells.

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2.5 Influence of roads on grassland birds

Noise and visual stimuli can contribute to a decline in the density of breeding grassland birds along roads (Reijnen et al. 1996). Across open landscapes, traffic can be seen at great distances, which can affect the responses of breeding birds (Reijnen et al. 1996). A study in an expanding urban area reported a reduction in the breeding and occurrence of grassland birds due to heavy traffic use (13,000-15,000 cars per day) (Forman et al. 2002).With moderate use (8000–15,000 cars per day) the presence of birds was unaffected while breeding was reduced (Forman et al. 2002). Conversely, both presence and breeding were unaffected by light traffic volumes (3000–8000 cars per day) (Forman et al. 2002). However, another study reported a decline in the density of sagebrush obligates along roads that were associated with natural gas development when there were fewer than 12 cars on the road per day (Ingelfinger and Anderson 2004). Interestingly, the mechanisms by which traffic noise reduces breeding birds' densities are reported as disturbances to communication, and stress (Reijnen and Foppen 1995). On the other hand, noise and visual stimuli may not explain road avoidance at shallow gas or oil wells in Canada, since shallow gas wells are visited only 1 to 4 times per year for maintenance (Koper et al. 2014).

Habitat fragmentation and edge avoidance are probable causes of the declines in grassland birds near roads. An analysis of data from the Breeding Bird Survey (BBS) revealed a significant change in the composition of the avian community at off-road sites compared to roadside areas (Wellicome and Kardynal 2014). Native grassland obligates such as Baird's Sparrows, Sprague Pipits, McCown's Longspurs and Chestnut-collared Longspurs, which are listed on Canadian Federal Species at Risk Act (SARA) were more abundant at off-road sites (Wellicome and Kardynal 2014). Increases in the presence of nest predators and unfavourable changes in vegetation characteristics along roads are plausible explanations of road avoidance

(Ingelfinger and Anderson 2004). Road avoidance may ultimately impact how birds select habitat at the landscape scale.

2.6 Habitat Selection and Quality

2.6.1 Habitat Selection at the Local and Landscape Scale

The factors affecting habitat selection differ at the local and landscape scale. At the landscape scale, distributions of grassland birds are typically influenced by habitat amount, proportion of edge and the characteristics of neighbouring habitat (Herkert 1994). Area-sensitive species are found in higher densities in large fragments, whereas the abundance of edge species is greater in small fragments (Herkert 1994). Grassland birds are also influenced by the diversity of neighbouring cover types and the distance to woody vegetation at the landscape scale (Ribic and Sample 2001). Although these neighbouring cover types is usually described as matrix (Ewers and Didham 2006), they are inhospitable to prairie obligate passerines, but not necessarily to habitat generalists, such as Horned Larks (Owens and Myres 1973).

At the local scale, however, vegetation structure and composition are critical in habitat selection since nest site requirements vary by species (Madden et al. 2000). For example, shrub cover influences the occurrence of Clay-colored Sparrows; however, Sprague's Pipits nest site selection is determined by the presence of visual obstructions (Madden et al. 2000). Although nest site selection is associated with a greater density of dead vegetation and litter, and less bare ground coverage (Davis 2005), at the landscape scale, these local habitat requirements are not represented in habitat selection. Consequently, habitat degradation and fragmentation from oil and gas development may have local implications, which are not represented at the landscape scale.

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2.6.2 Influences of Habitat Quality on Abundance, Clutch Size and Nesting Success

Many ecological studies rely on count data (abundance or presence only), which is not always a good indicator of habitat quality (Van Horne and Horne 1983). For instance, surpluses of terrestrial breeding birds may occupy poor quality habitat where no breeding takes place or breeding attempts are largely unsuccessful (Van Horne and Horne 1983). A possible explanation for high densities of birds in low quality habitat is that the potential benefits of large, continuous, high quality habitat declines when part of the food resources exist in matrix habitat (Estades 2001). Thus, high densities of breeding birds in poor quality habitat could have lower nesting success and reproduction (Fretwell and Calver 1969). Consequently, abundance estimates, in the absence of nesting success, feeding rates and clutch size, may not be adequate indicators of habitat suitability (Fretwell 1969).

Nesting success is not always correlated with habitat preferences (Chalfoun and Martin 2007). Though high densities of Brewer's Sparrows (*Spizella breweri*) occupied landscapes where shrub cover and height was greater, nesting success was lower in these areas possibly because nest predation and intraspecific competition could outweigh the benefits of greater food availability in preferred habitat (Chalfoun and Martin 2007). As such, the probability of nesting success is often influenced by the presence or absence of predators, which increases with proximity to edge (Klug et al. 2009; Ribic et al. 2012). It is also plausible that higher nest predations occur with inexperienced birds that are unaware of nest concealment strategies to avoid predators (Marzluff 1988). On the other hand, nest site selection could be a product of compromises based on available habitat (Marzluff 1988) and birds have incomplete knowledge of their environment (Pulliam and Danielson 1991), specifically the risk of predation (Öst et al. 2008). Furthermore, since the abundance of many predators is positively correlated with the

presence of structures for development (Ribic et al. 2012), risk of predation is possibly higher

along roads, and near to oil and gas infrastructure (Yoo 2014).

The clutch size of breeding birds is influenced by habitat quality (Ost et al. 2008). The

amount of energy that is available limits incubation, as posited by the energy-bottleneck

hypothesis (Bryan and Bryant 2012). As a result, breeding birds in low quality habitat with lower

food availability might lay a smaller clutch in preparation for future reproductive attempts (Ost et

al. 2008). Thus, lower clutch sizes would be expected in matrix habitat and along edges,

especially near to roads and oil infrastructure for species sensitive to habitat alterations.

However, since nesting success and clutch size in combination are good indicators of habitat

quality, and abundance can correlate significantly with habitat preferences and habitat use

(Akçakaya and Sjögren-Gulve 2000), a combine measure of abundance, clutch size and nesting

success should be reliable indicator of productive areas on a landscape.

2.7 Thresholds in Response to Edge

Nonlinear responses to distance to edge have been documented in grassland birds (Koper

et al. 2009; Sliwinski and Koper 2012). With increasing distance from croplands, roads and

wetlands, the abundance of grassland birds decline or increase and eventually reach an asymptote

(Sliwinski and Koper 2012). For instance, Sprague's Pipit abundance increases with declining

proximity to croplands, but was unchanged after approximately 1000 m (Koper et al. 2009). To

address conservation targets, when there are points at which the responses differ drastically,

threshold models are often used (Toms and Villard 2015). Threshold models, when applied to

nonlinear data, could identify breakpoints, which are points where the relationship between the

response and predictor variable changes abruptly or smoothly (Toms and Villard 2015).

Knowledge of the distance from an edge type at which habitat quality changes could assist

managers in estimating the footprint of various structures or activities, and consequently, limit

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impacts in vulnerable areas. Whilst the footprint of roads and croplands on grassland birds has been investigated (Koper et al. 2009; Sliwinski and Koper 2012; Kalyn Bogard and Davis 2014), the distances at which there are changes in the effect of roads and oil and gas infrastructure are yet to be determined.

2.8 Natural History of the Most Common Songbirds Found in the Study Area

2.8.1 Baird's Sparrow

Baird's Sparrows, like Sprague's Pipits, are grassland specialists (Green et al. 2002). They are found in mixed-grass and fescue prairie with scattered low-lying shrubs in summer (Owens and Myres 1973) and dense grassland areas with shrub patches in winter (Green et al. 2002). When foraging, Baird's Sparrows avoid open areas and often feed between grass clumps (Green et al. 2002) Although they were historically common in the Canadian and Dakotan prairies (Coues 1874) , conversion to cultivated fields have drastically reduced their occurrence and range (Green et al. 2002). Currently, sightings of Baird Sparrows are rare throughout their range (Green et al. 2002) . Thus in 2012, Baird Sparrows were listed as a species of Special Concern under the SARA as Canada supports 60 % the breeding population (COSEWIC 2012) . Baird's Sparrows are listed as endangered in Manitoba, but not in Alberta (COSEWIC 2012) . While there has been a -0.2 % decline from 1966-2010, there has been growth of 0.7 from 2010-2012 in Alberta (Sauer et al. 2014) .

2.8.2 Chestnut-collared Longspurs

Chestnut-collared Longspurs are native to the grasslands of North America and were generally associated with areas recently disturbed by fire or grazed by Bison (Hill and Gould 1997). As prairie obligates, they are locally abundant in drier short-grass to mixed-grass prairie

in the Great Plains of North America. Their breeding range extends from the southern peripheries of the prairies in Alberta, Saskatchewan, and Manitoba to southern Colorado. They have been observed in more than 8 of the southwestern states in the United States in winter (Dechant et al. 1998; Sedgwick 2004). An analysis of data from Christmas Bird Counts (CBC) and Breeding Birds Survey (BBS), which begun in US and Canada in 1966 and 1968, revealed a 90% and 93 % decline respectively of Chestnut-collared Longspurs by 2008 (Sauer et al. 2014). The massive decline has been attributed to habitat fragmentation and loss from agriculture and most recently oil and gas development (COSEWIC 2009). Chestnut-collared Longspurs are listed as threatened in Canada and have experienced a -4.1 % overall decline from 2010-2012 in Alberta (COSEWIC 2009; Sauer et al. 2014).

2.8.3 Savannah Sparrows

Savannah sparrows are found in open habitat and are widespread and abundant in North America. Although they occupy various habitats they avoid open woodlands (Wheelright and Rising 1993). Savannah sparrows breed in meadows, grasslands, tundra, marshes and agricultural fields (Wheelright and Rising 1993). They are reported to prefer moist grassy fields with minimal forbs and dense ground layer vegetation (Wiens 1969). Results from the North America Breeding Bird Survey from 1966-2012 reveal declines throughout most regions in the U. S. and Canada (Sauer et al. 2014). While there are 17 recognized subspecies, only *princeps*, which breeds on Sable Island in Nova Scotia, is listed as Special Concern under the SARA in Canada (Wheelright and Rising 1993; COSEWIC 2010b).

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2.8.4 Sprague's pipits

Sprague's pipits are native grassland specialists and are endemic to North America (Robbins and Dale 1999). Their breeding range is exclusive to the Northern Great Plains, which include: south central to east Alberta, southern Saskatchewan, south west Manitoba, northern South Dakota, northwest Minnesota and southern Montana (COSEWIC 2010b). During the winter they can be found in northern Mexico and the south-central states of the United States (COSEWIC 2010b). Sprague's Pipits are associated with native moist mixed-grass prairies that provide an intermediate degree of cover and forage almost exclusively on insects during the summer (Sutter and Brigham 1998). In hay fields, Sprague's Pipits choose similar nest site characteristics to those found in native prairie, and avoid alfalfa (Fisher and Davis 2011). Sprague pipits were once one the most abundant songbirds in undisturbed prairies (Owens and Myres 1973), but have experienced an 83% decline in Canada between 1968 and 2008 (COSEWIC 2010b). In Alberta, Sprague's Pipits experienced a -2.1 % overall decline from 2010-2012 and are listed as sensitive in the General Status of Alberta Wild Species report (COSEWIC 2010b; Government of Alberta 2014a).

2.8.5 Western Meadowlarks

Like the Savannah sparrow, the Western Meadowlark (*Sturnella neglecta*) is one of the most widely distributed and abundant grassland birds. Western meadowlarks inhabit various types of grassland habitats (Owens and Myres 1973), including weedy borders of roads and croplands (Lanyon 1994) and are not sensitive to edge (Davis 2004; Sliwinski and Koper 2012) . In addition, Western Meadowlarks responded positively to increases in grassland habitat that were previously croplands (Lanyon 1994). Furthermore, abundance of Western Meadowlarks is negatively correlated with the amount of woody vegetation in near to breeding sites or within

patches (Davis 2004). There is a significant yearly decline of -1.2 % in both U. S. and Canada from 1966-2012 (Sauer et al 2014). With the exception of Alberta, there have been declines in Western Meadowlarks over the past 40 years (Lanyon 1994). The Western Meadowlark is not listed under SARA or COSEWIC and is not considered at risk in Alberta or Canada (Pearson 2012).

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CHAPTER 3: LANDSCAPE-SCALE EFFECTS OF OIL AND GAS DEVELOPMENT ON GRASSLAND PASSERINES IN SOUTHERN ALBERTA

Abstract

Agriculture and, more recently, oil and gas development have contributed to extensive degradation and loss of temperate grasslands. I investigated the landscape-scale effects of oil and gas development, and roads, on grassland birds in southern Alberta using abundance, clutch size and nesting success data collected from 2010-2014. I estimated: (i) the distance at which there are effects of edge, and effects of shallow gas well density, using piecewise regressions; (ii) the locations and extent of habitat affected by infrastructure for obligate grassland species– Baird's Sparrow (*Ammodramus bairdii*), Chestnut-collared Longspur (*Calcarius ornatus*) and Sprague's Pipit (*Anthus spragueii*); and generalist species – Clay-colored Sparrows (*Spizella pallida*), Horned Lark (*Eremophila alpestris*), Savannah Sparrow (*Passerculus sandwichensis*), Vesper Sparrow (*Pooecetes gramineus)* and Western Meadowlark (*Sturnella neglecta*), and (iii) the total area affected by wells and roads. My findings suggest that the effects of roads, overall, extended to further distances than edge effects associated with natural gas wells, obligate species had more habitat affected by infrastructure than generalist species and shallow gas wells affected more habitat than did oil wells, due to their greater density on the landscape. Additionally, obligates, on average, were negatively affected by proximity to edge where as generalists were more productivity closer to edge. Reducing fragmentation caused by roads, minimizing the spread of non-native vegetation and management of cattle around gas wells could improve habitat quality for these focal species.

3.1 Introduction

Agriculture, and more recently oil and gas development, have led to extensive loss of habitat in temperate grasslands (Hoekstra et al. 2005; Riley et al. 2012). The flat topography of grasslands make them suitable for cultivation and the herding of livestock, and much of the oil and gas deposits are within native prairie (Shiyomi and Koizumi 2001; Riley et al. 2012). As a result, approximately 3 million hectares of cropland, forestland, rangeland and wetland were lost to oil and gas activities in North America from 2000 to 2012 (Allred et al. 2013), and only 30 %

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of the historical extent of native prairie remain in the Great Plains (Samson et al. 2004). Such activities have contributed to a 70 % decline in grassland birds globally (Sauer et al. 2014). Since activities on breeding grounds are proposed as a greater contributor to the decline of grassland birds than those on wintering grounds (Murphy 2003), the extraction of oil and gas in breeding grounds like Alberta, the third largest crude oil resource and natural gas producer worldwide (Government of Alberta 2015), could have a significant impact on the viability of breeding birds.

The inelastic demand for oil and gas (Dorian et al. 2006), and the roads required to facilitate transportation of products, may cause further degradation of the remaining native prairie, for numerous reasons. Effects of oil and gas drilling and the construction of energy infrastructure are unknown for most migratory birds, but some species clearly respond negatively to these activities; for example, the rate that sage grouse males visited leks was lower closer to sites that were drilled (Copeland et al. 2013). The noise associated infrastructure maintenance can impair acoustic signalling of birds (Riley et al. 2012). Furthermore, during drilling and the installation of oil infrastructure, soil is mixed and exposed allowing the spread of non-native plants (Riley et al. 2012) such as crested wheatgrass (*Agropyron cristatum*) and smooth brome (*Bromus inermis*), which many songbirds avoid (Dale et al. 2007). Perhaps because of this, Grasshopper Sparrows (*Ammodramus savannarum*), Chestnut-collared Longspurs (*Calcarius ornatus*), McCown's Longspurs (*Rhynchophanes mccownii*) and Sprague's Pipits (*Anthus spragueii)* abundances can be lower closer to shallow gas wells (Hamilton et al. 2011; Kalyn Bogard and Davis 2014).

Similarly, noise and visual stimuli can contribute to a decline in the density of breeding grassland birds along roads (Reijnen et al. 1996). Across open landscapes, traffic can be seen at great distances, which can affect the responses of breeding birds (Reijnen et al. 1996), and roads

can act as corridors to nest predators (Ingelfinger and Anderson 2004). Thus, native grassland obligates such as Baird's Sparrows (*Ammodramus bairdii*), Sprague Pipits, McCown's Longspurs and Chestnut-collared Longspurs may be more abundant at off-road sites (Wellicome and Kardynal 2014). While studies have investigated the effects of proximity to roads and croplands on grassland birds (Koper et al. 2009; Sliwinski and Koper 2012), the cumulative effects of oil and gas development and roads, and the threshold in response to roads and oil and gas infrastructure, are largely unknown.

Nonlinear responses to distance to edge have been documented in grassland birds (Koper et al. 2009; Sliwinski and Koper 2012). With increasing distance from croplands, roads and wetlands, the abundance of grassland birds often decline or increase and eventually reach an asymptote (Sliwinski and Koper 2012), suggesting that ecological thresholds may be present beyond which edge effects are negligible. For instance, Sprague's Pipit abundance increases with declining proximity to croplands, but was unchanged after approximately 1000 m (Koper et al. 2009). Similarly, changes in the abundance of grassland birds were negligible above 150 m from roads, 267 m from single bore pads and 150 m from multi bore pads (Thompson et al. 2015). To address conversation targets when there are tipping points or points at which the responses to edge change, threshold models are often used (Toms and Villard 2015). Threshold models, when applied to nonlinear data, could identify breakpoints, which are the points where the relationship between the response and predictor variable changes abruptly or smoothly (Toms and Villard 2015). Knowledge of the distance from an edge type at which abundance, for example, changes to a more desirable number could assist managers in estimating the footprint of various structures or activities, and consequently help managers to limit impacts in vulnerable areas.

While distance to infrastructure could have a nonlinear effect on grassland songbirds, grassland obligates and generalists might respond differently to the loss of habitat. Habitat loss reduces the amount of available habitat for birds and increases patch isolation (Ewers and Didham 2006; Koper et al. 2007). Obligate species, such as Grasshopper Sparrows (*Ammodramus savannarum*), Chestnut-collared Longspurs (*Calcarius ornatus*) and Baird's Sparrows (*Ammodramus bairdii*), have fewer foraging and nesting opportunities in small, fragmented patches and are often described as edge/area sensitive species (Davis 2005). Similarly, in forest ecosystems, where old growth and post burn stands are scarce, obligate species reliant on these habitats also become rare (Schmiegelow and Mönkkönen 2002). Habitat generalists, however, are able to forage and nest in small, fragmented patches; consequently, they are less likely to be negatively affected by habitat loss or fragmentation (Andrén and Andren 1994).

In addition to the nonlinear effects of infrastructure on abundance, fitness of grassland birds is also affected by proximity to edge and habitat loss (Hethcoat and Chalfoun 2015). Predation is the largest contributor to nest survival, which is a critical measure of fitness (Martin 1992). Since nest predation and parasitism are higher in smaller patches, migratory birds occupying such habitat have lower reproductive rates and rely on immigration from source populations in large, continuous habitat (Robinson et al. 1995). Consequently, the nest survival of sagebrush-obligate songbirds was negatively affected by habitat loss due to energy infrastructure (Hethcoat and Chalfoun 2015). Additionally, the clutch size of breeding birds is influenced by habitat quality (Ost et al. 2008), which is another measure of fitness. Considering that food availability limits incubation, as posited by the energy-bottleneck hypothesis (Bryan and Bryant 2012), breeding birds in poor quality habitat might lay smaller clutches in preparation

for future reproductive attempts (Ost et al. 2008). Thus, lower clutch sizes would be expected in matrix habitat and along edges, especially near to roads and oil infrastructure for some grassland songbirds. Further, since nesting success and clutch size in combination are good indicators of habitat quality, and abundance can correlate significantly with habitat preferences and habitat use (Akçakaya and Sjögren-Gulve 2000), a combine measure of abundance, clutch size and nesting success should be reliable indicator of productive areas on a landscape.

In this study, I investigated the landscape-scale effects of oil and gas infrastructure on the abundance, clutch size and nesting success of obligate and generalist grassland passerines. The obligate species were Baird's Sparrow, Chestnut-collared Longspur and Sprague's Pipit and the generalist species were Clay-colored Sparrows (*Spizella pallida*), Horned Lark (*Eremophila alpestris*), Savannah Sparrow (*Passerculus sandwichensis*), Vesper Sparrow (*Pooecetes gramineus)* and Western Meadowlark (*Sturnella neglecta*) (Vickery and Herkert 1995). I determined the distance to which there was an effect of infrastructure, estimated the species-specific quantity of habitat affected by a single oil or gas well, and the proportion of habitat affected by distance to energy infrastructure. I predicted that (i) the distance at which there were effects of oil wells would be greater than that of shallow gas wells for passerines sensitive to habitat alterations, (ii) obligate species would have a larger portion of their habitat affected by roads, oil wells and shallow gas wells and (iii) the cumulative footprints of shallow gas wells would be greater than that of oil wells at the landscape scale because shallow gas wells are found at higher densities.

3.2 Methods

3.2.1. Study Area

The study area encompassed areas within southern Alberta to the Saskatchewan border, to the east; the US border, to the south and extended to the west at 51°15"14.356' and north at 112°44" 30.073' (Figure 3.1.). Within this study area, the sites for the empirical data collection were located in 75 mixed-grass prairie fields in southern Alberta (approximately 50°33'51" N 111°53'56" W) within a 111 km radius of the center of the study area (Figure 1). While all sites were dominated by native plant species such as needle-and-thread grass (*Stipa comata*), blue grama grass (*Bouteloua gracilis*) and silver sagebrush (*Artemisia cana*), there were also a few small patches of exotic species like goatsbeard (*Tragopogon dubius*) and crested wheatgrass (Koper et al. 2014).

All sites were surveyed from 2010-2014 in previous studies that were designed to investigate the effects of oil and gas wells on the abundance, nesting success and clutch size on grassland birds at a local scale. Abundance data were drawn from surveys conducted from 2010-2011 at 34 sites. Sites were each 1.6 x 1.6 km, and contained 0 – 16 gas well pads per 2.56 square kilometers (mean oil well density of 0.65 per km^2 and up to 36 well gas well heads per section). Nesting success and clutch size data were drawn from the above study, and, to increase the available sample size, were also drawn from research conducted in the same region from 2012-2014. In the latter data set, sites were each 0.8 x 0.8 km, and contained 0 or 1 oil well (16 sites with pump jacks, 12 with screw pumps, 13 control sites with no oil wells or compressor stations). All center points were at least 400m away from other oil wells, and sites contained 0 to 36 gas wellheads per 2.56 square kilometers.

The four most abundant types of petroleum infrastructure usually found in southern Alberta include: shallow gas wells, which do not produce any noise and are usually not connected to permanent roads; oil wells, including pump jacks and progressive pumps, which produce noise and always have gravel roads connected to them; compressor stations, which also produce noise and are also associated with roads; and pipelines, which are silent (Patey Le Drew 2013). Natural gas is removed from subsurface sediments by shallow gas wells and transported through pipelines (Demirbas 2010). Natural gas must be pressurized in intervals of 40 – 100 miles, which is maintained by compressor stations (Kerr-McGee Gathering LLC 2014). Usually, pressure differentials usually push the crude oil to the surface, which is found below natural gas deposits (Patey Le Drew 2013). However, when there is low pressure within an oil deposit compared to the surface, some form of pumping mechanism is required (Patey Le Drew 2013). Consequently, pump jacks and progressive pumps act as artificial lifts, pulling crude oil to the surface (Patey Le Drew 2013).

3.2.2 Data Collection

3.2.2.1 Abundance Data

Point-count plots were used to survey breeding birds. Ten, six minute, 100-m radius point counts were conducted within each 1.6 x 1.6 km site two times per year (May to July 2010 and 2011). Plot locations were chosen using a simple random approach and were at least 300 m away from each other. Surveys were conducted between sunrise and 10:00 AM, and the visits were alternated among observers to account for variability in detectability. Observations were summed across rounds, and not averaged, to allow for negative binomial and Poisson distributions. For more details, see (Rodgers 2013)

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3.2.2.2 Nesting Occurrence and Success

Two observers flushed birds from nests by dragging thirty-metre ropes, with tin cans attached, in each study plot. This allowed observers to find the locations of nests from which the adults flushed. Two randomly selected non-overlapping 1000*100-m plots were searched for nests twice per year in the 1.6 x 1.6 km sites, which were surveyed from mid-May to August 2010-2012. At the 0.8 x 0.8 km sites, surveyed from 2012-2014, two 400*100-m plots were searched for nests three times per year from 20 May - 30 July 2012-2014. In all cases, once a nest was located, the GPS location was noted, a stake was placed at 10 m west and a plastic stake chaser at 10 m south, eggs or nestlings were counted, a nest card was filled out and photograph was taken of the nest. Monitoring of the nests occurred at 2-5 day intervals and increased to every 2-3 days when fledging was expected. We considered nests successful if at least one nestling fledged. If there were droppings or depressions at the edge of the nest when a fledgling was not found and fledging was possible based on the estimated age of the nest, or if at least one fledging was seen or heard near the nest, we assumed that nesting was successful. If there was physical evidence of nest predation, including damage of the nest or the presence of feathers, or if nestlings were absent but fledgling was possible based on the age of the nest, then we assumed nesting was unsuccessful

3.2.3 Statistical Analyses

3.2.3.1 GIS layers

The GIS layer indicating the location of the oil and gas wells was provided by Cenovus and the road and land class classification layer were retrieved from the Natural Resources Canada website (Natural Resources Canada 2012; Natural Resources Canada 2013). The oil and

gas layer contained the bottom hole location of all abandoned, suspended, drilled, potential and active wells within the study area up to December 2014. Oil and gas wells initiated after field data collection began were excluded. The road layer was generated through workshops and meetings with the relevant government entities and was published on the 31st May 2007 (Natural Resources Canada 2012). The land cover layer "circa 2000-Vector" (Land Cover Classification – LCC) was used to identified the habitat types in my study area. The Centre for Topographic Information Earth Sciences Sector Natural Resources Canada created the LCC, which is a vectorized dataset from Landsat 5 and 7 ortho-images of forested and agriculture regions in Canada (Natural Resources Canada 2013). Estimating the distance of point count plots and nests to the nearest road, shallow gas well and oil well, and estimation of shallow gas well density per 2.56 km^2, was conducted in ArcMap 10.2.1 (ESRI 2013).

Eight species were selected for analysis based on sufficient sample sizes across the studies. These species included: Baird's Sparrow, Chestnut-collared Longspur, Clay-colored Sparrow, Horned Lark, Savannah Sparrow, Sprague's Pipit, Vesper Sparrow and Western Meadowlark. Sparse data were trimmed to minimize effects of influential outliers, such that if there was less than one plot, or nest of that species, per 100 m as distance to edge increased, then all observations above that distance were excluded. The sample sizes for Baird's Sparrow, Clay-colored Sparrow and Horned Lark nests were low *(n<7)*. Consequently, they were excluded from the nesting success and clutch size analysis.

3.2.3.2 Estimating Edge Effect Distances

Data analyses were conducted in R 3.2.0 (sample code can be found in Appendix I) (R Core Team 2014). A likelihood ratio test, which compared the log-likelihoods of a negative binomial regression model and Poisson regression model, implemented using the pscl package

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(Jackman 2015), was used to assess goodness of fit for a Poisson versus negative binomial model for the abundance and clutch size data (Table 3.1).

A piecewise regression (PWR), implemented through the segmented package (GLM as input), was used to determine the distance at which there were significant changes in effects of edge on songbird abundance, nesting success and clutch size (Muggeo 2015). A piecewise regression was selected because it can estimate generalized linear relationships, which allows for non-normal distributions and can be linked with logistic exposure models (Shaffer 2004), and it could identify threshold changes in responses to distance to infrastructure. This approach was, therefore, useful for determining the footprint of each type of infrastructure. The PWR is an iterative process (Muggeo 2015), and does not require estimation of starting points for breakpoints. While the number of breakpoints was limited to one see also Thompson et al. 2015, the model was allowed to search for the position of the breakpoints. To confirm whether a PWR best described the relationship between the response variables, distance to edge and shallow gas well density, each model was compared against a Null model and a generalized linear model (GLM), which had no breakpoints. The model equations for were as follows:

Null equation

$$\mu_1 = \exp(\alpha + \beta_1)$$

$$u_2 = \frac{1}{(1 + exp^{-(\alpha+\beta_1)})}$$

Where μ_1 is the predicted relative abundance or clutch size, α is the intercept; β_1 is zero and u_2 is the probability of nesting success.

(ii) GLM equation

$$\mu_1 = \exp(\alpha + \beta_1 x_1)$$

$$u_2 = \frac{1}{(1 + exp^{-(\alpha + \beta_1 x_1)})}$$

Where μ_1 is the predicted relative abundance or clutch size, α is the intercept, β_1 is the slope/mean, x_1 is distance to oil well, distance to shallow gas well, distance to road or shallow gas well density and u_2 is the probability of nesting success.

(ii) PWR equation

$$\mu_1 = \exp(\alpha + \beta_1 x_1)$$

$$\mu_2 = \exp\{\alpha + d(\beta_1 - \beta_2) + \beta_2 x_1\}$$

$$u_3 = \frac{1}{(1 + exp^{-\{\alpha + d(\beta_1 - \beta_2) + \beta_2 x_1\}})}$$

Where μ_1 is the predicted relative abundance or clutch size before the breakpoint and μ_2 is after, α is the intercept, d is the breakpoint, β_1 and β_2 are the slope/mean before and after the breakpoint respective, x_1 is distance to oil well, distance to shallow gas well, distance to road or shallow gas well density and u_3 is the probability of nesting success.

If any of the models were within 2 AIC units of the best-fitting model, then the less complex model was selected (Arnold 2010; Thompson et al. 2015). Thus, when ΔAIC between the Null and GLM was less than 2, then the Null model was selected. If ΔAIC between the GLM and PWR was less than 2, then the GLM was selected. If the Null model was the best-fitting model, then I assumed there was no effect of distance to edge or gas well density. If the GLM was the best-fitting model and the slope was different from zero, then I assumed that there was

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an effect and the effect lasted throughout the range of my data. If the PWR was the best-fitting model and either of the slopes was different from zero, then I assumed that there was a threshold effect. When only the first slope was different from zero, then I assumed that the effect was up to the breakpoint, which suggested that the acute effect of edge was present up to breakpoint. When only the second slope or both slopes were different form zero, then I assumed that the effect lasted throughout the range of the data. The best model describing the effects of edge was then used to determine the distance at which there were effects of oil wells, shallow gas wells and roads on each response variable.

To assess how edges affected species with similar responses to fragmentation and degradation, I grouped species by life-history strategy. Obligate grassland species/obligates were Baird's Sparrow, Chestnut-collared Longspur and Sprague's Pipits. Generalist grassland species/generalists were Clay-colored Sparrows, Horned Larks, Savannah Sparrows, Vesper Sparrow and Western Meadowlark (Beason 1995; Vickery and Herkert 1995).

3.2.4 Landscape Analyses

3.2.4.1 Predicted Abundance, Clutch Size and Nesting Success

The oil well, shallow gas well and road layers were modified using Euclidian Distance to estimate distance to the nearest feature. The modified layers were raster files, where each cell was the distance to nearest edge feature (oil well, shallow gas well and road). Since the modified oil well, shallow gas well and road layers were inclusive of non-grassland areas, I clipped each modified layer using the extent of grasslands in my study area. The grassland layer was produced from the Circa 2000-Vector layer described previously.

Maps predicting abundance, clutch size and the probability of nesting success based on distance to oil well, distance to shallow gas well, distance to road, and gas well density were

created based on the equations of the best-fitting models describing effects of these landscape elements when a GLM or PWR was the best fitting model and the effect was significant. Of the 96 predictive models, 54 of the best-fitting models were GLMs, 23 were PWRs, and 19 were Nulls. If the GLM was the best-fitting model, then the model equation was applied throughout the study area. If the PWR was the best-fitting model, then the model equation for the first segment was used up to the breakpoint. After the breakpoint, the model equation for the second segment was used (Table 3.3. – Table 3.5). However, predicted values were not allowed to exceed biologically possible values, which was occasionally a risk with predictions based on linear models that exceeded distances from edge for which I had data. Predicted abundance values and clutch sizes were modified to ensure that predicted values did not exceed biologically maximum values for these variables. Maximum possible relative abundances for each species were estimated based on the maximum abundances that we observed in our data set. Thus, when distances to edge extended beyond the range of our available data, I assumed a consistent abundance that corresponded with the predicted value at the highest distance to edge available to us. To evaluate whether it was reasonable to assume that above the furthest distance used to create the model there would be little to no change in mean abundance, I used a Student's t-test to determine if there was a difference in mean abundance values at the further distances excluded from the model against the maximum predicted values from the models; there was no difference ($t = -0.005$, df = 48, p-value = 0.9961). Nonetheless, caution must be taken when interpreting results exceeding the range of values for which I have data for abundance (up to 2581 m for oil wells, 1482 m for gas wells, 1957 m for roads, and above a density of 36 per 1 x 1-mile section for gas well density). Predicted abundance estimates were back calculated to the original units [abundance per 0.031 square kilometer] using the inverse of the log-link function. Maximum

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possible clutch sizes were estimated based on maximum clutch sizes described in the published literature: Chestnut-collared Longspur – 5, Savannah Sparrow – 6 (Wheelwright & Rising, 1993), Sprague's Pipit – 6 (Robbins and Dale 1999), Vesper Sparrow – 6 (Jones and Cornley 2002) and Western Meadowlark –6 (Lanyon 1994). The nesting success estimates were converted from log odds to probability of nesting success using the inverse of logit.

In habitat suitability modeling, variables that are good indicators of habitat quality may be combined by either addition, multiplication, a minimum function model or assuming a compensatory relationship (Downey et al. 2004). Usually knowledge on how a species uses different variables in a habitat is used to inform which model equation should be used (Downey et al. 2004). However, in this case, since abundance could not exceed the maximum value predicted by the models, clutch size were limited by the maximum number of eggs a species could lay, the sum or product of nesting success should not exceed 1, and I assumed that each predictor should be equally weighted equally, then additive and multiplicative models were not suitable. Further, there were insufficient data in the literature available to determine if the effect of multiple edges were compensatory or were best described by a minimum function *a-priori* for my focal species. As such, I chose to compare the fit of the minimum function and the compensatory-arithmetic relationships to create the overall abundance, clutch size, and probability of nesting success layers. The following models were used:

(i) Minimum function$= Minimum\ (V_{OW}, V_{SGW}, V_{Road}, V_{Den})$

(ii) Compensatory $= \frac{V_{OW} + V_{SGW} + V_{Road} + V_{Den}}{n}$

Where $V_{OW}, V_{SGW}, V_{Road}, V_{Den}$ are the predicted responses associated with distance to edge or density and *n* is the number of variables. If a minimum function model had the lowest error, then this suggests that the edge feature with the most negative effect outweighs the effect of the others

on abundance, clutch size or nesting success in a plot/cell. If a compensatory model had the lowest error, then this suggests that there is a cumulative effect of distance to edge and gas well density on abundance, clutch size or nesting success in a plot/cell.

I used cross validation to compare the fit of the compensatory and minimum value models. The observed abundance, clutch size and nesting success values were used to determine the predictive error of each abundance, clutch size and probability of nesting success layer for all species. The observed values, which were used to create the Null, GLM and PWR models, were converted to a geostatistical layer using Ordinary Krigging. Ordinary Krigging is an interpolation method where it is assumed that there is an unknown mean in the data set (ESRI 2012). Furthermore, the distance between points and the spatial arrangement of observations are used to predict values in unmeasured locations (ESRI 2012). For each layer, the maximum number of neighbours to include was five, the minimum number of neighbours was two, the sector type was four and 45 degrees, the number of lags was 12, the model type was stable and no anisotropy was used. The additional parameters used for each layers can be found in Appendix II. The predicted values at each observation point were extracted from the minimum function and compensatory layer for abundance, clutch size and nesting success for each species and were compared with the geostatistical layer of observed values. To estimate the predictive error of the minimum function and compensatory layers, the root mean squared error ($\sqrt{\Sigma \ (Observed - Predicted)/n}$) was calculated. The model with the lowest error was used for subsequent productivity estimates.

3.2.4.3 Productivity Potential

I developed an index of productivity potential per raster cell using the equation $\frac{Abundance \times Clutch\ Size \times Probabilty\ of\ Nesting\ Sucess}{P_{max}}$, estimated using the minimum or compensatory

layer, whichever fit better. P_{max} was the highest possible productivity value that could occur in a

given cell. This index is a function of predicted abundance, clutch size and probability of nesting

success based on distance to three types of edge, and shallow gas well density, but does not

include habitat variables that might be critical for suitability, like the presence or absence of

exotics, and does not measure survivorship of fledglings or older individuals, or include a

measure of annual nest attempts. Thus, it could be considered a potentially useful, but not

comprehensive, measure of productivity potential of each cell. Furthermore, Baird's Sparrow,

Clay-colored Sparrow and Horned Lark were excluded from the productivity landscape analysis

because it was not possible to assess the effects of distance to edge and gas well density on

nesting success and clutch size due to small sample sizes *(n<7)*.

To evaluate the extent to which habitat availability was influenced by edge effects, the quantity

of habitat available for each species greater than or equal to productivity potentials of 25%, 50%

and 75 % were estimated. Maps were created to illustrate locations where (i) productivity was

above zero, and greater than or equal to 0.25 and 0.5 for all species; (iv) productivity was above

zero and greater than or equal to 0.25 and 0.5 for generalist grassland species and; (v)

productivity was above zero and greater than or equal to 0.25 and 0.5 for obligate grassland

species. Productivity estimates based on life-history patterns were pooled and a single analysis

was done to estimate the effect of edge on obligates and generalists. Productivity estimates were

not estimated for Baird's Sparrow, Clay-colored Sparrow and Horned Lark.

3.2.4.2 Footprint of Oil Wells, Shallow Gas Wells and Roads

       To determine the proportion of the habitat affected by edge, the total area of grassland

habitat below the threshold for the best-fitting GLM or PWR each threshold (the breakpoint

/maximum value in my data) was estimated. The available habitat was estimated from the

grassland layer extracted from the LCC. Footprint estimates based on life-history patterns were pooled and a single analysis was done to estimate the effect of edge on obligates and generalists. To compare the species-specific footprints of oil wells relative to shallow gas wells within our study area, I also calculated the ecological footprints relative to power produced. Power, measured as the total horsepower produced by a typical well per hour, was divided by the amount of habitat affected overall by one well, resulting in a power/edge effect ratio. The amount of habitat was estimated by calculating a circular area around a well, where the radius was equal to the breakpoint / maximum values used to create the model. The power estimates were derived from production outputs from Cenovous' Rosemary plant in Brooks Alberta (Cenovus, 2015, unpublished data).

3.3 Results

3.3.1 Edge Effects

There were thresholds, in some cases, in the effect of distance to edge and gas well density on abundance, clutch size and nesting success (Table 3.2, Table 3.3. and Table 3.3). In 66 cases, there was no effect of distance to edge or shallow gas well density since the best fitting model was the Null model or the slopes for either the PWR or GLM were not different from zero. There were 15 cases when the effect of distance to edge or density lasted throughout the range of my data, 8 cases when it lasted up to the threshold and 10 when it lasted beyond the threshold. As such, in most cases, the effects of edge extended far away from edges, when they were present.

3.3.1.1 Abundance

The GLM was the best-fitting model for Baird's Sparrow, Horned Lark and Western Meadowlark abundance, while the PWR was best for Chestnut-collared Longspur, Clay-colored Sparrow, Savannah Sparrow, Sprague's Pipit and Vesper Sparrow abundance on distance to oil wells (Table 3.2, Table 3.5, Figure 3.2). However, Baird' Sparrow, Horned Lark, Chestnut-collared Longspur, Clay-colored Sparrow and Western Meadowlark abundance were not significantly affected by distance to oil well (Table 3.5). There was no effect of distance to oil well on Savannah Sparrow abundance up to 1190.00 m; thereafter, abundance increased. Conversely, there was no effect of distance to oil well on Sprague's Pipits above 149.30 m and abundance was higher further away from wells.

The GLM best described how Baird's Sparrow, Clay-colored Sparrow and Savannah Sparrow were affected by distance to shallow gas wells, while the PWR was best suited for Chestnut-colored Longspur, Horned Lark, Savannah Sparrow, Sprague's Pipit, Vesper Sparrow and Western Meadowlark (Table 3.2, Table 3.5, Figure 3.3). Horned Lark and Savannah Sparrow abundance were not significantly affected by distance to shallow gas wells. Both Baird's Sparrow and Clay-colored Sparrow abundance was higher closer to gas wells and declined significantly with increasing distance. Below 247.20 m and 804.50 m, Chestnut-collared Longspur and Western Meadowlark abundance increased sharply further away from wells, but was unchanged thereafter. Vesper Sparrow abundance was also unchanged above 35.60 m, but was higher closer to wells. Sprague's Pipit abundance peaked at 760.40 m, and then declined afterwards.

The effect of distance to road on Baird's Sparrow, Clay-colored Sparrow, Vesper Sparrow and Western Meadowlark abundance was best described by the GLM, Chestnut-

collared Longspur, Horned Lark, Savannah Sparrow, Sprague's Pipit and Vesper Sparrow was best fitted by the threshold model (Table 3.2, Table 3.5, Figure 3.4). Chestnut-collared Longspur, Horned Lark and Meadowlark abundance were not affected by distance to road. However, Clay-colored Sparrow abundance declined with increasing distance from roads. Conversely, the abundance of Baird's Sparrow was higher further away from road, Similarly, there was no effect of distance to road on Savannah Sparrow abundance above 1120.00 m, but abundance was higher closer to roads. Conversely, there was no effect of roads on Chestnut-collared Longspur abundance until 44.57 m, and above this distance, abundance increased as proximity to roads decreased.

The Null model was the best fitting model for Clay-colored Sparrow, Horned Lark and Vesper Sparrow abundance versus shallow gas well density, while the effects on Baird's Sparrow and Sprague's Pipit abundance were best fitted by the PWR and Chestnut-collared Longspur, Savannah Sparrow and Western Meadowlark abundance were best-fitted by the GLM (Table 3.2, Table 3.5, Figure 3.5). In addition, the effect of gas well density Savannah Sparrow was not significant. Chestnut-collared Longspur, Savannah Sparrow and Western Meadowlark abundance were higher at lower gas well densities. However, Baird's Sparrow and Sprague's Pipit declined significantly when the number of gas wells per section exceeded 6.08 and 5.95 wellheads per section respectively.

3.3.1.2 Clutch Size

The effect of distance to oil well on Chestnut-collared Longspur, Sprague's Pipit, Vesper Sparrow and Western Meadowlark clutch sizes were best fitted by the GLM on Savannah Sparrow was best modeled by the PWR (Table 3.3, Table 3.6, Figure 3.6). Chestnut-collared, Vesper Sparrow, Sprague's Pipit and Western Meadowlark clutch sizes were not affected by

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distance to oil well. However, Savannah Sparrow clutch size was higher nearer to oil wells and there was no effect above 2727.00 m.

The Null model was the best-fitting model for Western Meadowlark clutch size and distance to shallow gas well, but the effect on Sprague's Pipit and Vesper Sparrow clutch size were best modeled by the GLM and Chestnut-collared Longspur, Savannah Sparrow and Vesper Sparrow by the PWR (Table 3.3, Table 3.6, Figure 3.7). The effect of distance to shallow gas well on Vesper Sparrow clutch size was not significant Sprague's Pipit and Vesper Sparrow clutch sizes were higher further away from wells. While there was no effect of distance to gas wells above 35.35 m for Chestnut-collared Longspur, and clutch sizes were higher further away from wells, Savannah Sparrow abundance declined only above 1652.00 m, and before that, there was no effect.

The GLM and Savannah Sparrow best fit the effect of distance to road on Chestnut-collared Longspur, Sprague's Pipit, Vesper Sparrow and Western Meadowlark clutch size (Table 3.3, Table 3.6, Figure 3.8). The effect of distance to road on Chestnut-collared Longspur and Western Meadowlark clutch size was not significant. However, Vesper Sparrow clutch size was higher nearer to roads. While there was no effect of distance to road below 390.00 m, above the said distance, clutch size declined sharply for Savannah Sparrow.

The Null model was the best-fitting model for Chestnut-collared longspur, Vesper Sparrow and Western Meadowlark clutch size, while the effect on Savannah Sparrow and Sprague's Pipit was best fitted by the PWR model for shallow gas well density (Table 3.3, Table 3.6, Figure 3.9). The effect of gas well density on Sprague's Pipit clutch size was not significant Savannah Sparrow clutch size was unaffected by gas well density below 14.94 gas wells per section, but above this density, there was a large decline in clutch size.

3.3.1.3 Nesting Success

The GLM was the best-fitting model for Chestnut-collared Longspur, Savannah Sparrow, Sprague's Pipit and Vesper Sparrow and Western Meadowlark clutch size versus distance to oil well. (Table 3.4, Table 3.7, Figure 3.10). The effect of distance to oil well on Chestnut-collared Longspur, Sprague's Pipit and Vesper Sparrow nesting success was not significant. However, Savannah Sparrow nesting success was higher further away from oil wells. Conversely, Western Meadowlark nesting success was lower further away from oil wells.

The Null model was the best-fitting model for Western Meadowlark nesting success versus distance to shallow gas well, while the GLM was best suited for the effects on Chestnut-collared Longspur, Sprague's Pipit and Vesper Sparrow and PWR for Savannah Sparrow (Table 3.4, Table 3.7, Figure 3.11). The effect of distance to shallow gas well on Sprague's Pipit and Vesper Sparrow nesting success was not significant. Above 210.00 m, the probability of nesting success increased for Chestnut-collared Longspur. On the other hand, the probability of nesting success for Savannah Sparrow increased as proximity to shallow gas well increased until 2167.00 m where there was no change above this distance.

The GLM was the best-fitting model for Chestnut-collared Longspur, Savannah Sparrow, Sprague's Pipit Vesper Sparrow and Western Meadowlark clutch size versus road (Table 3.4, Table 3.7). Additionally, the effect of distance to road on Chestnut-collared Longspur, Savannah Sparrow, Sprague's Pipit and Vesper Sparrow and Western Meadowlark nesting success was not significant.

The Null model was the best-fitting model for Savannah Sparrow, Sprague's Pipit and Western Meadowlark nesting success versus gas well density, while the GLM was best suited for Chestnut-collared Longspur and PWR for Vesper Sparrow (Table 3.4, Table 3.7, Figure 3.13).

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Chestnut-collared Longspur nesting success declined with increasing gas well density. Similarly, Vesper Sparrow nesting success declined as gas well density increased up to and beyond 14.45 gas wells per section.

3.3.2 Distance to the Effect of Edge

The distance to which there was an effect of distance to edge and density varied among species and independent variables (Table 3.8). On average, the effect of roads extended to the furthest distance of 1655.43 m $\pm$ 404.75, followed by shallow gas wells at 1383.59 m $\pm$ 542.56 and oil wells at 851.01 m $\pm$ 1277.47. The average density to which there was an effect of gas wells was 33.87 per 2.56 km^2 $\pm$ 6.43.

The average distance to which there was an effect of edge was similar for obligate and generalist species. For obligate species, on average, the effect of roads extended to farthest distances, 1627.00 m $\pm$ 572.1, and the effect of shallow gas wells extended to 1375.00 m $\pm$ 212.41. Since there was only one model for distance to oil wells for obligates, an average distance could not be evaluated because there were no other species showing edge effects. For generalist species, road effects extended to the furthest average distance of 16584.00 m $\pm$ 350.63 followed by oil wells at 1553.00 m $\pm$ 284.76 and shallow gas wells 1392.00 m $\pm$ 542.563. The density to which there was an effect for obligates was 36 per 2.56 km^2 $\pm$ 0 and 32 per 2.56 km^2 $\pm$ 6.43 for generalists.

3.3.3. Quantity of Habitat Affected by and Footprint of Oil Wells, Shallow Gas Wells and Roads

3.3.3.1. Quantity Of Habitat Affected by Oil Wells, Shallow Gas Wells and Roads

Obligate species had a larger portion of habitat affected by edge when compared to generalist species, as predicted. Overall, effects of oil wells, shallow gas wells and roads affected

48.26 % of grassland in the study area. For obligate species, 64.76 % of the available habitat was affected by edge, whereas 48.92 % of generalist habitat was affected.

The quantity of habitat affected by oil wells, shallow gas wells and roads varied across species (Table 3.8). As, predicted, in general, shallow gas wells had a larger effect than oil wells since 56.82 % of the available habitat was affected, where as 14.12 % was affected by oil wells. Roads affected 73.84 % of the available habitat.

3.3.3.2 Footprint of Oil and Gas Wells

Though the energetic yield of a typical shallow gas well was greater, the footprint was smaller than oil wells. The power from one shallow gas well was estimated at 8671.13 hp/h, while an oil well produces, on average, 65.14 hp/h. As averaged across all species' abundance, clutch size and nesting success in response to distance to wells, 9. 18 km^2 ± 11.84 was affected by an oil well and 7.14 km^2 ± 4.45 by a shallow gas well. Consequently, the average quantity of habitat affected per unit of energy produced was 1.41 x 10^{-1} km^2 /hp/h for oil wells and 8.24 x 10^{-4} km^2 /hp/h for shallow gas wells, which suggests that a larger extent of habitat is affected by oil wells per unit of energy produced.

3.3.4 Predictive Maps

3.3.4.1 Prediction Error

In most cases, the maps created using a compensatory relationship outperformed the maps based on a minimum function (Table 3.9). However, the average predictive error (root mean square) assuming a compensatory relationship was 1.56, compared with 1.48 assuming a minimum function relationship. The minimum function and compensatory models were not used for Chestnut-collared Longspur clutch size, Vesper Sparrow clutch size, Vesper Sparrow nesting

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success and Western Meadowlark nesting success because there was only one predictor. Additionally, no layer was created for Western Meadowlark clutch size or Sprague's Pipit nesting success because there was no predictor with a significant effect.

3.3.4.2 Productivity Potential

Though the quantity of productive habitat varied with species, obligate species had more medium and poor quality habitat than generalist species (Table 3.10, Figure 3.13-Figure 3.17). Overall, 90.47 % of the available habitat was of low or poor quality for both generalists and obligates. For generalists, 50.42 % was poor and 44.52% was low. Similarly, 34.48 % of the available habitat was poor and 51.55 % was low for obligates. Only, 0.37 % of the available habitat was of medium quality for generalists, where as 13.90% was productive for obligates. Generalists had a greater quantity of high quality habitat than obligates (generalists –4.69 %, obligates–0.06%).

On average, obligate species had a larger quantity of shared productive habitat (Table 3.11, Figure 3.18-Figure 3.23). Above a productivity of zero, the entirety of the available habitat was productive for generalists, while 53.97 % was productive for all obligate species combined. Conversely, at and above 0.25, generalist species had less productive habitat (generalists –13.7 %, obligates–44.97%). At an above a productivity of 0.5, however, there was no productive habitat for generalist, while 2.34% of the available habitat was productive at that value for obligates. However, above 0.75, neither generalist had productive habitat. Also, there were no locations within the study area where all species had productivity values above 0.75, 0.5 or 0.25, but above 0, 50.95% was commonly productive for all focal species.

3.4 Discussion

In many cases, thresholds were evident in the response of grassland passerines to distance to oil wells, shallow gas wells, roads, and density of shallow gas wells. In cases where thresholds were not found, it is possible that they did exist at a further distance (beyond 2581 m for oil wells, 1482 m for gas wells, 1957 m for roads, and above a density of 36 per 1 x 1-mile section for gas well density), but the absence of observations at such distances made it impossible to detect them. Obligate species had a larger portion of their habitat affected by infrastructure when compared to generalist species, and had lower productivity near edge, as predicted. Furthermore, at the landscape scale, the quantity of habitat affected by edge associated with shallow gas wells was larger than that for oil wells, as shallow gas wells are found at higher densities.

Overall, obligate passerines had low productivity in the study area and closer to edge. Many obligates require large, continuous tracks of undisturbed habitat (Robbins and Dale 1999; Green et al. 2002). In the case of Chestnut-collared Longspurs, which are associated with areas that were recently disturbed by fire or grazing because they prefer sparse vegetation (Hill and Gould 1997) the disturbances around wells and roads cause higher occurrences of fast growing exotics, which they avoid (Riley et al. 2012). When wells are installed, disturbances associated with visitation for maintenance, removal of native vegetation and increases in road densities for well access can lower habitat quality for obligates (Riley et al. 2012; Koper et al. 2014). Furthermore, noises associated with oil wells and roads could increase their footprint beyond the degraded vegetation that occur when they are installed/ created (Reijnen and Foppen 1995; Habib et al. 2007; Bayne et al. 2008).

Similarly, generalist species had low productivity in the study area, but higher productivity closer to edge, although the effect of edge on abundance, clutch size and nesting success varied among species. Although generalist species are able to occupy an array of habitat

types, such as exotic vegetation found near wells and roads because they utilise diverse prey and food resources (Wheelwright and Rising 1993; Knapton 1994; Jones and Cornely 2002), there was still a negative effect of infrastructure, in many cases. While Savannah Sparrow abundance was higher further away from edge, suggesting a negative effect, clutch size decreased with increasing proximity to edge. Conversely, Vesper Sparrow abundance was low throughout the study area, and even more so further away from edge, and clutch size increased when proximity to edge decreased. Since birds produce lower clutch sizes when foraging opportunities are low (Ost et al. 2008), it is plausible that in the study area, there were more foraging opportunities for generalists in areas where there less birds (closer to edge for Savannah Sparrows and further away for Vesper Sparrow). In many cases, nesting success was higher closer to edge, which is unexpected because nestling predation is largest cause of nest failure (Finch 1989; Klug et al. 2009; Ribic et al. 2012), and predation risk is often higher close to edge (Ribic et al. 2012). However, predicted nesting success was high (above 0.5) for both obligates and generalists, which suggests little effect of distance to edge and or little nestling predation. Western Meadowlark clutch size was unaffected by distance to edge and there was a similar effect of edge on abundance when compared to obligates, which could explain their higher overall productivity. Thus, the low overall productivity for generalist could be attributed to higher predicted clutch sizes in areas where abundance was low.

Roads can fragment habitat to a greater extent than oil and shallow gas wells because they are linear features, which could explain their higher threshold value. Roads act as corridors for predators (Ingelfinger and Anderson 2004;Wellicome and Kardynal 2014), are associated with noise from traffic (Reijnen and Foppen 1995), occupy more space and are associated with invasive vegetation (Ingelfinger and Anderson 2004). Additionally, traffic noises can negatively

affect clutch size (Halfwerk et al. 2011), and closer to roads, the probability of nesting success is lower (Summers et al. 2011), perhaps due to higher occurrences of parent mortality (Kuitunen et al. 1998; Mumme et al. 2000; Jack et al. 2015). As such, disturbances associated with roads can have negative effects on grassland birds, particularly obligate species. Thus, grassland obligates, such as Baird's Sparrows, Sprague Pipits, McCown's Longspurs and Chestnut-collared Longspurs, are more abundant at off-road sites (Wellicome and Kardynal 2014) and are less abundant closer to roads (Sliwinski and Koper 2012). Though I found lower abundances of obligates near to roads, there was no effect on clutch size, which has been previously reported (Summers et al. 2011). Further, a majority of the study sites were in low traffic areas, which may also explain the positive effect of roads on nesting success, in some cases, or no effect, in others. Roads with higher traffic volumes may have greater, and more consistently negative, effects on grassland birds.

The distance to which there was an effect of edge was similar for oil wells, gas wells and roads for generalist species. Though the effect of roads and oil wells might be similar as both are associated with increased noise and changes in vegetation structure, in contrast to my results, the footprint of shallow gas wells was predicted to be relatively small because such disturbances are not associated with them. Gas wells are found at higher densities than oil wells, and cattle occurrences are higher around gas wells (Koper et al. 2014). Thus, changes in litter depth and height, which are due in part to the presence of cattle, can extend the footprint of gas wells beyond the area that was disturbed to install the well (Koper et al. 2014) up to similar distances with roads and oil wells.

Studies have suggested that vegetation and associated disturbances from roads are major contributors to the negative effects of oil and gas infrastructure, and help to explain responses

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among species. In other research, the influence of vegetation structure was found to be larger than density of or proximity to gas wells (Kalyn Bogard and Davis 2014), explaining lower abundances of Grasshopper Sparrows, Chestnut-collared Longspurs, McCown's Longspurs and Sprague's Pipits near shallow gas wells (Hamilton et al. 2011). Interestingly, on wintering grounds, Western Meadowlarks and Eastern Meadowlarks (*Sturnella magna*) were found more frequently at active oil well sites, perhaps because vegetation characteristics were more favorable (Lawson et al. 2011). Furthermore, there have been mixed responses (nesting and fledgling success) of Baird's Sparrows, Sprague's Pipits, Savannah Sparrows and Western Meadowlarks to distance to oil wells, gas wells and roads, possibly attributed to the varying effects of crested wheatgrass, which is negative on obligates (Ludlow et al. 2015). On the other hand, roads are known to have negative impacts on grassland songbirds (Forman et al. 2002; Ingelfinger and Anderson 2004; Wellicome and Kardynal 2014), but other studies have not quantified the combined effects of roads and wells on the abundance, clutch size and nesting success of songbirds or estimated thresholds in response to distance to such edges or gas well density.

The scope of the results of this study is limited due to the assumptions about roads and vegetation characteristics and type of model used. Firstly, noise from roads and wells have been found to affect grassland birds (Blickley et al. 2012). However, such effects were not quantified in this study or the variable effects of high impact or low impact roads. Thus, it was assumed that the effects of all roads were equal, regardless of frequency of use or size. Secondly, though the sites in this study have little to minimal crested wheatgrass, which has negative effects on Sprague's Pipits and Baird's Sparrows (Ludlow et al. 2015), there are large amounts in other areas within the study. Thus, the models used to create the predictive maps incorrectly assume similar vegetation characteristics and structures across the landscape, which might result in an

overestimation of habitat suitability for Baird's Sparrows and Sprague's Pipits. Thirdly, although all sites in this study were at least 2 km away from cropland edges, there are documented effects of croplands on grassland songbirds. For example, the density of Horned Larks are higher in cultivated areas (Owens and Myres 1973), and Sprague's Pipits and Chestnut-collared Longspurs avoid croplands up to 0.91 and 1.95 km respectively (Sliwinski and Koper 2012). Lastly, it might be difficult to infer the thresholds found in this study to other regions since thresholds often vary among populations (Johnson 2013). For instance, a threshold model best described the population dynamics of breeding birds in a forested areas in one region, but a study conducted in a neighbouring area found no support for threshold models (van der Hoek et al. 2013). Since habitat amount and vegetation characteristic vary in the Northern plains (Barker and Whitman 1988), it might not be possible to generalize the effects of distance to edge in this study to other regions.

A large quantity of habitat was affected by edge and the distance to which there was effect of edge extend to distances beyond 1000 m, which have very strong management implications. More than close 50% of obligate and generalist habitat were affected by energy infrastructure, and obligate habitat was affected to greater extent. Thresholds have been reported within 500 m of energy infrastructure for songbird abundance (Thompson et al. 2015) and beyond 1000 m from edge (Sliwinski and Koper 2012). Since Baird's Sparrow, Chestnut-collared Longspur and Sprague's Pipit are listed under the Species at Risk Act in Canada (COSEWIC 2009; COSEWIC 2010b; COSEWIC 2012), minimizing the impacts of development are critical in promoting recovery, especially in undisturbed areas.

It was difficult to identify habitat where productivity was high for all species because ideal habitat varied. For instance, Savannah Sparrows are associated select for habitat with a high

density of ground layer vegetation (Wiens 1969), where as Chestnut-collared Longspurs occurrence is more in areas with short, sparse ground vegetation (Hill and Gould 1997).Though the presumed habitat heterogeneity in large patches could potentially support various species (Freemark and Merriam 1986), a large quantity of habitat was affected by infrastructure limiting the prevalence of such areas. However, obligate species shared much productive habitat, which suggest that it might be possible to apply management strategies that benefit Sprague's Pipits and Chestnut-collared Longspur. Such strategies, conversely, might not benefit all the focal species in my study equally.

Though many assumptions limit the scope of the results, it is apparent that roads have the largest overall effect on generalist species, notwithstanding the comparably large effects of oil wells and roads. Given the correlations between grazers and shallow gas wells (Koper et al. 2014), reducing the footprints of gas wells, and probably oil wells, must involve management of grazers. Since the quantity of habitat affected by shallow gas wells per unit of energy produced is lower than oil wells, shallow gas may be relatively environmentally sustainable.

Though some generalist species had higher productivity closer to edge, they are more vulnerable to nest predators especially when nest cover is compromised along edges (Winter et al. 2005). Furthermore, Alberta is has the third largest crude oil resource and is the third largest natural gas producer worldwide (Government of Alberta 2015), and 10,000 to 15,0000 new wells are drilled each year (Government of Alberta 2014b). As such, improving habitat by limiting fragmentation, the spread of non-native vegetation and managing stocking rates to ensure that nest cover is not comprised could benefit generalist species, and would also promote productivity for obligate species.

The findings from this study confirm that there are effects of oil and gas infrastructure on grassland songbirds at the landscape scale, but these effects vary between species. Since abundance is not always a good indicator of habitat quality, the combined measure of productivity, including the estimated distances at which there are effects of edge, provided additional detail on habitat suitability. Furthermore, though the estimated threshold distances could vary if measured in a different region, they could be used to identify areas where additional disturbances should be avoided since the effects of existing infrastructure do not to extend to these areas. However, it would be useful to repeat observations at distances beyond the maximum distance used in this study to determine the threshold values since in some cases, the effects of edge lasted throughout the range of my data.

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Table 3.1. Goodness-of-fit Tests for abundance and clutch size assuming Poisson (P) and negative binomial distributions (NB) for distance to oil well, distance to shallow gas well and distance to road. A likelihood ratio test for non-normal distributions, implemented by OdTest (Lawless 1987; Cameron and Trivedi 2003), was used to determine if negative binomial was a better fit than Poisson. If the p-value was less than alpha (0.1), then it was assumed that negative binomial was a better fit than Poisson.

Response	Species	Error Distribution Used	Likelihood Ratio Test (OdTest) NB versus P
Abundance	Baird's Sparrow	Negative Binomial	2.20E-16
	Chestnut-collared Longspur	Negative Binomial	2.20E-16
	Clay-colored Sparrow	Negative Binomial	2.20E-16
	Horned Lark	Negative Binomial	2.20E-16
	Savannah Sparrow	Negative Binomial	2.20E-16
	Sprague's Pipit	Negative Binomial	2.20E-16
	Vesper Sparrow	Negative Binomial	2.20E-16
	Western Meadowlark	Negative Binomial	2.20E-16
Clutch Size	Chestnut-collared Longspur	Poisson	0.04542
	Savannah Sparrow	Poisson	0.5
	Sprague's Pipit	Poisson	0.5
	Vesper Sparrow	Poisson	0.5
	Western Meadowlark	Poisson	0.09048

Table 3.2. AIC and Δ *AIC* values for NULL, GLM and PWR models for abundance, where BAIS is Baird's Sparrow (*Ammodramus bairdii*), CCLO is Chestnut-collared Longspurs (*Calcarius ornatus*), SAVS is Savannah Sparrow (*Passerculus sandwichensis*), SPPI is Sprague's Pipits (*Anthus spragueii*), VESP is Vesper Sparrows (*Pooecetes gramineus*) and WEME is Western Meadowlark (*Sturnella neglecta*).

Predictor	Species	Best-Fitting-Model	NULL AIC	NULL Δ *AIC*	GLM AIC	GLM Δ *AIC*	PWR AIC	PWR Δ *AIC*
Distance to Oil Well	BAIS	GLM	2786.9	374	2412.9	0	2413	0.1
Distance to Road	BAIS	GLM	2786.9	279.9	2508.5	1.5	2507	0
Distance to Shallow Gas Well	BAIS	GLM	2786.9	101.4	2685.5	0	2686.6	1.1
Shallow Gas Well Density	BAIS	PWR	2786.9	11.2	2784.3	8.6	2775.7	0
Distance to Oil Well	CCLO	GLM	3317.8	405.7	2912.2	0.1	2912.1	0
Distance to Road	CCLO	PWR	3317.8	306.8	3015.9	4.9	3011	0
Distance to Shallow Gas Well	CCLO	PWR	3317.8	72.2	3250.6	5	3245.6	0
Shallow Gas Well Density	CCLO	GLM	3317.8	15.087	3304.295	1.582	3302.713	0
Distance to Oil Well	CCSP	GLM	961.52	85.26	877.63	1.37	876.26	0
Distance to Road	CCSP	GLM	961.52	46.62	914.9	0	915.8	0.9
Distance to Shallow Gas Well	CCSP	GLM	961.52	29.09	932.43	0	933.85	1.42
Shallow Gas Well Density	CCSP	NULL	961.52	0	962.89	1.37	964.53	3.01
Distance to Oil Well	HOLA	GLM	1500.9	179.4	1321.5	0	1322.7	1.2
Distance to Road	HOLA	PWR	1500.9	101.2	1402.6	2.9	1399.7	0
Distance to Shallow Gas Well	HOLA	PWR	1500.9	31.1	1476.2	6.4	1469.8	0
Shallow Gas Well Density	HOLA	NULL	1500.9	0	1502.1	1.2	-	-
Distance to Oil Well	SAVS	PWR	3554.4	416.7	3139.8	2.1	3137.7	0
Distance to Road	SAVS	PWR	3554.4	296.4	3261.1	3.1	3258	0
Distance to Shallow Gas Well	SAVS	GLM	3554.4	125.7	3428.9	0.2	3428.7	0
Shallow Gas Well Density	SAVS	GLM	3554.4	6.3	3549	0.9	3548.1	0
Distance to Oil Well	SPPI	PWR	2673.4	337.8	2344.5	8.9	2335.6	0
Distance to Road	SPPI	GLM	2673.4	230.3	2445	1.9	2443.1	0

Distance to Shallow Gas Well	SPPI	PWR	2673.4	90.7	2591	8.3	2582.7	0
Shallow Gas Well Density	SPPI	PWR	2673.4	11.7	2664.1	2.4	2661.7	0
Distance to Oil Well	VESP	PWR	1142.068	174.358	971.1246	3.4146	967.71	0
Distance to Road	VESP	GLM	1142.068	98.768	1043.6	0.3	1043.3	0
Distance to Shallow Gas Well	VESP	PWR	1142.068	78.568	1065.773	2.273	1063.5	0
Shallow Gas Well Density	VESP	NULL	1142.068	0	1143.379	1.311	1144.3	2.232
Distance to Oil Well	WEME	GLM	2582.4	327.8	2254.6	0	2255.2	0.6
Distance to Road	WEME	GLM	2582.4	215.9	2366.5	0	2367.1	0.6
Distance to Shallow Gas Well	WEME	PWR	2582.4	97.6	2489	4.2	2484.8	0
Shallow Gas Well Density	WEME	GLM	2582.4	9.8	2573.5	0.9	2572.6	0

Table 3.3. AIC and Δ *AIC* values for NULL, GLM and PWR models for clutch size, where CCLO is Chestnut-collared Longspurs (*Calcarius ornatus*), SAVS is Savannah Sparrow (*Passerculus sandwichensis*), SPPI is Sprague's Pipits (*Anthus spragueii*), VESP is Vesper Sparrows (*Pooecetes gramineus)*.

Predictor	Species	Best-Fitting-Model	NULL		GLM		PWR	
			AIC	Δ *AIC*	AIC	Δ *AIC*	AIC	Δ *AIC*
Distance to Oil Well	CCLO	GLM	1037.864	116.7188	921.1452	0	922.5021	1.3569
Distance to Road	CCLO	GLM	1037.864	63.8605	974.0035	0	974.6632	0.6597
Distance to Shallow Gas Well	CCLO	PWR	1037.864	43.5283	1010.359	16.0233	994.3357	0
Shallow Gas Well Density	CCLO	NULL	1037.864	0	1039.853	1.989	-	-
Distance to Oil Well	SAVS	PWR	2602.996	45.765	2561.132	3.901	2557.231	0
Distance to Road	SAVS	PWR	2602.996	93.61	2523.712	14.326	2509.386	0
Distance to Shallow Gas Well	SAVS	PWR	2602.996	16.617	2591.904	5.525	2586.379	0
Shallow Gas Well Density	SAVS	PWR	2602.996	3.492	2604.401	4.897	2599.504	0
Distance to Oil Well	SPPI	GLM	202.8959	56.9231	145.9728	0	148.3202	2.3474
Distance to Road	SPPI	GLM	202.8959	36.477	166.4189	0	-	-
Distance to Shallow Gas Well	SPPI	GLM	202.8959	3.0994	199.7965	0	201.0989	1.3024
Shallow Gas Well Density	SPPI	PWR	202.8959	21.4286	200.8655	19.3982	181.4673	0
Distance to Oil Well	VESP	GLM	524.4848	66.8697	457.6151	0	497.5793	39.9642
Distance to Road	VESP	GLM	524.4848	10.1156	514.3692	0	576.7183	62.3491
Distance to Shallow Gas Well	VESP	GLM	524.4848	56.6329	467.8519	0	526.865	59.0131
Shallow Gas Well Density	VESP	NULL	524.4848	0	526.4375	1.9527	580.5725	56.0877
Distance to Oil Well	WEME	GLM	261.1408	62.4487	198.6921	0	-	-
Distance to Road	WEME	GLM	261.1408	2.3996	258.7412	0	261.2267	2.4855
Distance to Shallow Gas Well	WEME	NULL	261.1408	0	262.8826	1.7418	-	-
Shallow Gas Well Density	WEME	NULL	261.1408	0	263.1352	1.9944	262.4858	1.345

Table 3.4. AIC and Δ *AIC* values for NULL, GLM and PWR models for nesting success, where CCLO is Chestnut-collared Longspurs (*Calcarius ornatus*), SAVS is Savannah Sparrow (*Passerculus sandwichensis*), SPPI is Sprague's Pipits (*Anthus spragueii*), VESP is Vesper Sparrows (*Pooecetes gramineus*).

Predictor	Species	Best-Fitting-Model	NULL		GLM		PWR	
			AIC	Δ *AIC*	AIC	Δ *AIC*	AIC	Δ *AIC*
Distance to Oil Well	CCLO	GLM	576.26	67.5633	509.88	1.1833	508.6967	0
Distance to Road	CCLO	GLM	576.26	56.12	520.14	0	520.5	0.36
Distance to Shallow Gas Well	CCLO	PWR	576.26	23.87	554.56	2.17	552.39	0
Shallow Gas Well Density	CCLO	GLM	576.26	6.34	569.92	0	570.32	0.4
Distance to Oil Well	SAVS	GLM	1481.3	28.011	1453.6	0.311	1453.289	0
Distance to Road	SAVS	GLM	1481.3	47.434	1433.988	0.122	1433.866	0
Distance to Shallow Gas Well	SAVS	PWR	1481.3	20.373	1464.4	3.473	1460.927	0
Shallow Gas Well Density	SAVS	NULL	1481.3	0.9	1480.4	0	-	-
Distance to Oil Well	SPPI	GLM	109.8	64.6753	46.017	0.8923	45.1247	0
Distance to Road	SPPI	GLM	109.8	6.87	103.45	0.52	102.93	0
Distance to Shallow Gas Well	SPPI	GLM	109.8	8.06	101.74	0	-	-
Shallow Gas Well Density	SPPI	NULL	109.8	0	111.57	1.77	-	-
Distance to Oil Well	VESP	GLM	349.14	93.61	255.53	0	258.6047	3.0747
Distance to Road	VESP	GLM	349.14	30.39	318.75	0	320.5393	1.7893
Distance to Shallow Gas Well	VESP	GLM	349.14	48.14	301	0	302.2021	1.2021
Shallow Gas Well Density	VESP	PWR	349.14	2.2212	349.72	2.8012	346.9188	0
Distance to Oil Well	WEME	GLM	171.98	71.11	101.84	0.97	100.87	0
Distance to Road	WEME	GLM	171.98	10.37	161.61	0	162.17	0.56
Distance to Shallow Gas Well	WEME	NULL	171.98	0	173.14	1.16	173.3589	1.3789
Shallow Gas Well Density	WEME	NULL	171.98	0	173.95	1.97	175.95	3.97

Table 3.5. Parameters for best-fitting models for abundance, which include β, β_2 (slopes), C_1, C_2 (intercepts) and UCL, UCL_2 and LCL, LCL_2 (upper and lower confidence intervals for the slope), where BAIS is Baird's Sparrow (*Ammodramus bairdii*), CCLO is Chestnut-collared Longspurs (*Calcarius ornatus*), SAVS is Savannah Sparrow (*Passerculus sandwichensis*), SPPI is Sprague's Pipits (*Anthus spragueii*), VESP is Vesper Sparrows (*Pooecetes gramineus*) and WEME is Western Meadowlark (*Sturnella neglecta*). Shaded values indicate that the slope was different from zero.

Predictor	Species	Model	β	UCL	LCL	β_2	UCL_2	LCL_2	C_1	C_2
Distance to Oil Well	BAIS	GLM	-6.08E-07	1.28E-04	-1.29E-04	-	-	-	0.81	-
Distance to Road	BAIS	GLM	3.35E-04	4.90E-04	1.80E-04	-	-	-	0.56	-
Distance to Shallow Gas Well	BAIS	GLM	-2.84E-04	-5.20E-05	-5.17E-04	-	-	-	0.94	-
Shallow Gas Well Density	BAIS	PWR	1.15E-01	2.65E-01	-3.61E-02	-2.71E-02	-1.56E-02	-3.87E-02	0.69	1.11
Distance to Oil Well	CCLO	GLM	-3.88E-06	6.58E-05	-7.36E-05	-	-	-	1.32	-
Distance to Road	CCLO	PWR	3.45E-01	2.16E+02	-2.15E+02	2.27E-04	3.78E-04	7.56E-05	-18.47	1.14
Distance to Shallow Gas Well	CCLO	PWR	2.07E-03	3.36E-03	7.71E-04	-1.48E-04	1.29E-04	-4.25E-04	0.95	1.49
Shallow Gas Well Density	CCLO	GLM	-3.20E-02	-1.97E-02	-4.44E-02	-	-	-	1.50	-
Distance to Oil Well	CCSP	GLM	-2.10E-04	-3.63E-05	-3.83E-04	-	-	-	-0.74	-
Distance to Road	CCSP	GLM	-1.39E-02	-2.98E-04	-1.16E-03	-	-	-	-0.95	-
Distance to Shallow Gas Well	CCSP	GLM	-7.27E-04	-1.01E-04	-1.44E-03	-	-	-	-0.51	-
Distance to Oil Well	HOLA	GLM	-1.48E-04	4.86E-05	-3.45E-04	-	-	-	-0.28	-
Distance to Road	HOLA	PWR	2.18E+00	4.70E+02	-4.65E+02	-1.05E-04	1.27E-04	-3.36E-04	-139.60	-0.34
Distance to Shallow Gas Well	HOLA	PWR	9.71E+00	4.09E+03	-4.07E+03	3.81E-05	3.63E-04	-2.87E-04	-48.30	-0.42
Distance to Oil Well	SAVS	PWR	-1.77E-04	2.87E-05	-3.84E-04	2.35E-04	4.52E-04	1.90E-05	1.56	1.77
Distance to Road	SAVS	PWR	-2.56E-04	-7.99E-05	-4.32E-04	4.56E-04	1.01E-03	-9.60E-05	1.68	0.88
Distance to Shallow Gas Well	SAVS	GLM	6.06E-05	1.61E-04	-3.98E-05	-	-	-	1.21	1.62
Shallow Gas Well Density	SAVS	GLM	-1.30E-02	-5.28E-03	-2.07E-02	-	-	-	1.64	-
Distance to Oil Well	SPPI	PWR	1.51E-02	2.73E-02	2.95E-03	-7.31E-05	3.22E-05	-1.78E-04	-1.40	0.87
Distance to Road	SPPI	GLM	9.60E-05	1.68E-04	3.20E-04	-	-	-	0.70	-
Distance to Shallow Gas Well	SPPI	PWR	6.23E-04	9.83E-04	2.62E-04	-1.05E-03	-3.27E-04	-1.77E-03	0.62	1.89
Shallow Gas Well Density	SPPI	PWR	1.69E-02	5.31E-02	-1.93E-02	-3.19E-02	-1.70E-02	-4.68E-02	0.80	1.09
Distance to Oil Well	VESP	PWR	4.25E+01	3.91E+02	-3.06E+02	8.86E-05	3.37E-04	-1.59E-04	-3674.00	-1.03
Distance to Road	VESP	GLM	-6.12E-04	-2.87E-04	-2.75E-04	-	-	-	-0.50	-

Distance to Shallow Gas Well	VESP	PWR	-2.82E-03	-6.43E-05	-5.58E-03	4.02E-04	9.43E-04	-1.39E-04	-0.50	-1.26
Distance to Oil Well	WEME	GLM	-7.90E-05	1.32E-04	-7.28E-05	-	-	-	-	-
Distance to Road	WEME	GLM	6.87E-05	4.39E-05	-2.02E-04	-	-	-	0.71	-
Distance to Shallow Gas Well	WEME	PWR	4.24E-04	7.45E-04	1.02E-04	-7.77E-04	7.44E-05	-1.63E-03	0.61	1.58
Shallow Gas Well Density	WEME	GLM	-1.42E-02	-5.66E-03	-4.14E-03	-	-	-	0.83	-

Table 3. 6. Parameters for best-fitting models for clutch size, which include β, β_2 (slopes), C_1, C_2 (intercepts) and UCL, UCL_2 and LCL, LCL_2 (upper and lower confidence intervals for the slope), where CCLO is Chestnut-collared Longspurs (*Calcarius ornatus*), SAVS is Savannah Sparrow (*Passerculus sandwichensis*), SPPI is Sprague's Pipits (*Anthus spragueii*), VESP is Vesper Sparrows (*Pooecetes gramineus*) and WEME is Western Meadowlark (*Sturnella neglecta*). Shaded values indicate that the slope was different from zero.

Predictor	Species	Model	β	UCL	LCL	β_2	UCL_2	LCL_2	C_1	C_2
Distance to Oil Well	CCLO	GLM	-2.83E-05	8.76E-05	-1.44E-04	-	-	-	1.10	-
Distance to Road	CCLO	GLM	-1.10E-04	7.41E-05	-2.95E-04	-	-	-	1.14	0.81
Distance to Shallow Gas Well	CCLO	PWR	6.67E+00	9.36E+00	3.98E+00	-4.19E-05	1.59E-04	-2.43E-04	-232.30	1.09
Distance to Oil Well	SAVS	PWR	-2.10E-04	-1.27E-04	-2.93E-04	-2.02E-01	4.80E+00	-5.20E+00	1.30	550.40
Distance to Road	SAVS	PWR	1.89E-04	6.04E-04	-2.26E-04	-1.33E-03	-9.06E-04	-1.75E-03	1.24	1.84
Distance to Shallow Gas Well	SAVS	PWR	1.92E-05	1.37E-04	-9.88E-05	-1.36E-03	-3.17E-04	-2.41E-03	1.23	3.51
Shallow Gas Well Density	SAVS	PWR	5.49E-03	1.50E-02	-4.01E-03	-6.17E-02	-1.98E-02	-1.04E-01	1.21	2.21
Distance to Oil Well	SPPI	GLM	-1.17E-03	1.75E-04	-2.51E-03	-	-	-	1.62	-
Distance to Road	SPPI	GLM	-1.43E-03	-4.88E-04	-2.36E-03	-	-	-	1.55	-
Distance to Shallow Gas Well	SPPI	GLM	4.34E-04	7.33E-04	1.35E-04	-	-	-	0.97	-
Shallow Gas Well Density	SPPI	PWR	5.96E-03	3.44E-02	-2.25E-02	-1.47E+01	1.17E+03	-1.20E+03	1.24	-251.70
Distance to Oil Well	VESP	GLM	-3.73E-05	1.01E-04	-1.75E-04	-	-	-	1.18	-
Distance to Road	VESP	GLM	-4.45E-04	-9.58E-05	-7.94E-04	-	-	-	1.26	
Distance to Shallow Gas Well	VESP	GLM	6.94E-05	4.60E-04	-3.21E-04	-	-	-	1.16	
Distance to Oil Well	WEME	GLM	4.82E-04	1.67E-03	-7.09E-04	-	-	-	1.16	-
Distance to Road	WEME	GLM	-2.31E-04	4.00E-04	-8.62E-04	-	-	-	1.30	-

Table 3.7 Parameters for best-fitting models for nesting success, which include β, β_2 (slopes), C_1, C_2 (intercepts) and UCL, $\mathbf{UCL_2}$ and LCL, $\mathbf{LCL_2}$ (upper and lower confidence intervals for the slope), where CCLO is Chestnut-collared Longspurs (*Calcarius ornatus*), SAVS is Savannah Sparrow (*Passerculus sandwichensis*), SPPI is Sprague's Pipits (*Anthus spragueii*), VESP is Vesper Sparrows (*Pooecetes gramineus*) and WEME is Western Meadowlark (*Sturnella neglecta*). Shaded values indicate that the slope was different from zero.

Predictor	Species	Model	β	UCL	LCL	β_2	UCL_2	LCL_2	C_1	C_2
Distance to Oil Well	CCLO	GLM	1.31E-04	4.69E-04	-2.07E-04	-1.06E-02	6.70E-04	-2.19E-02	3.21	25.56
Distance to Road	CCLO	GLM	-2.10E-04	1.46E-04	-5.65E-04	-	-	-	3.44	-
Distance to Shallow Gas Well	CCLO	PWR	-4.94E-03	1.32E-03	-1.12E-02	1.42E-03	2.28E-03	5.64E-04	3.94	2.61
Shallow Gas Well Density	CCLO	GLM	-5.43E-02	-2.53E-02	-8.33E-02	-	-	-	3.56	-
Distance to Oil Well	SAVS	GLM	2.00E-04	3.99E-04	1.26E-06	-	-	-	3.28	-
Distance to Road	SAVS	GLM	2.64E-04	5.42E-04	-1.46E-05	-	-	-	3.29	-
Distance to Shallow Gas Well	SAVS	PWR	-4.44E-04	-2.32E-04	-6.55E-04	-5.79E-01	6.78E+01	-6.89E+01	3.66	1258.00
Distance to Oil Well	SPPI	GLM	-7.37E-01	2.05E+02	-2.06E+02	5.35E-03	1.25E-02	-1.82E-03	98.62	1.93
Distance to Road	SPPI	GLM	1.09E-03	2.32E-03	-1.46E-04	-	-	-	3.00	-
Distance to Shallow Gas Well	SPPI	GLM	-9.95E-06	3.42E-03	-3.44E-03	-	-	-	3.68	-
Distance to Oil Well	VESP	GLM	2.18E-03	4.85E-03	-5.03E-04	-	-	-	2.95	-
Distance to Road	VESP	GLM	4.28E-04	1.32E-03	-4.61E-04	-	-	-	3.35	-
Distance to Shallow Gas Well	VESP	GLM	3.44E-04	1.58E-03	-8.96E-04	-	-	-	3.54	-
Shallow Gas Well Density	VESP	PWR	1.14E-01	2.05E-01	2.39E-02	-2.98E-01	-4.01E-03	-5.93E-01	3.19	9.15
Distance to Oil Well	WEME	GLM	-9.12E-03	-2.75E-03	-1.55E-02	2.75E-02	7.26E-02	-1.77E-02	4.34	-7.03
Distance to Road	WEME	GLM	6.71E-04	2.21E-03	-8.73E-04	-	-	-	2.84	-

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Table 3.8 Quantity of habitat affected by distance to oil well, distance to shallow gas well, distance to road and shallow gas well density on abundance, clutch size and nesting success based on PWR breakpoints, where BAIS is Baird's Sparrow (*Ammodramus bairdii*), CCLO is Chestnut-collared Longspurs (*Calcarius ornatus*), SAVS is Savannah Sparrow (*Passerculus sandwichensis*), SPPI is Sprague's Pipits (*Anthus spragueii*), VESP is Vesper Sparrows (*Pooecetes gramineus*) and WEME is Western Meadowlark (*Sturnella neglecta*).

Response	Predictor	Species	Distance/Density to Effect	Area Affected (km^2)	Habitat Unaffected (km^2)	Proportion Affected
Abundance	Distance to Road	BAIS	1957	24494.05	7243.37	0.77
Abundance	Distance to Shallow Gas Well	BAIS	1482	14726.28	9928.68	0.60
Abundance	Shallow Gas Well Density	BAIS	36	24558.12	122.32	1.00
Abundance	Distance to Road	CCLO	1957	24494.05	7243.37	0.77
Abundance	Distance to Shallow Gas Well	CCLO	1482	14726.28	9928.68	0.60
Abundance	Shallow Gas Well Density	CCLO	36	24558.12	122.32	1.00
Abundance	Distance to Road	CCSP	1957	24494.05	7243.37	0.77
Abundance	Distance to Shallow Gas Well	CCSP	1482	14726.28	9928.68	0.60
Abundance	Distance to Oil Well	SAVS	2581	6454.08	16062.39	0.29
Abundance	Distance to Road	SAVS	1120	20472.63	11264.79	0.65
Abundance	Distance to Shallow Gas Well	SAVS	1482	14726.28	9928.68	0.60
Abundance	Shallow Gas Well Density	SAVS	36	24558.12	122.32	1.00
Abundance	Distance to Oil Well	SPPI	149.3	998.26	21518.21	0.04
Abundance	Distance to Shallow Gas Well	SPPI	1482	14726.28	9928.68	0.60
Abundance	Shallow Gas Well Density	SPPI	36	24558.12	122.32	1.00
Abundance	Distance to Road	VESP	1957	24494.05	7243.37	0.77
Abundance	Distance to Shallow Gas Well	VESP	235.6	10662.63	13992.34	0.43
Abundance	Distance to Shallow Gas Well	WEME	804.5	10662.63	13992.34	0.43
Abundance	Shallow Gas Well Density	WEME	17.98	24029.51	650.94	0.97
Clutch Size	Distance to Shallow Gas Well	CCLO	1432	10662.63	13992.34	0.43
Clutch Size	Distance to Oil Well	SAVS	2727	6454.08	16062.39	0.29
Clutch Size	Distance to Road	SAVS	1583	24494.05	7243.37	0.77
Clutch Size	Distance to Shallow Gas Well	SAVS	2182	16213.84	8441.13	0.66
Clutch Size	Shallow Gas Well Density	SAVS	37	24563.22	117.23	1.00
Clutch Size	Distance to Road	SPPI	966	18817.60	12919.81	0.59
Clutch Size	Distance to Shallow Gas Well	SPPI	997	13857.63	10797.33	0.56
Clutch Size	Distance to Road	VESP	1804	25724.58	6012.84	0.81

Nesting Success	Distance to Shallow Gas Well	CCLO	1766	16213.84	8441.13	0.66
Nesting Success	Shallow Gas Well Density	CCLO	36	24558.12	122.32	1.00
Nesting Success	Distance to Oil Well	SAVS	665	998.26	21518.21	0.04
Nesting Success	Distance to Shallow Gas Well	SAVS	2167	16213.84	8441.13	0.66
Nesting Success	Shallow Gas Well Density	VESP	36	24558.12	122.32	1.00
Nesting Success	Distance to Oil Well	WEME	238.4	998.26	21518.21	0.04

Table 3.9. Root Mean Squared errors for maps of predictive abundance, clutch size and nesting success assuming a compensatory and minimum function relationship, where CCLO is Chestnut-collared Longspurs (*Calcarius ornatus*), SAVS is Savannah Sparrow (*Passerculus sandwichensis*), SPPI is Sprague's Pipits (*Anthus spragueii*), VESP is Vesper Sparrows (*Pooecetes gramineus*) and WEME is Western Meadowlark (*Sturnella neglecta*). "*" indicates that neither a mean or minimum function layer was validated because there was only one predictor. If there was no predictor with a significant effect on clutch size, nesting success or abundance, then a layer was not created or validated because I assumed that the effect was unchanged through the study area.

Predictor	Species	Error for Mean Model	Error for Minimum Model
Abundance	CCLO	2.376	3.139
Abundance	SAVS	1.558	1.872
Abundance	SPPI	3.013	1.114
Abundance	VESP	0.638	0.456
Abundance	WEME	2.042	1.350
Clutch Size*	CCLO	2.816	-
Clutch Size	SAVS	1.974	2.486
Clutch Size	SPPI	1.800	2.158
Clutch Size*	VESP	1.296	-
Nesting Success	CCLO	0.342	0.345
Nesting Success	SAVS	0.290	0.358
Nesting Success*	VESP	0.274	-
Nesting Success*	WEME	0.397	

Table 3.10 Proportion of productive habitat versus available habitat for Chestnut-collared Longspurs (*Calcarius ornatus*), Savannah Sparrows (*Passerculus sandwichensis*), Sprague's Pipits (*Anthus spragueii*), Vesper Sparrows (*Pooecetes gramineus*) and Western Meadowlark (*Sturnella neglecta*) based on abundance, clutch size and nesting success, where

$Productivity\ (P) = \dfrac{Abundance \times Clutch\ Size \times Probability\ of\ Nesting\ Success}{P_{max}}$. Productivity estimates based on life-history patterns were

pooled and a single analysis was done to estimate the effect of edge on obligates and generalists.

Species	Productivity			
	P<0.25	0.25=<P>0.5	0.5=<P>0.75	P>=0.75
	Poor	Low	Medium	High
Chestnut-collared Longspur	0.4464	0.1805	0.1012	0.0000
Savannah Sparrow	0.3353	0.3882	0.0047	0.0000
Sprague's Pipit	0.0558	0.5702	0.1013	0.0009
Vesper Sparrow	0.3991	0.0671	0.0000	0.0000
Western Meadowlark	0.2348	0.4007	0.0023	0.0902

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Table 3.11. Quantity of shared productive habitat for obligates– Chestnut-collared Longspurs (*Calcarius ornatus*) and Sprague's Pipits (*Anthus spragueii*) and generalists– Savannah Sparrows (*Passerculus sandwichensis*), Vesper Sparrows (*Pooecetes gramineus*) and Western Meadowlark (*Sturnella neglecta*), based on abundance, clutch size and nesting success, where $Productivity\ (P) = \frac{Abundance \times Clutch\ Size \times Probabilty\ of\ Nesting\ Sucess}{P_{max}}$. Productivity estimates based on life-history patterns were pooled and a single analysis was done to estimate the effect of edge on obligates and generalists.

| Scenario	Total Area (km^2)	Proportion
Productivity above zero for all species	9193.28	0.51
Productivity above 0.25 for all species	0.00	0.00
Productivity above 0.5 for all species	0.00	0.00
Productivity above 0 for generalists	18042.88	1.00
Productivity above 0.25 for generalists	2471.25	0.14
Productivity above 0.5 for generalists	0.00	0.00
Productivity above 0 for obligate species	12144.36	0.54
Productivity above 0.25 for obligate species	8553.99	0.45
Productivity above 0.5 for obligate species	445.61	0.02
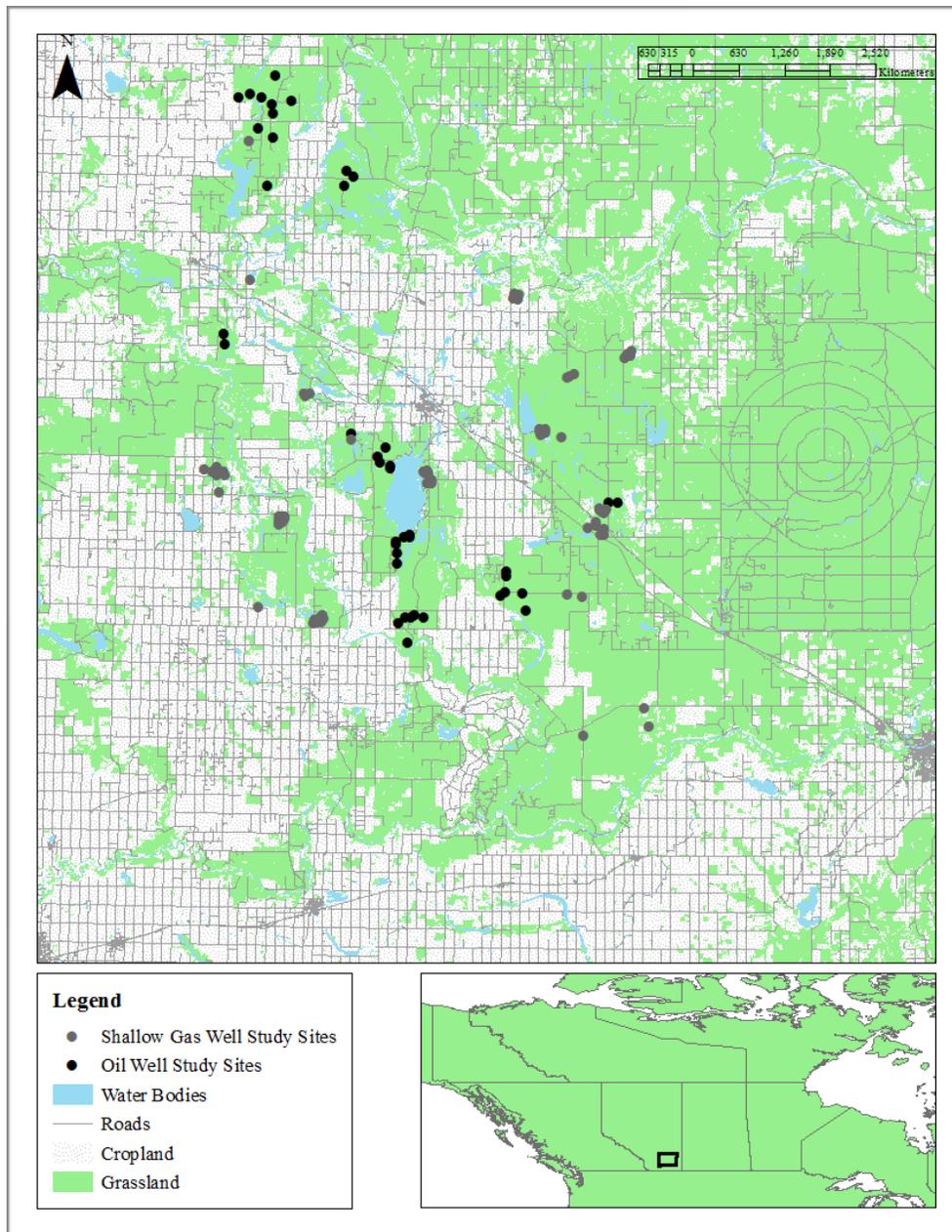
Figure 3.1. Map of study area in southern Alberta, Canada. Abundance and nesting data were collected from 2010-2013 in a shallow gas well study. Nesting data were collected from 2012-2014 in an oil well study.
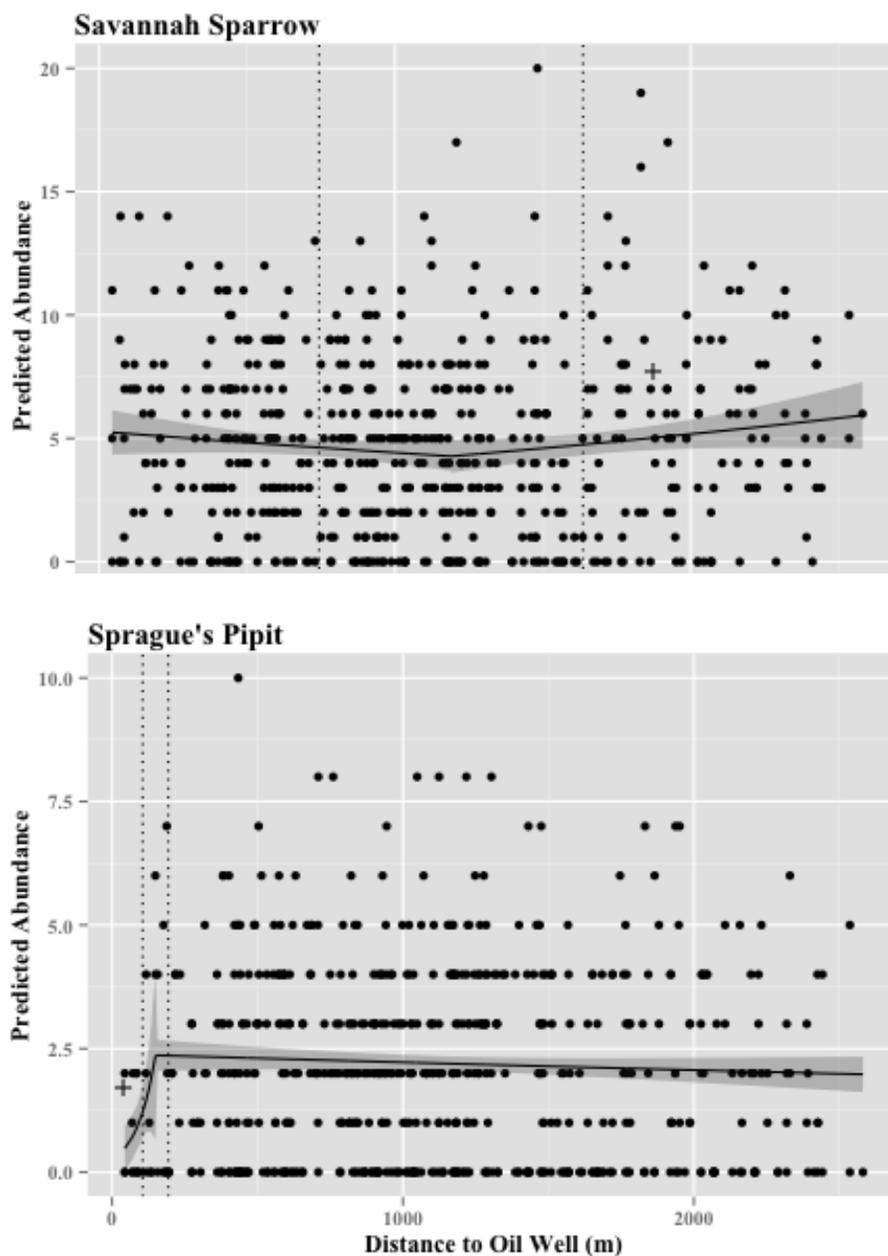
Figure 3.2. Plots for best fitting models of predicted abundance, resulting from the sum of observations over two point counts, versus distance to oil well, where the broken vertical lines are the confidence intervals for the breakpoint and the shaded regions are the confidence bands for the predicted values. If the NULL model was the best fitting model or none of the slopes for the GLM or PWR were significant, then no plot was created. "+" indicates that the slope was different from zero for the PWR.
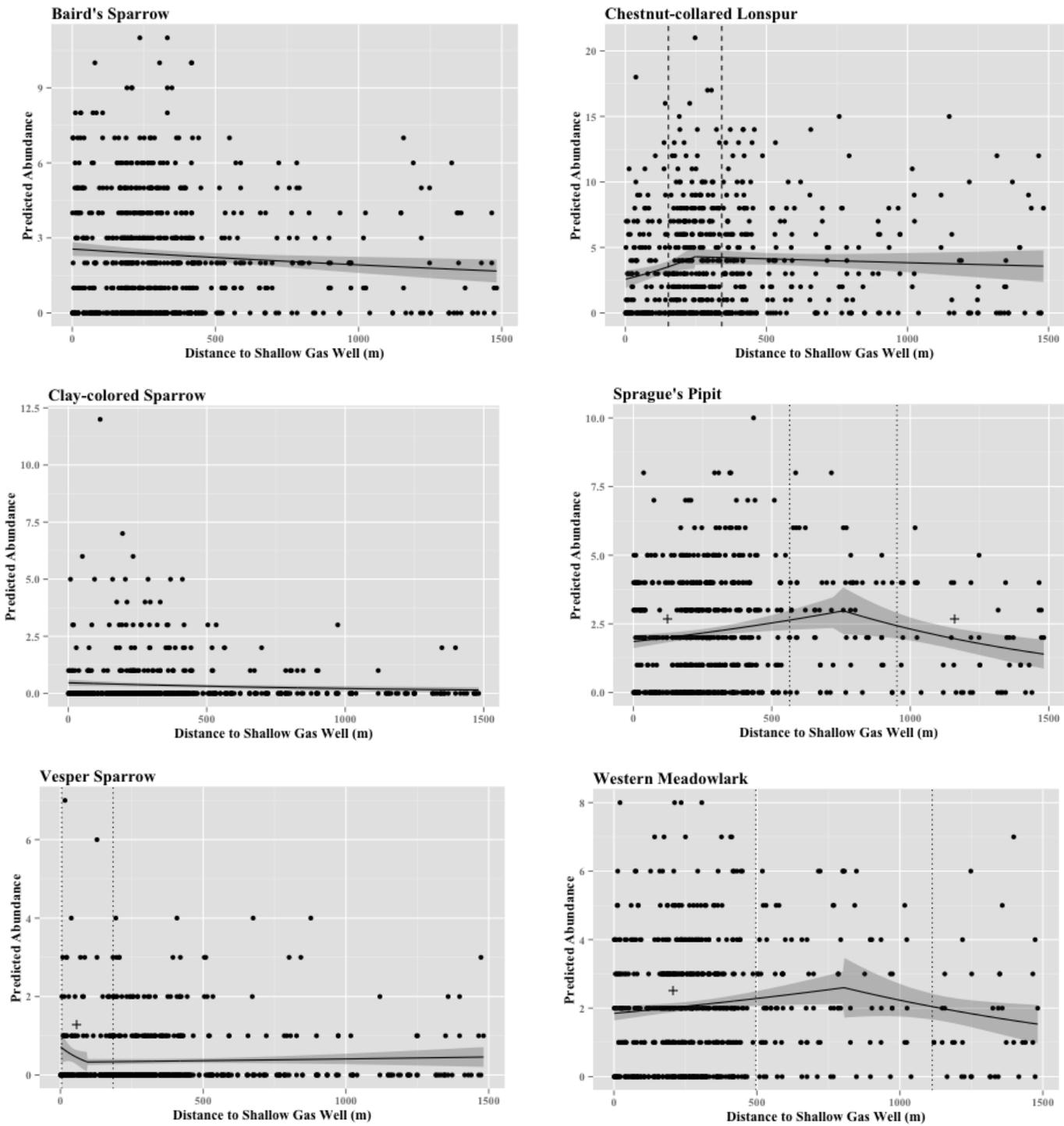
Figure 3.3. Plots for best fitting models of predicted abundance, resulting from the sum of

observations over two point counts, versus distance to shallow gas, where the broken vertical lines are the confidence intervals for the breakpoint and the shaded regions are the confidence bands for the predicted values If the NULL model was the best fitting model or none of the slopes for the GLM or PWR were significant, then no plot was created. "+" indicates that the slope was different from zero for the PWR.

Baird's Sparrow

Chestnut-collared Lonspur

Confidence Interval for Breakpoint: -758.5, 854.3

Clay-colored Sparrow

Savannah Sparrow

Vesper Sparrow

Sprague's Pipit

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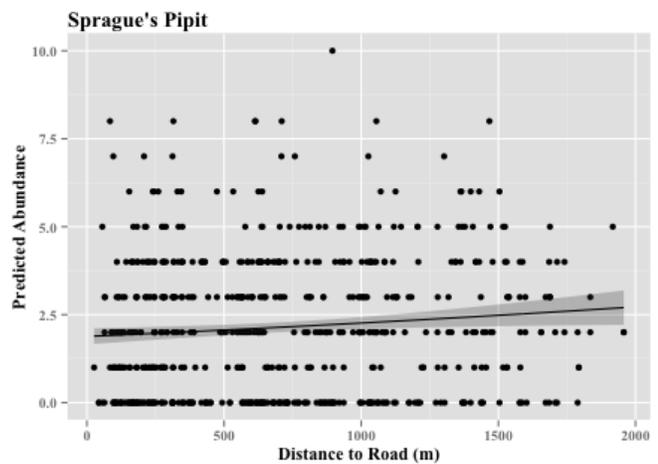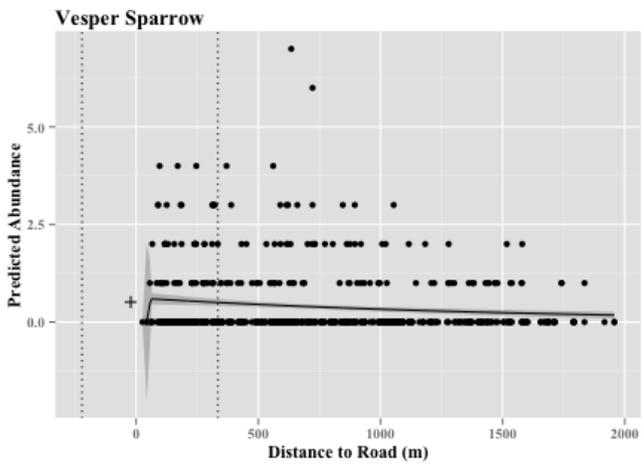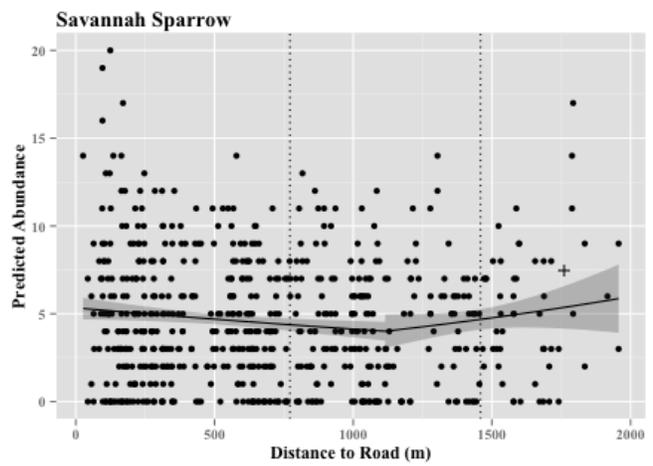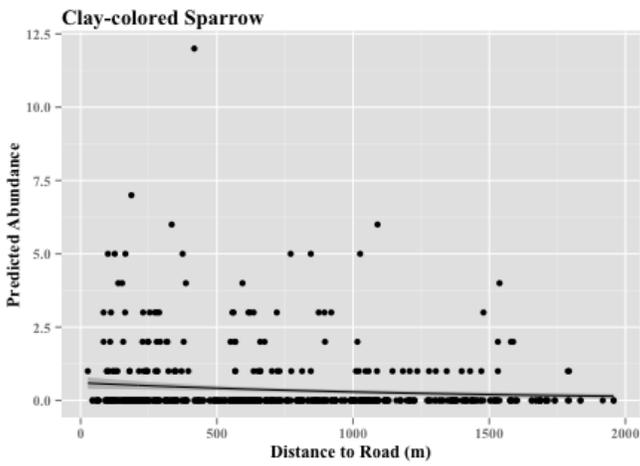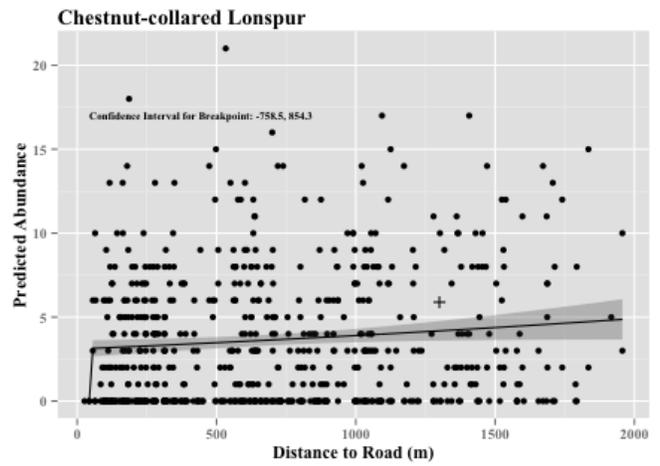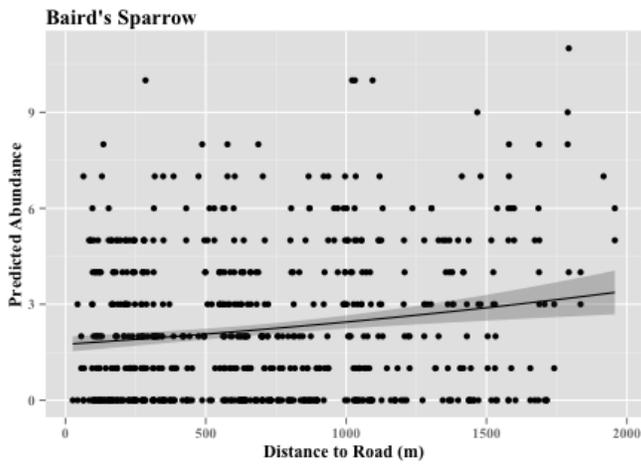
Figure 3.4. Plots for best fitting models of predicted abundance, resulting from the sum of observations over two point counts, versus distance to road, where the broken vertical lines are the confidence intervals for the breakpoint and the shaded regions are the confidence bands for the predicted values. If the NULL model was the best fitting model or none of the slopes for the GLM or PWR were significant, then no plot was created. "+" indicates that the slope was different from zero for the PWR.
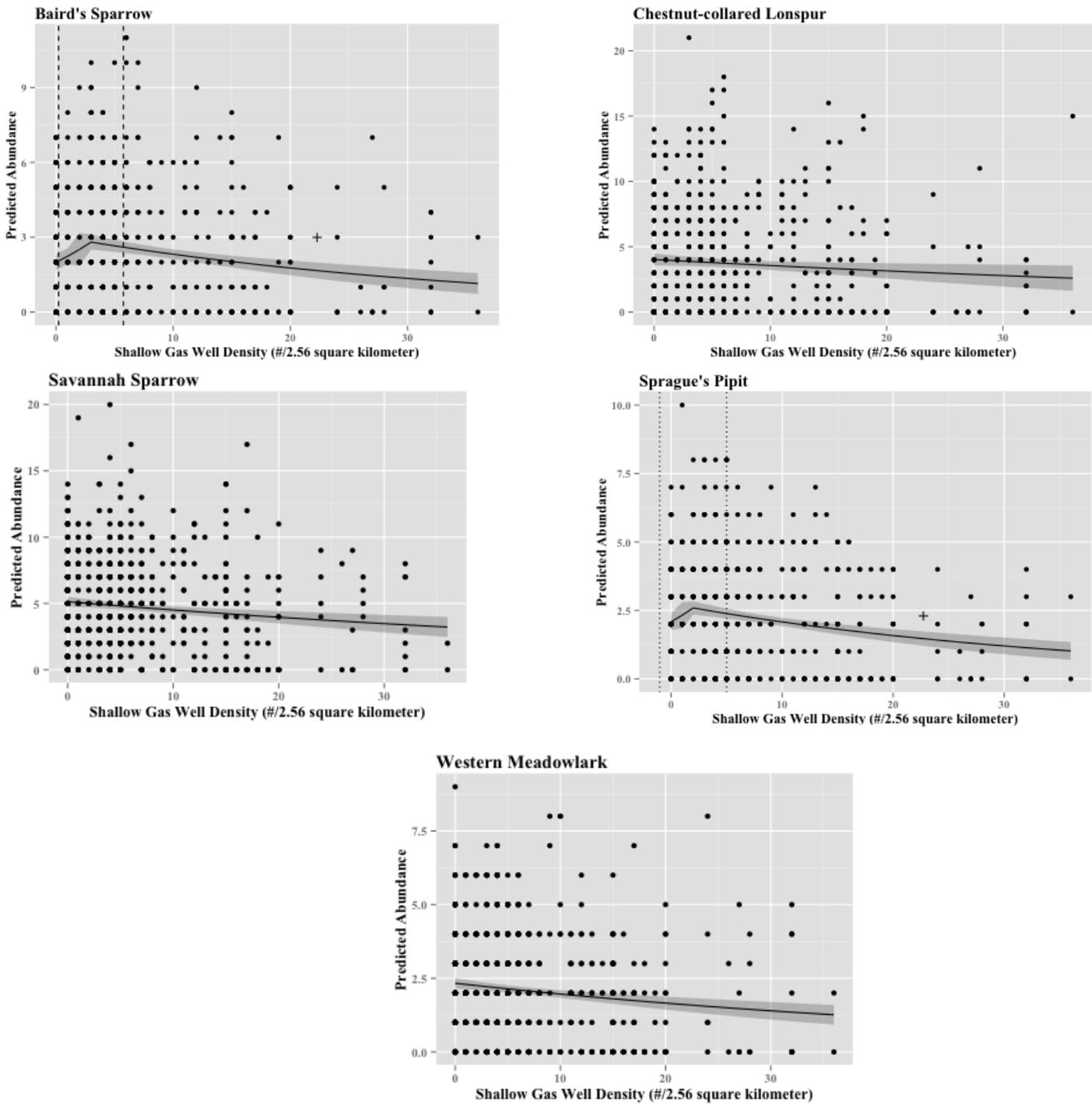
Figure 3.5. Plots for best fitting models of predicted abundance, resulting from the sum of observations over two point counts, versus shallow gas well density (#/ 2.56 km$^{2)}$, where the broken vertical lines are the confidence intervals for the breakpoint and the shaded regions are the confidence bands for the predicted values If the NULL model was the best

fitting model or none of the slopes for the GLM or PWR were significant, then no plot was created. "+" indicates that the slope was different from zero for the PWR.

Savannah Sparrow

(Plot: Predicted ClutchSize versus Distance to Oil Well (m). Text within plot: "Confidence Interval for Breakpoint:-19890, 25340")
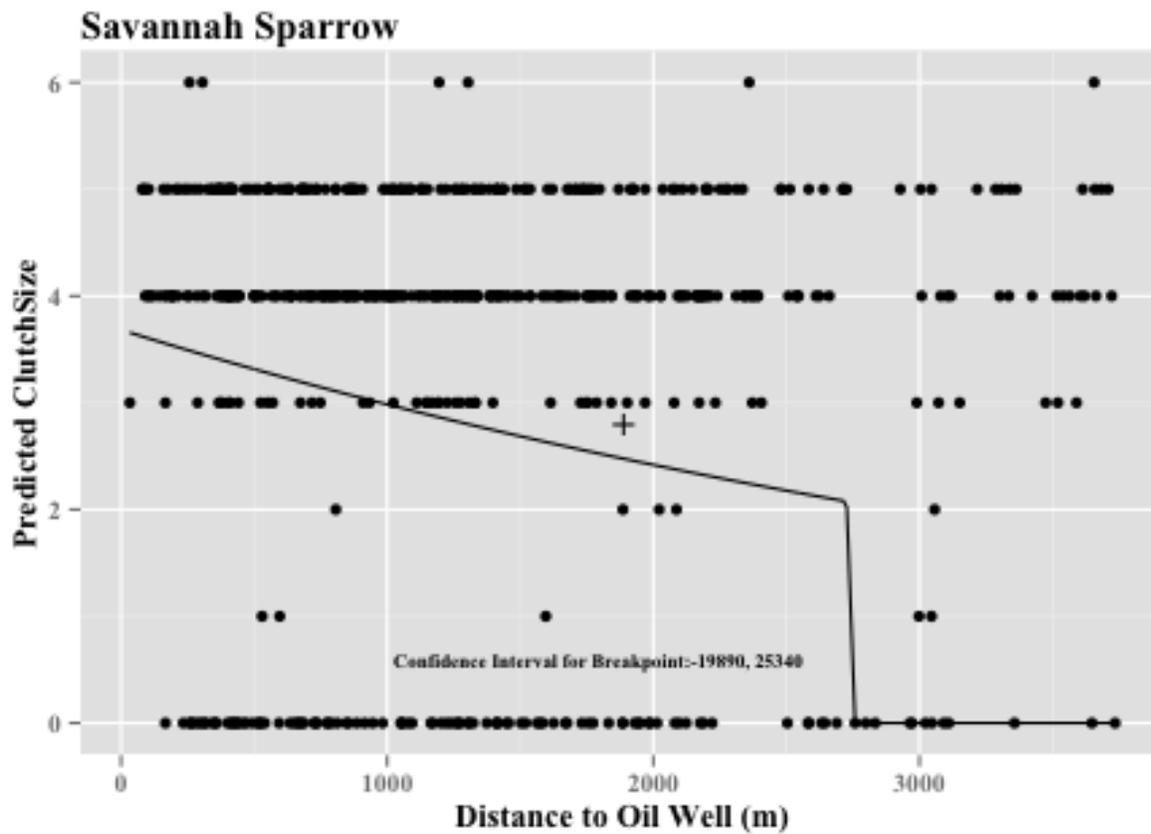
Figure 3.6. Plots for best fitting models of predicted clutch size versus distance to oil well, where the broken vertical lines are the confidence intervals for the breakpoint and the shaded regions are the confidence bands for the predicted values. If the NULL model was the best fitting model or none of the slopes for the GLM or PWR were significant, then no plot was created. "+" indicates that the slope was different from zero for the PWR.

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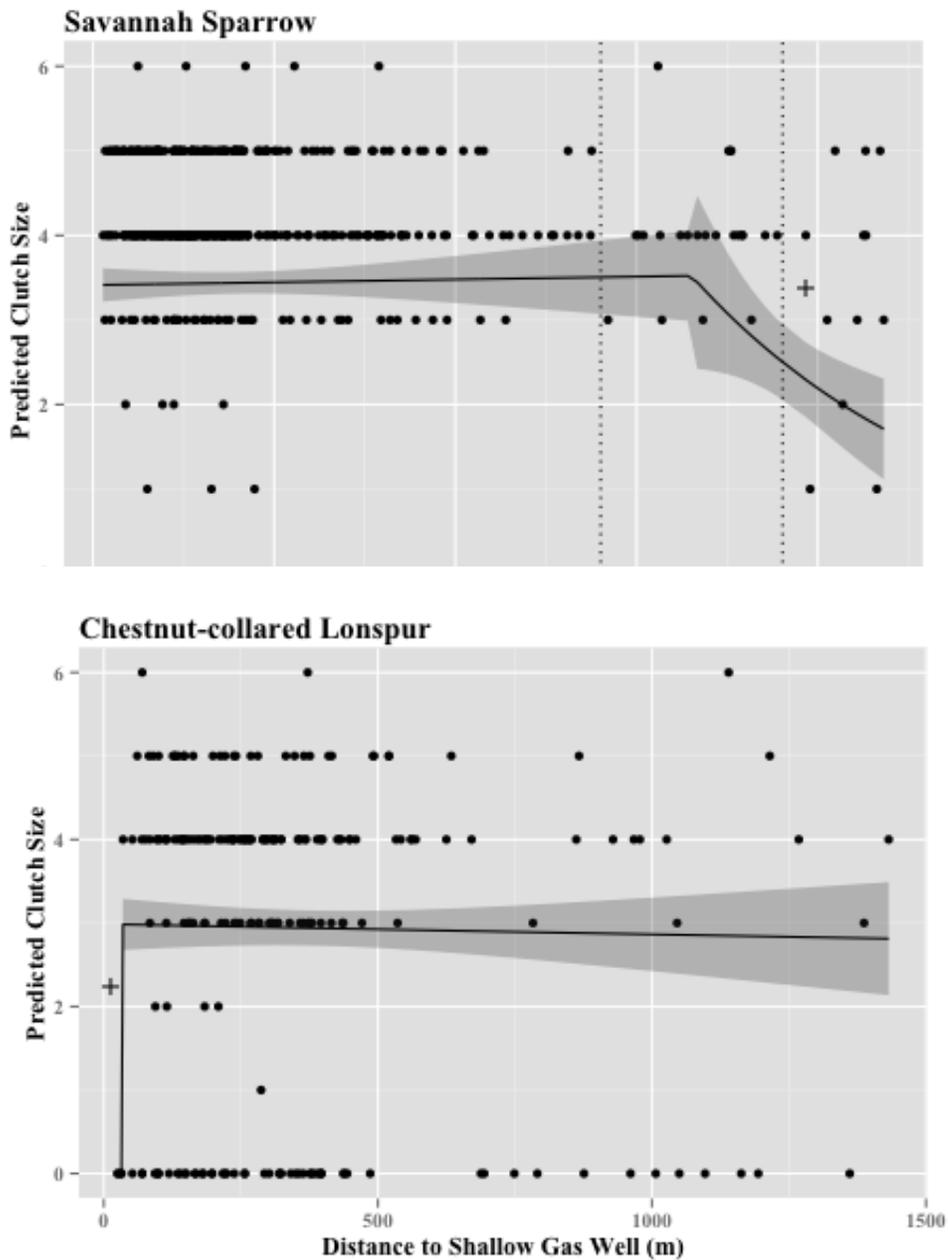
Figure 3.7. Plots for best fitting models of predicted clutch size versus distance to road, where the broken vertical lines are the confidence intervals for the breakpoint and the shaded regions are the confidence bands for the predicted values. If the NULL model was the best fitting model or none of the slopes for the GLM or PWR were significant, then no plot was created. "+" indicates that the slope was different from zero for the PWR.
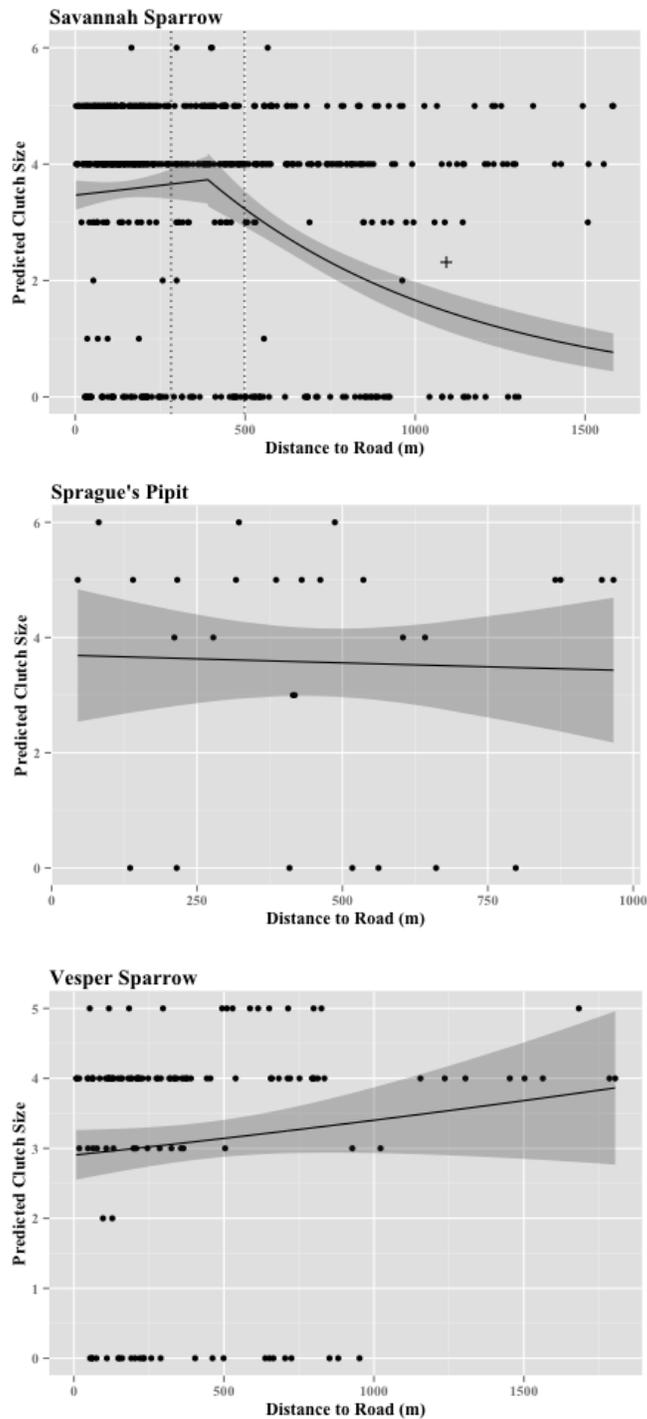
Figure 3.8. Plots for best fitting models of predicted clutch size versus distance to road, where the broken vertical lines are the confidence intervals for the breakpoint and the shaded regions are the confidence bands for the predicted values. If the NULL model was the best fitting model or none of the slopes for the GLM or PWR were significant, then no plot was created. "+" indicates that the slope was different from zero for the PWR.

Savannah Sparrow
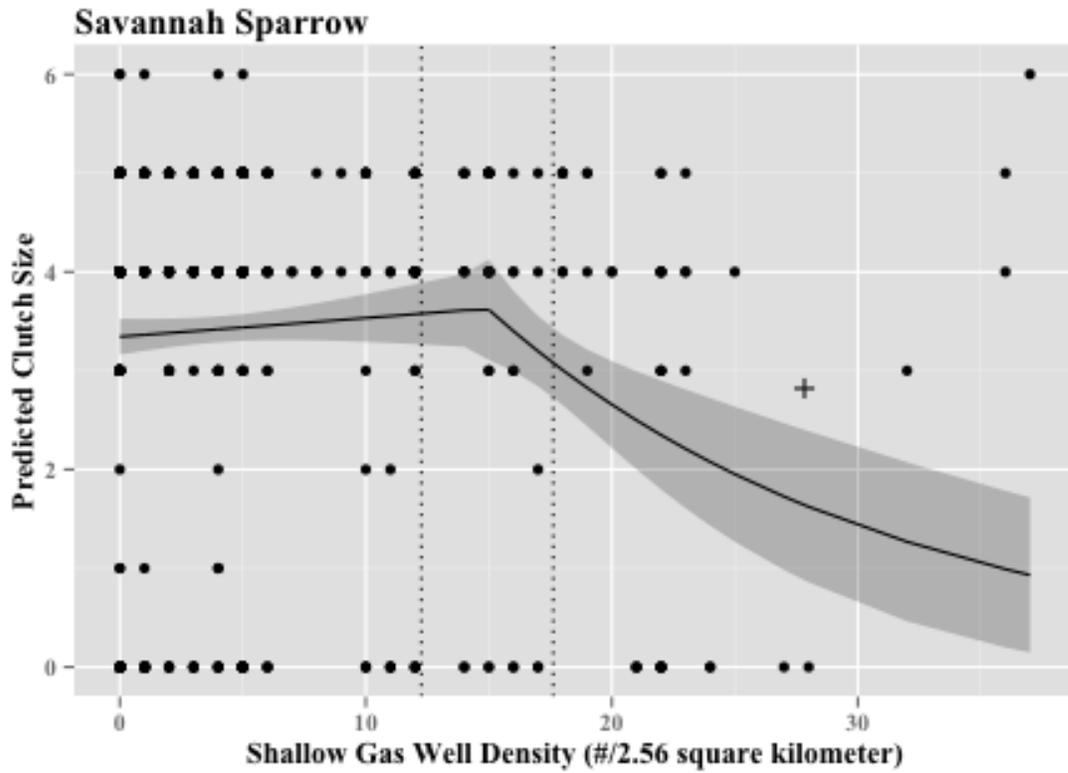
3.9. Plots for best fitting models of predicted clutch size versus gas well density (#/ 2.56 km^2, where the broken vertical lines are the confidence intervals for the breakpoint and the shaded regions are the confidence bands for the predicted values. If the NULL model was the best fitting model or none of the slopes for the GLM or PWR were significant, then no plot was created. "+" indicates that the slope was different from zero for the PWR.

96
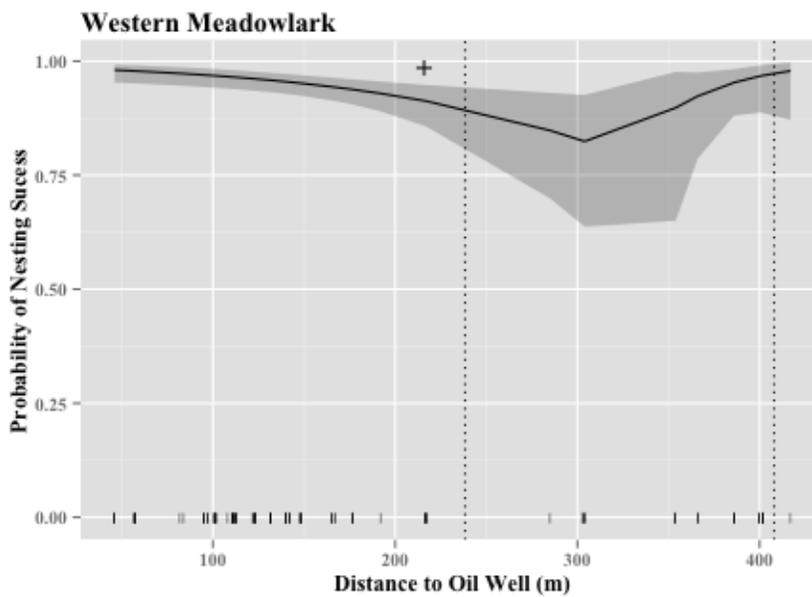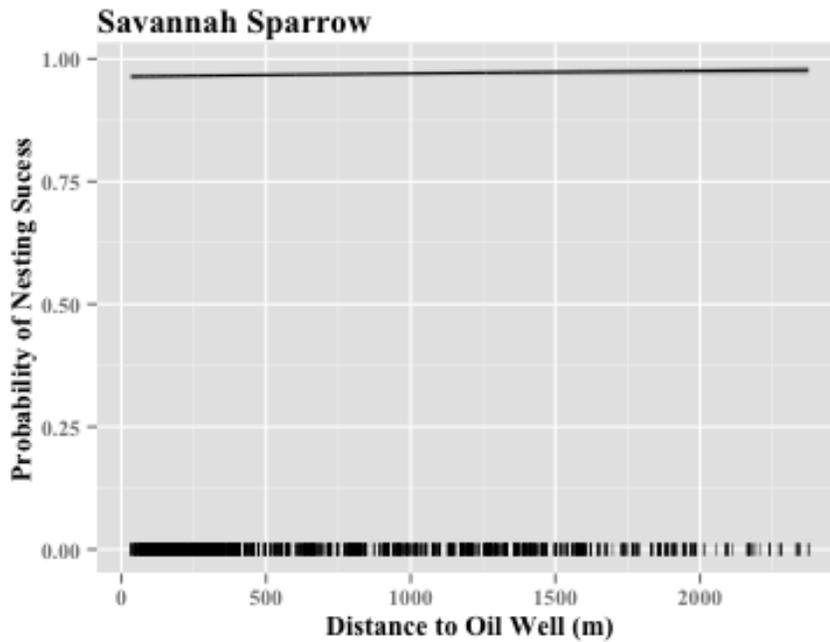
Figure 3.10. Plots for best fitting models of probability of nesting success versus distance to oil well, where the broken vertical lines are the confidence intervals for the breakpoint and the shaded regions are the confidence bands for the predicted values. If the NULL model was the best fitting model or none of the slopes for the GLM or PWR were significant, then no plot was created. "+" indicates that the slope was different from zero for the PWR. "|" indicates that there was an observation.
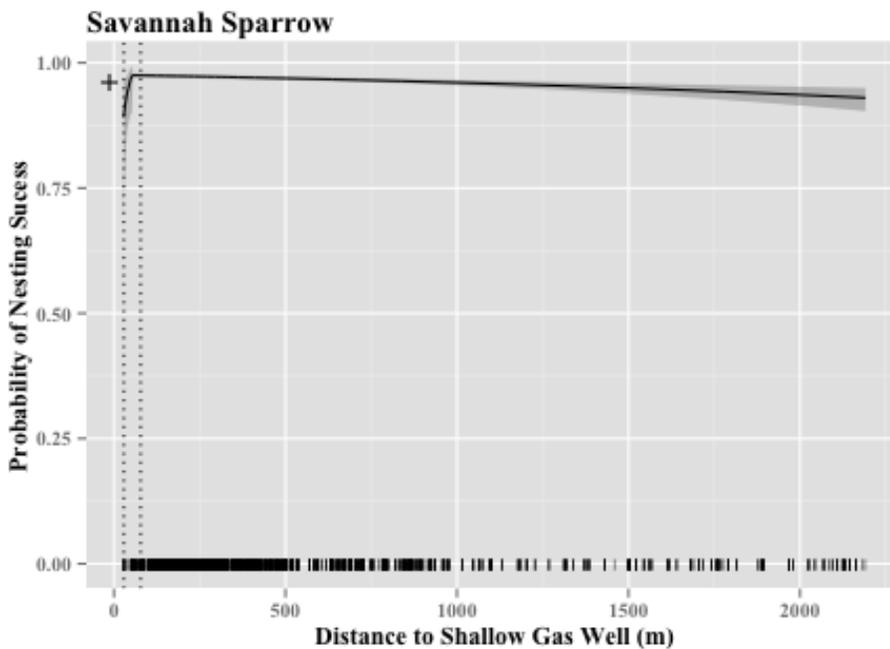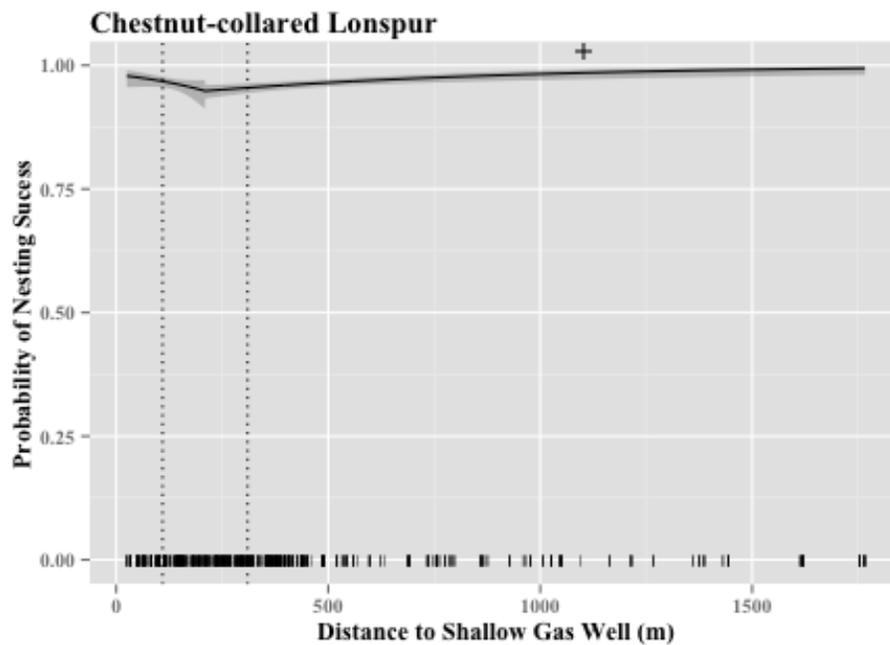
Figure 3.11. Plots for best fitting models of probability of nesting success versus distance to shallow gas well, where the broken vertical lines are the confidence intervals for the breakpoint and the shaded regions are the confidence bands for the predicted values If the NULL model was the best fitting model or none of the slopes for the GLM or PWR were significant, then no plot

was created. "+" indicates that the slope was different from zero for the PWR. "|" indicates that there was an observation.
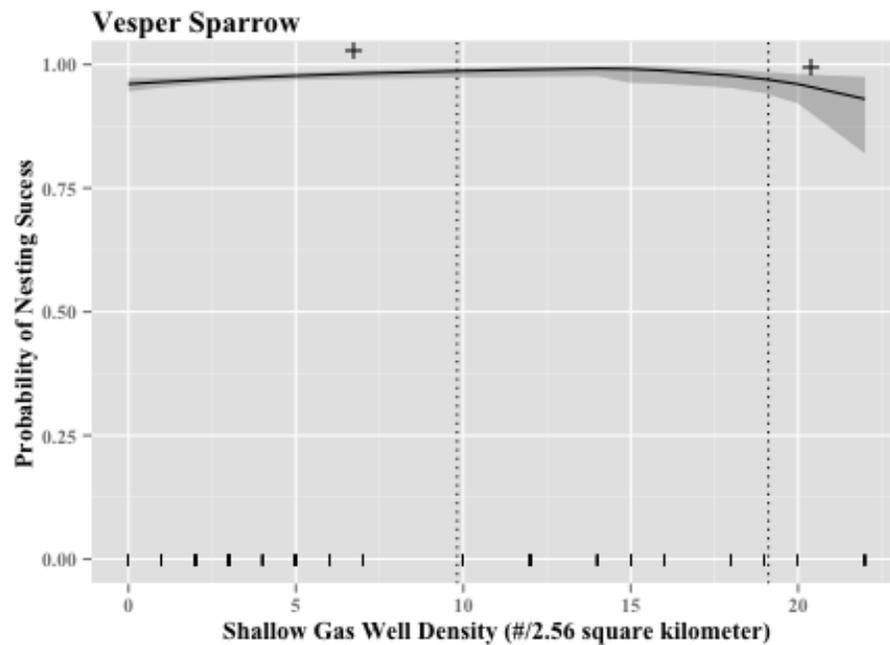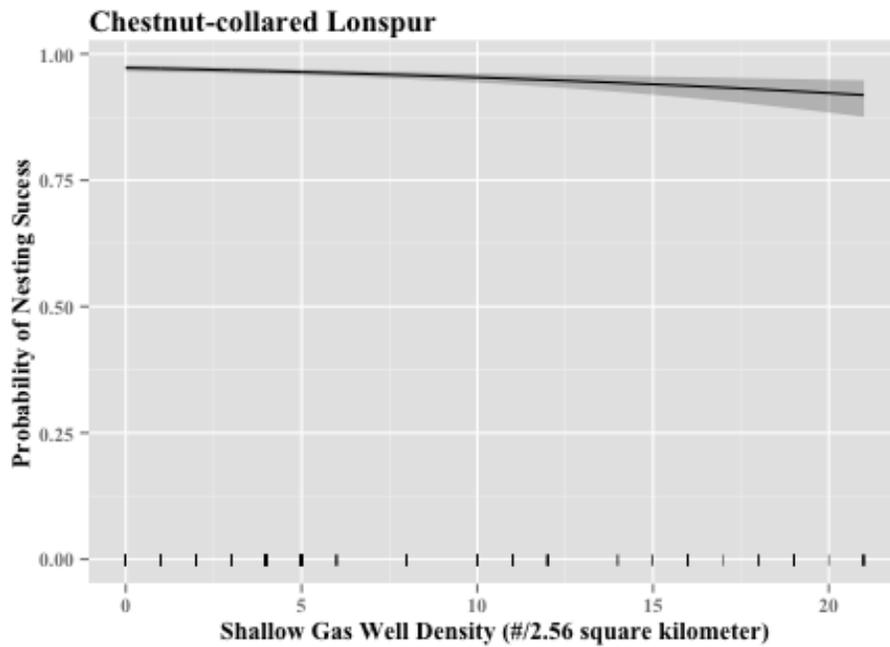
Figure 3.12. Plots for best fitting models of probability of nesting success versus gas well density (#/ 2.56 km$^{2)}$, where the broken vertical lines are the confidence intervals for the breakpoint and the shaded regions are the confidence bands for the predicted values. If no the NULL model was the best fitting model, no plot was created. "+" indicates that the slope was different from zero. "|" indicates that there was an observation.
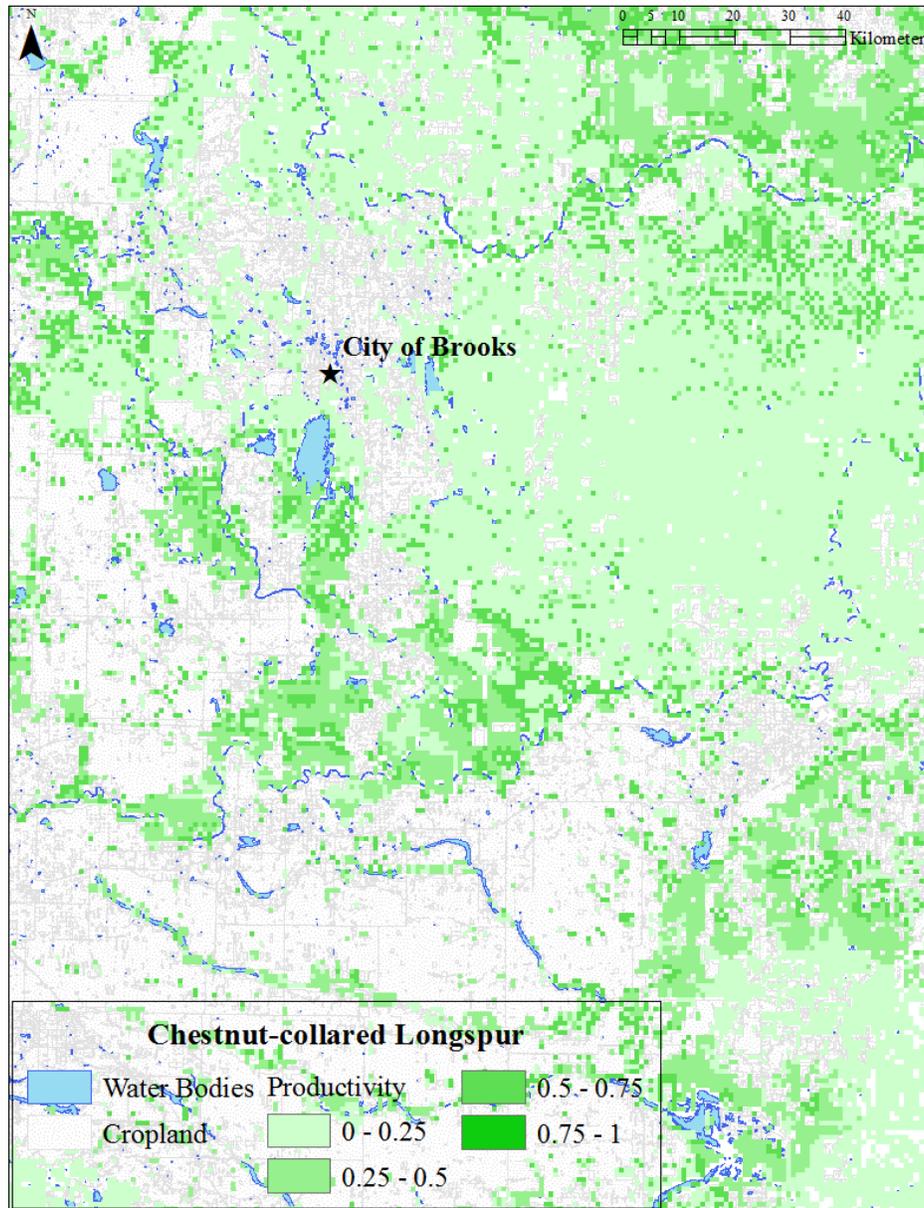
Figure 3.13. Relative productivity for Chestnut-collared Longspur (*Calcarius ornatus*), $Productivity\ (P) = \frac{Abundance \times Clutch\ Size \times Probabilty\ of\ Nesting\ Sucess}{P_{max}}$, was estimated as a function of distance to oil well, distance to shallow gas well, distance to road and shallow gas well density, when the effect was significant, in southern Alberta, Canada (data collected from May 2010 to July 2014).
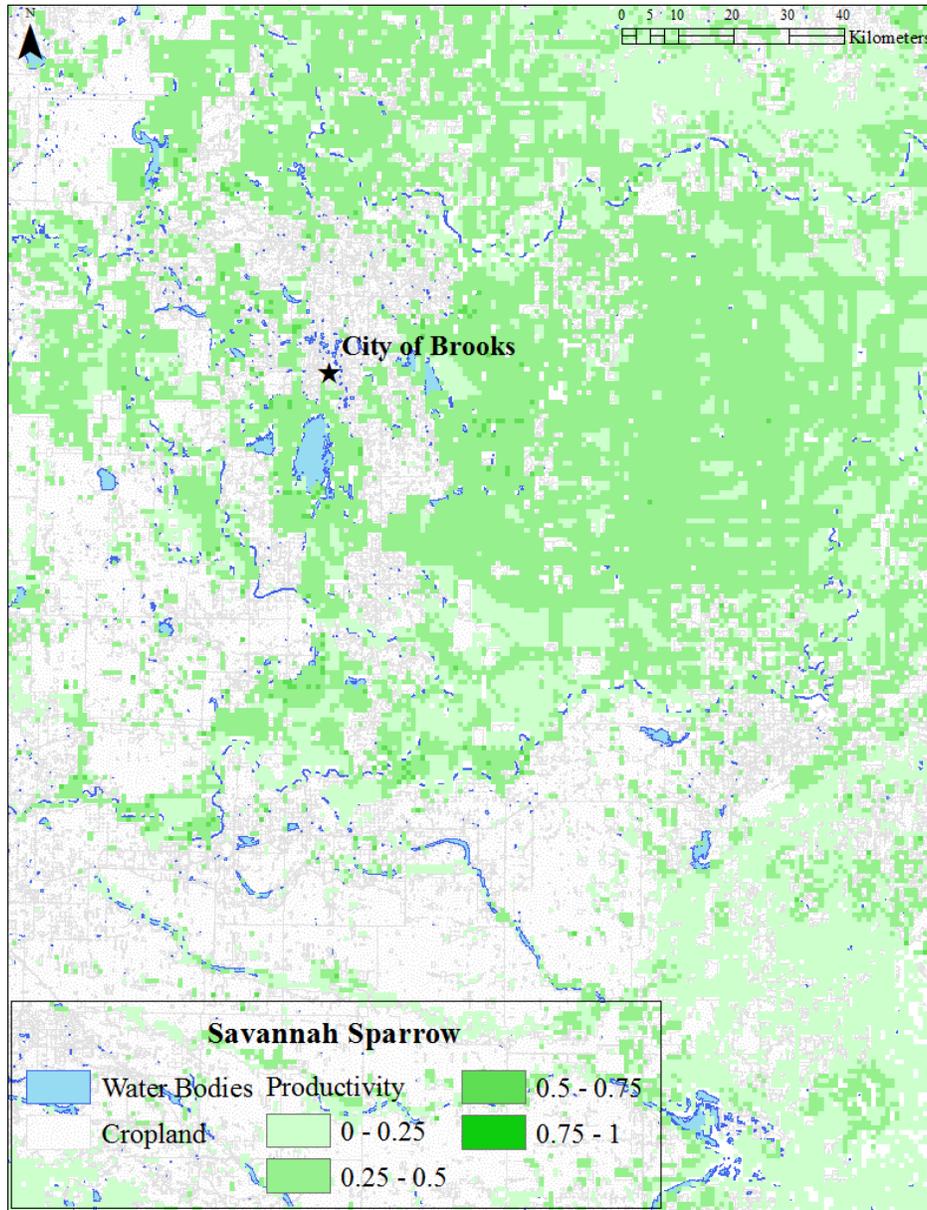
Figure 3.14. Relative productivity for Savannah Sparrow (*Passerculus sandwichensis*),

$$Productivity\ (P) = \frac{Abundance \times Clutch\ Size \times Probabilty\ of\ Nesting\ Sucess}{P_{max}},\ \text{was estimated as a function of}$$

distance to oil well, distance to shallow gas well, distance to road and shallow gas well density, when the effect was significant, in southern Alberta, Canada (data collected from May 2010 to July 2014).
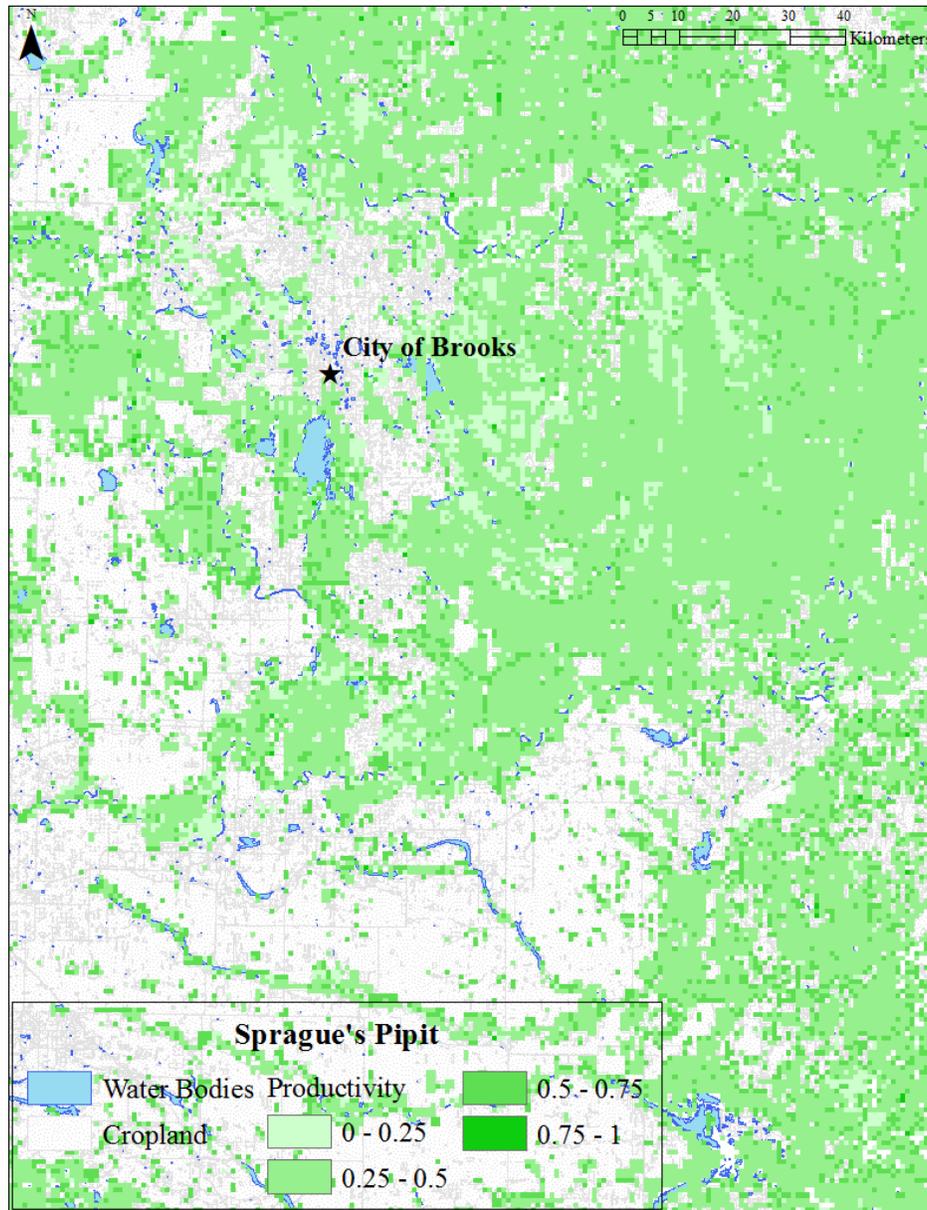
Figure 3.15. Relative productivity for Sprague's Pipit (*Anthus spragueii*), *Productivity* (P) = $\frac{Abundance \times Clutch\ Size \times Probabilty\ of\ Nesting\ Sucess}{P_{max}}$, was estimated as a function of distance to oil well, distance to shallow gas well, distance to road and shallow gas well density, when the effect was significant, in southern Alberta, Canada (data collected from May 2010 to July 2014).
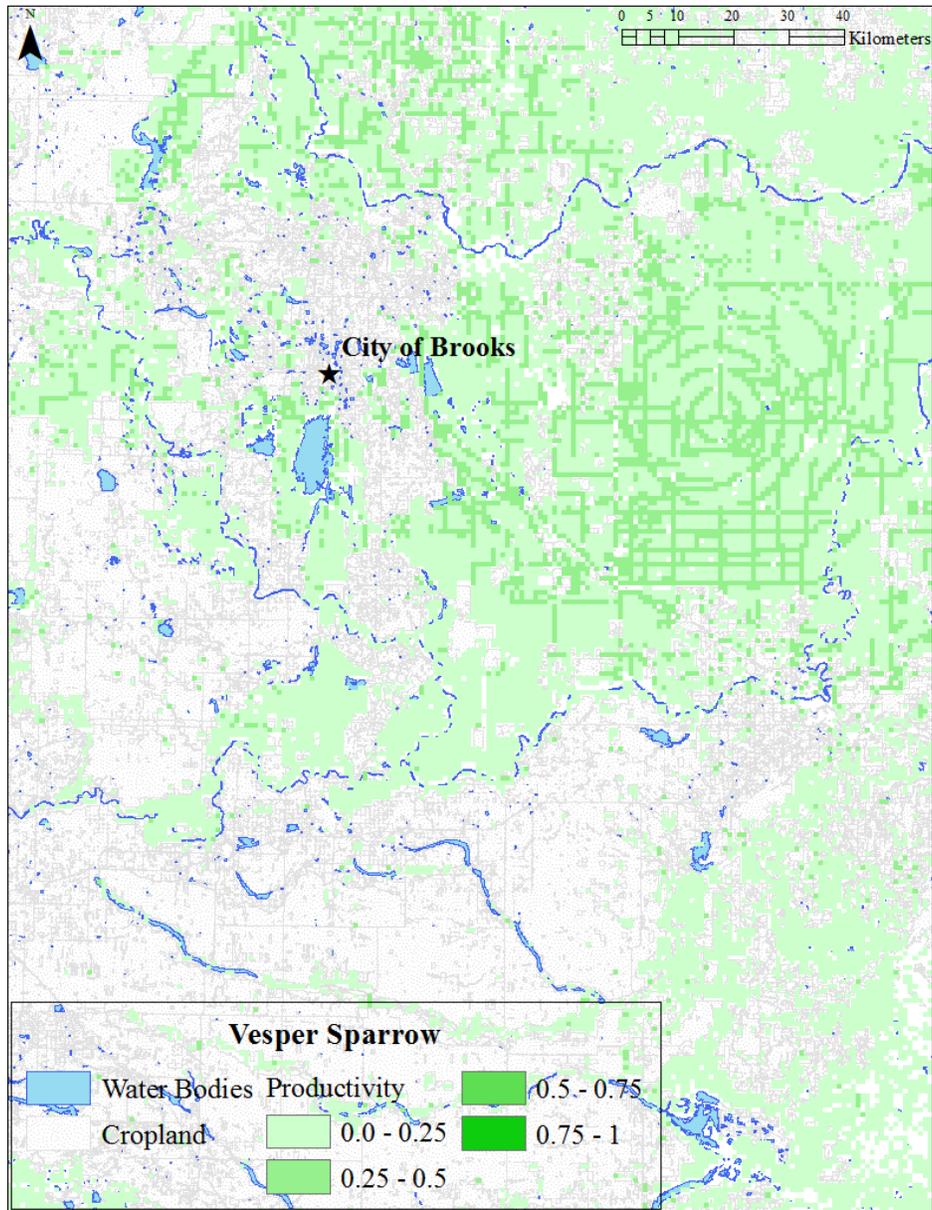
Figure 3.16. Relative productivity, for Vesper Sparrow (*Pooecetes gramineus*) was estimated as a function of distance to oil well, distance to shallow gas well, distance to road and shallow gas well density, when the effect was significant, in southern Alberta, Canada (data collected from May 2010 to July 2014).
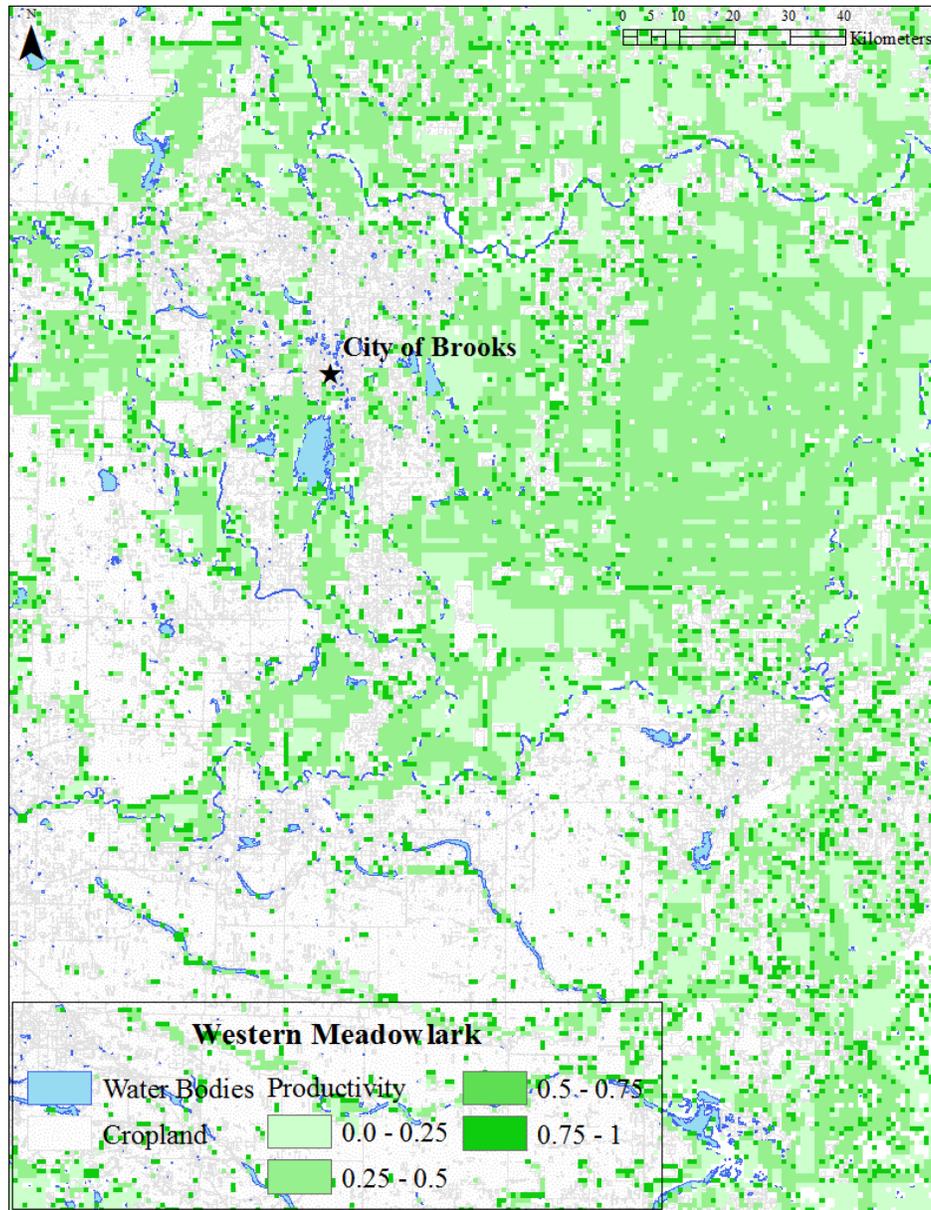
Figure 3.17. Relative productivity for Western Meadowlark (*Sturnella neglecta*) was estimated as a function of distance to oil well, distance to shallow gas well, distance to road and shallow gas well density, when the effect was significant, in southern Alberta, Canada (data collected from May 2010 to July 2014).
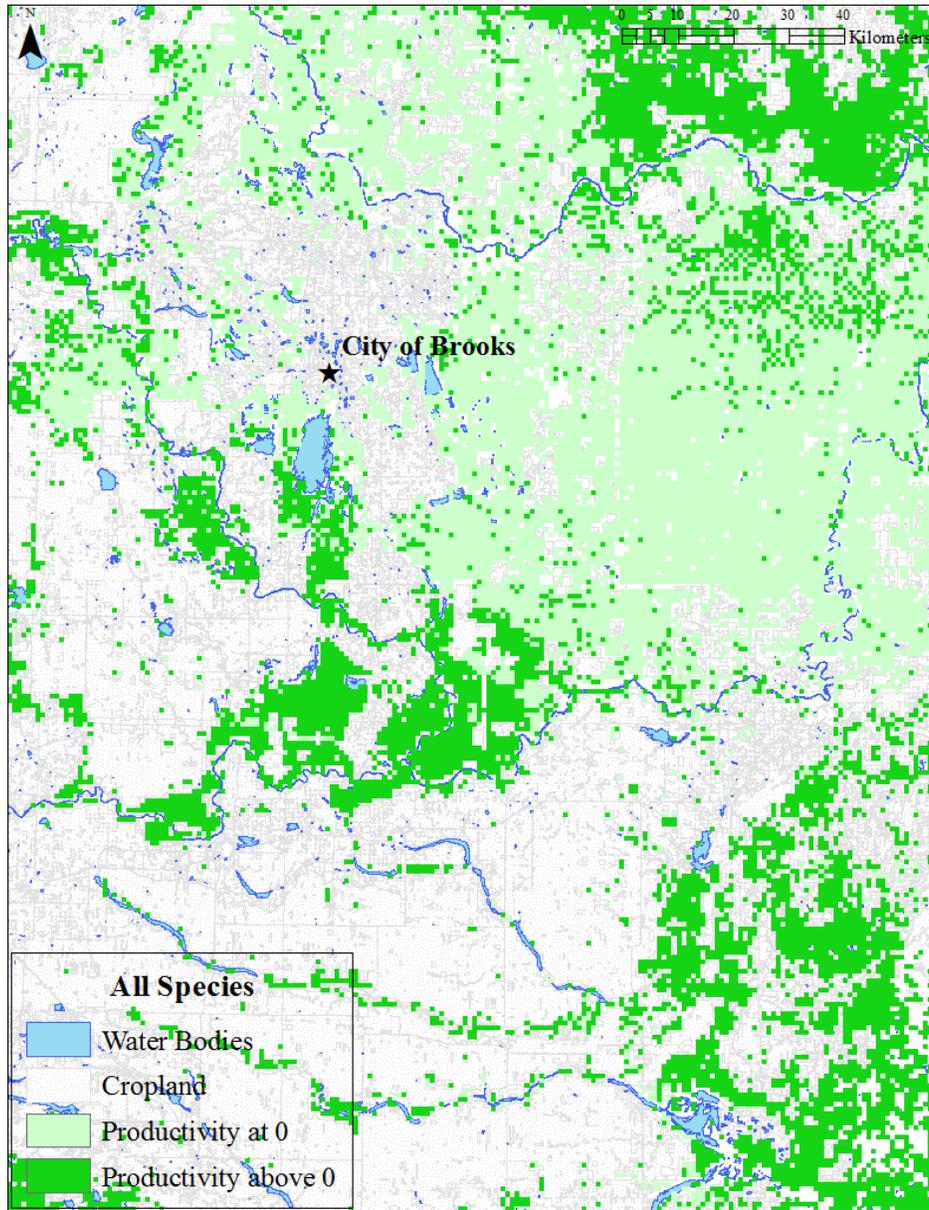
Figure 3.18. Regions in the study area where the relative productivity was above zero for Chestnut-collared Longspur (*Calcarius ornatus*), Savannah Sparrow (*Passerculus sandwichensis*), Sprague's Pipit (*Anthus spragueii*), Vesper Sparrow (*Pooecetes gramineus*) and Western Meadowlark (*Sturnella neglecta*) (data collected from May 2010 to July 2014).
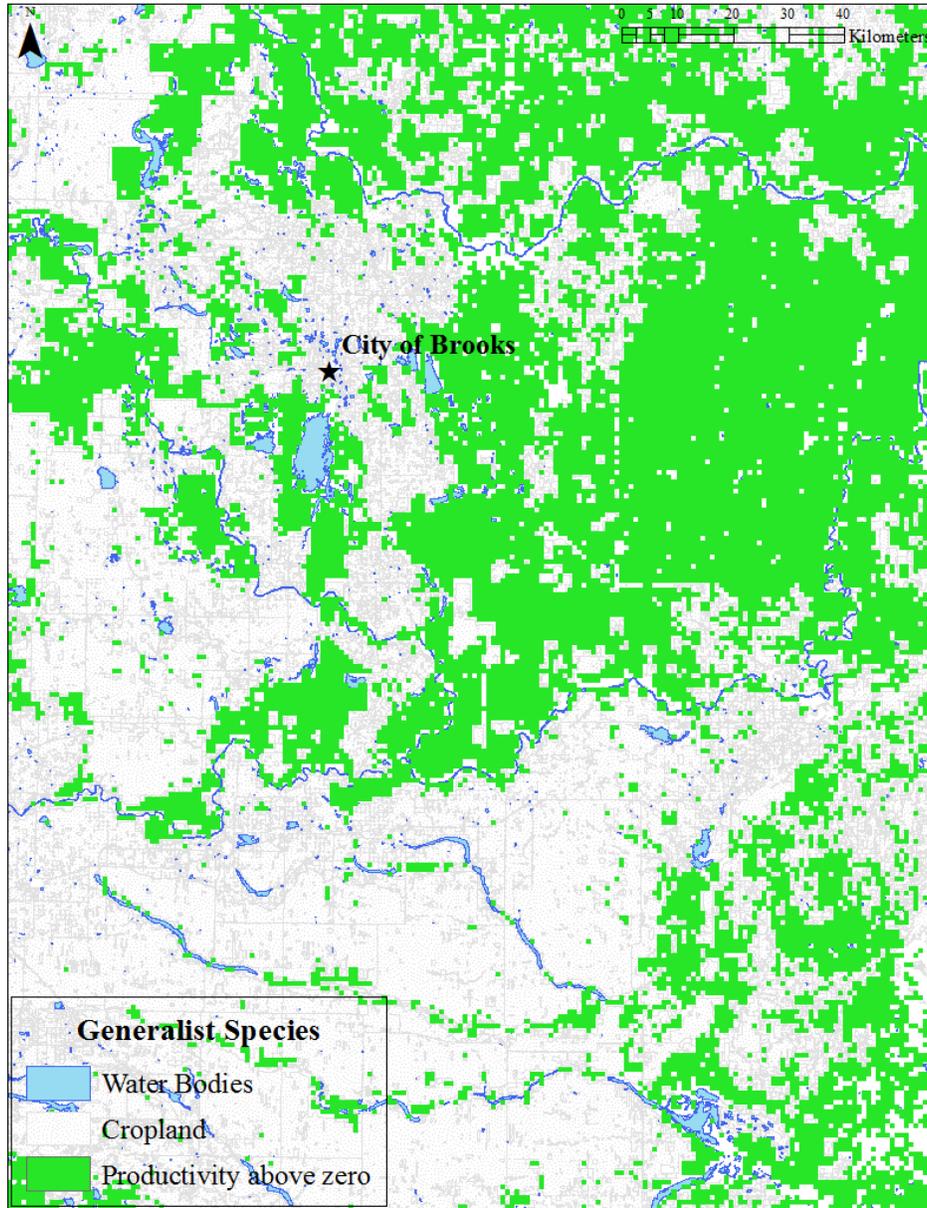
Figure 3.19. Regions in the study area where the relative productivity, *Productivity* (P) = $\frac{Abundance \times Clutch\ Size \times Probabilty\ of\ Nesting\ Sucess}{P_{max}}$, was greater than 0 for generalist species, which were Savannah Sparrow (*Passerculus sandwichensis*), Vesper Sparrow (*Pooecetes gramineus*) and Western Meadowlark (*Sturnella neglecta*) (data collected from May 2010 to July 2014).
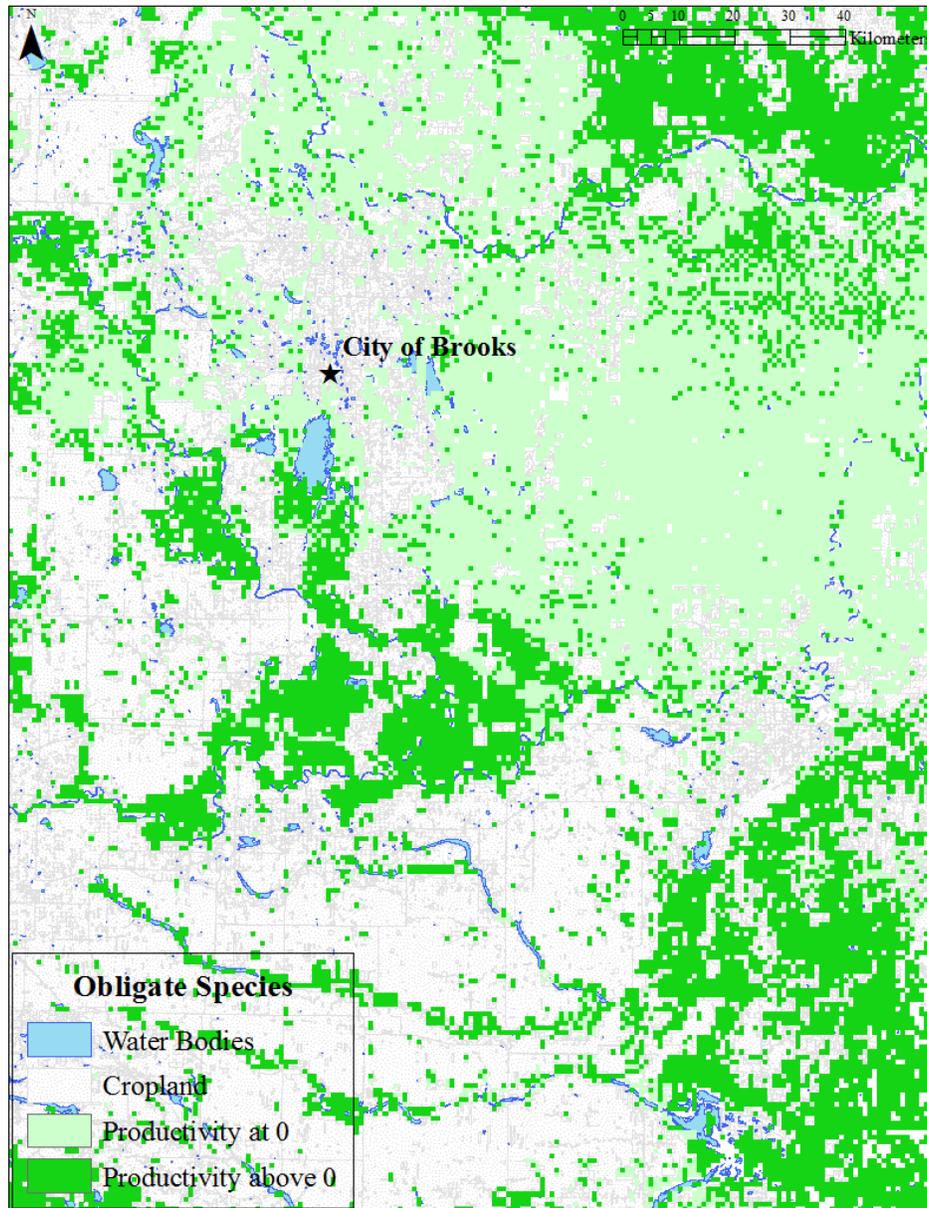
Figure 3.20. Region in the study area where the relative productivity, *Productivity* $(P) =$ $\frac{Abundance \times Clutch\ Size \times Probabilty\ of\ Nesting\ Sucess}{P_{max}}$, was greater than 0 for obligate species, which were Chestnut-collared Longspur (*Calcarius ornatus*) and Sprague's Pipit (*Anthus spragueii*) (data collected from May 2010 to July 2014).
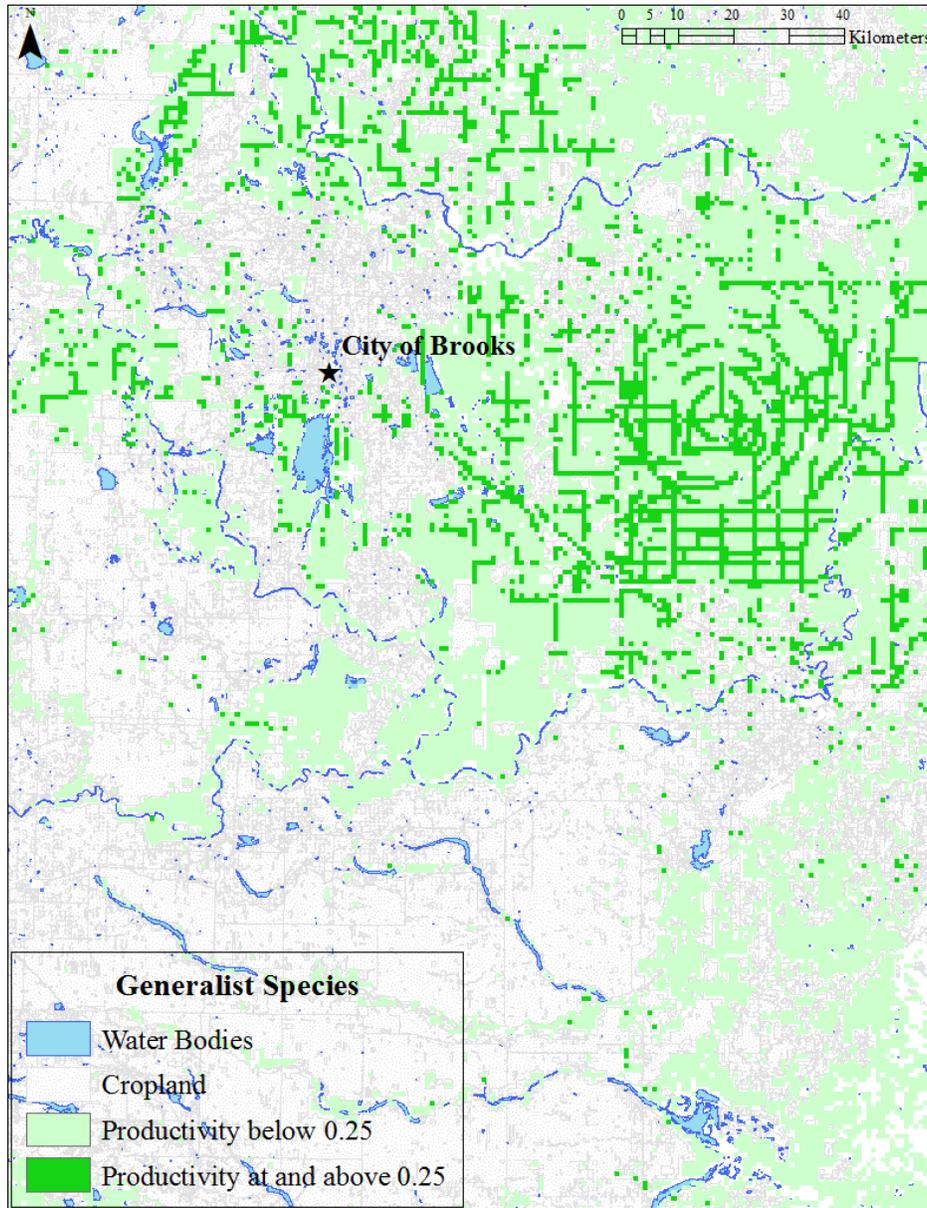
Figure 3.21. Regions in the study area where the relative productivity, *Productivity* $(P) = \frac{Abundance \times Clutch\ Size \times Probabilty\ of\ Nestin□\ Sucess}{P_{max}}$, was greater than or equal to 0.25 for generalist species, which were Savannah Sparrow (*Passerculus sandwichensis*), Vesper Sparrow (*Pooecetes gramineus*) and Western Meadowlark (*Sturnella neglecta*) (data collected from May 2010 to July 2014).
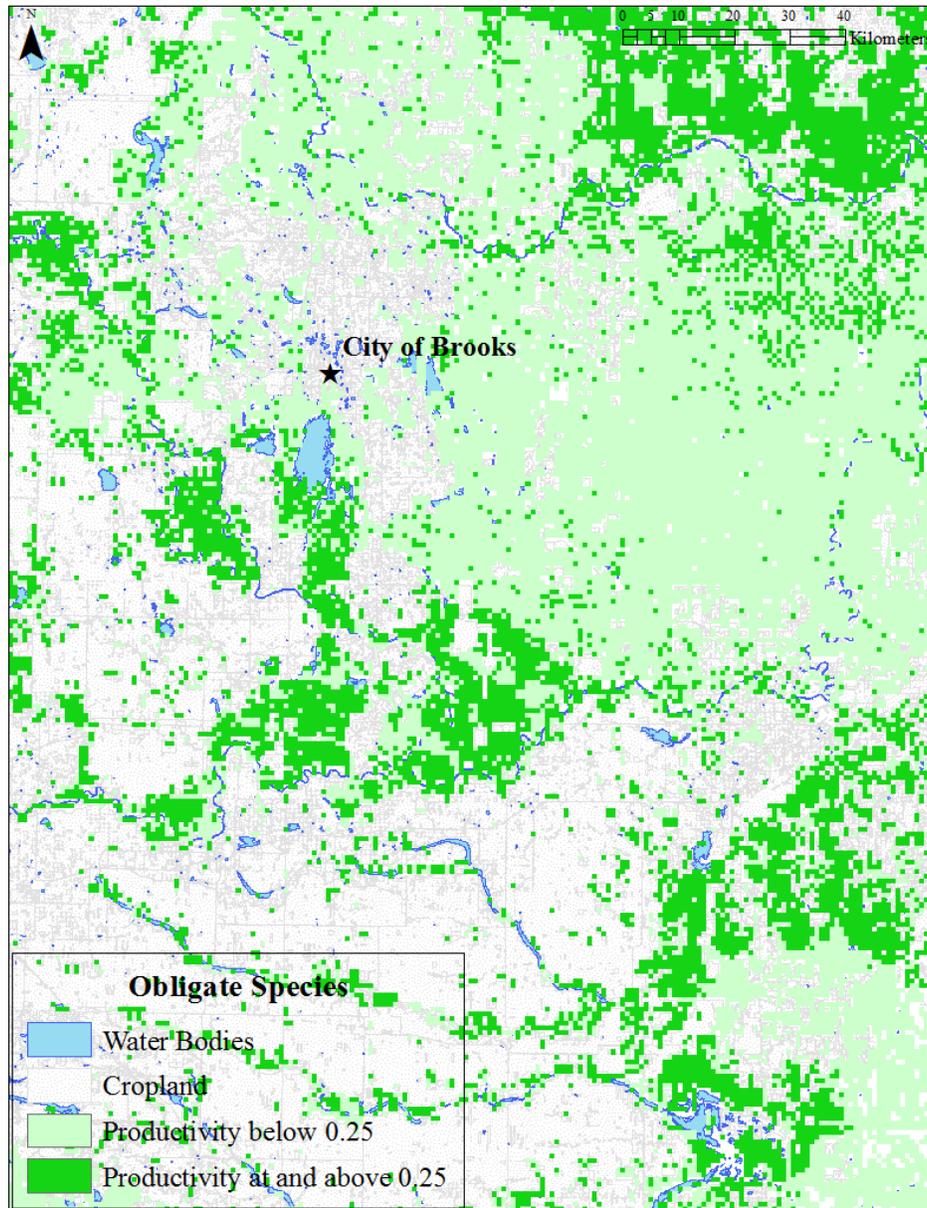
Figure 3.22. Region in the study area where the relative productivity, *Productivity* $(P) = \frac{Abundance \times Clutch\ Size \times Probabilty\ of\ Nesting\ Sucess}{P_{max}}$, was greater than or equal to 0.25 for obligate species, which were Chestnut-collared Longspur (*Calcarius ornatus*) and Sprague's Pipit (*Anthus spragueii*) (data collected from May 2010 to July 2014).
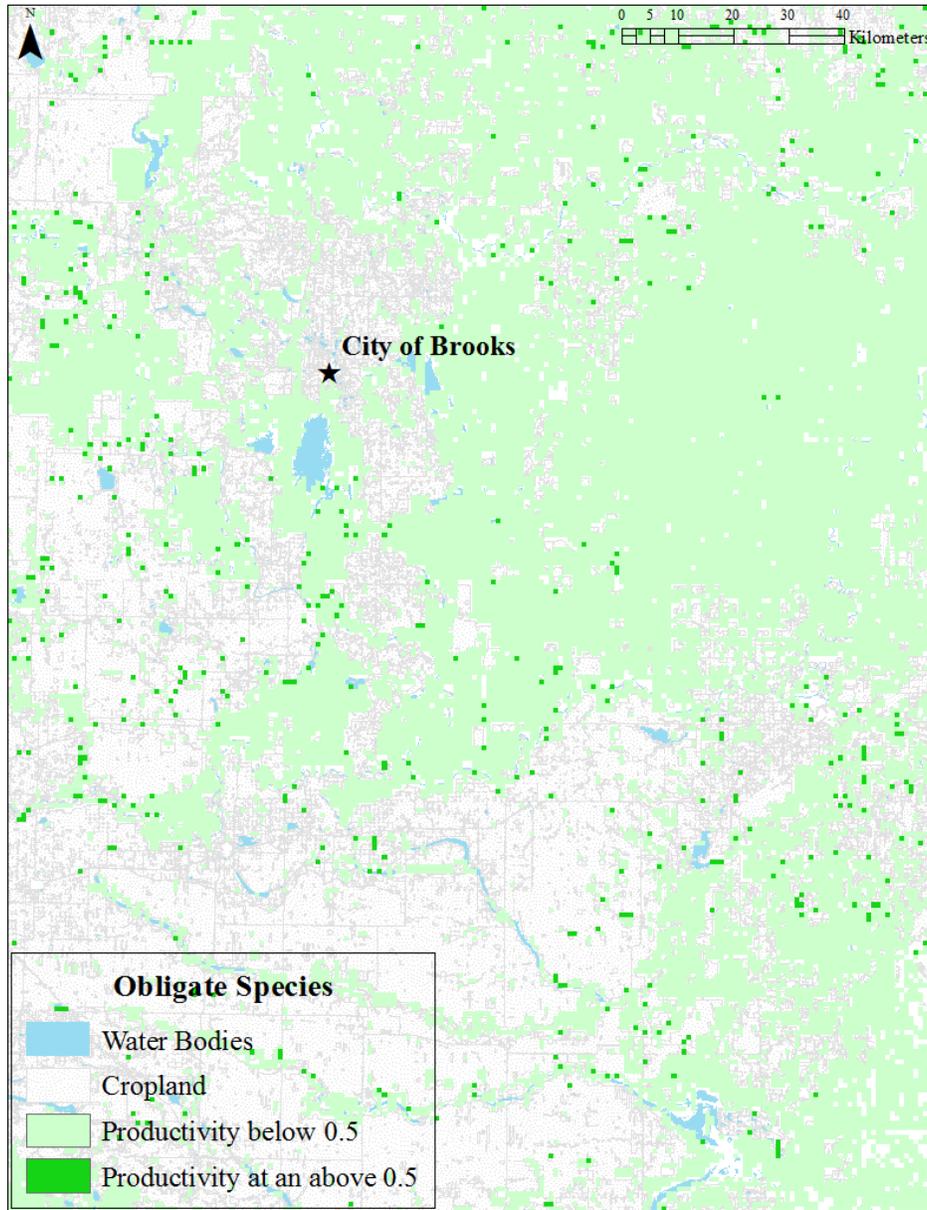
Figure 3.23. Regions in the study area where the predicted productivity, *Productivity* (*P*) = $\frac{Abundance \times Clutch\ Size \times Probabilty\ of\ Nesting\ Sucess}{P_{max}}$ is greater than or equal to 0.5 for obligate species, which were Chestnut-collared Longspur (*Calcarius ornatus*) and Sprague's Pipit (*Anthus spragueii*) (data collected from May 2010 to July 2014).

CHAPTER 4: MANAGEMENT IMPLICATIONS

The effects of distance to wells and roads vary with species and the measurement used to assess fitness. The extent to which there was an effect of distance to edge was similar for grassland obligates and generalist species. However, obligates, on average, were negatively affected by proximity to edge whereas generalists were more productive closer to edge. The effects of oil wells extended to the furthest distances for obligate and generalist species followed by roads for obligates and shallow gas wells for generalists. Overall, shallow gas wells affected a larger proportion of habitat since they are found at higher densities than oil wells. However, a comparison of the amount of energy a typical shallow gas well produces versus the area of habitat affected shows that they have a lower footprint than oil wells, suggesting they are more ecologically efficient.

The estimated buffer distances around roads and wells in this study could be used to identify areas where additional disturbances should be avoided since the effects of existing infrastructure do not to extend to these areas. It is expected that these distances will vary across regions and with vegetation characteristics. However, it would be useful to repeat observations at distances beyond the maximum distance used in this study to determine the threshold values since in some cases, the effects of edge lasted throughout the range of my data.

Since Baird's Sparrow, Chestnut-collared Longspur and Sprague's Pipit are listed under the Species at Risk Act in Canada (COSEWIC 2009; COSEWIC 2010b; COSEWIC 2012), minimizing the impacts of development are critical in promoting recovery. Potential mechanisms explaining negative effects of wells include noise, changes in vegetation characteristics (Habib et al. 2007; Bayne et al. 2008) and the presence of the tall structure (Riley et al. 2012). Furthermore, obligates are reported to avoid roads (Sutter et al. 2000). As such, it was not

surprising that the effect of roads extended to further distances than shallow gas wells since they act as corridors for predators (Ingelfinger and Anderson 2004; Wellicome and Kardynal 2014), are associated with noise from traffic (Reijnen and Foppen 1995), occupy more space and are associated with invasive vegetation (Ingelfinger and Anderson 2004). Additionally, an increase in road density is associated with the installation of oil wells, suggesting that the measured effects of oil (but not shallow gas) wells could partially be attributed to roads. Since the traffic volumes around the study sites are low, the impacts of roads could be due to increases in predation or functional degradation of vegetation. Nevertheless, minimizing the effects of roads and oil wells by replanting native vegetation or avoiding their placement in undisturbed areas could have a large, positive impact on productivity of obligates. This does not mean, however, that reducing the disturbances associated with shallow gas wells is not also critical, or that its presence does not affect obligates (Riley et al. 2012).

The fact that the distance to which there was an effect shallow gas wells was similar oil wells for generalist demonstrates that effects of all infrastructures, even those that are short and have a small footprint, must be managed. It is possible that the measured effects of gas wells are due to the higher occurrence of grazers near wells, which affect vegetation structure (Koper et al. 2014), making some areas suitable for generalists since they are not area or disturbance sensitive. Presumably, removing grazers from recently disturbed areas (Kalyn Bogard and Davis 2014), or reducing stocking rates (Pipher 2011), would improve the quality of potential nesting sites around gas wells. Conversely, since generalist abundance, clutch size and probability of nesting success seems to be lower further away from wells, confirming whether generalists are in fact more fit around wells is critical. Accordingly, limiting disturbances in habitat beyond threshold

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values for obligates, and restoring vegetation characteristic in disturbed areas, could benefit generalists, although their responses to distance to edge vary.

Oil wells appear to have a larger footprint than shallow gas wells, which could be problematic because Alberta has the third largest crude oil resource, is the third largest natural gas producer worldwide (Government of Alberta 2015) and10,000 to 15,000 new wells are drilled each year (Government of Alberta 2014b). Though limiting the number of new wells would be the most effective strategy to conserve habitat, because the oil and gas industry is the largest contributor to Alberta's Gross Domestic Product (Government of Alberta 2015), and provides 27 % to Canada's overall (Canadian Energy Pipeline Association 2015), such recommendations are not feasible. Limiting wells and roads, however, especially in areas that were previously undisturbed, could boost the overall productivity of grassland songbirds.

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Appendix I Annotated code used to run the statistical analysis and create the graphs for Chestnut-collared Longspur.

```
##############################################################################
##############################################################################
#####Identifying Distribution for Clutch Size and Abundance Data ####################
##############################################################################
##############################################################################
require(segmented)# for PWR
require(MASS)# for NB models
require(pscl)# to run likelihood ratio test for P vs NB
# DtoRoad is Distance to Road
# DtoOW is Distance to Oil Well
# DtoSGW is Distance to Shallow Gas Well
# CCLO is Baird's Sparrow
# DtOW and DtoSGW models for clutch size and nesting sucess were run,
#but because there were no observations under 100 m, figures were not created
# even when the slope was different from zero
##############################################################################
############################### Abundance ###################################
##############################################################################
# Import Abundance Data
Abundance <- read.delim("~/OneDrive/Documents/Master's Thesis/
                Inputs for Statistical Software/Text/ Abundance(edited).txt")
# Histogram to look at the spread of the data
hist(Abundance$CCLO)
###### It does not appear normally distributed
############ TEST FOR NORMALITY- Shapiro–Wilk test ##########
# If the p-value is less than alpha, then we reject the null hypothesis
# The null hypothesis is that the population is normally distributed
shapiro.test(Abundance$CCLO)#p-value < 2.2e-16
# The population is not normally distributed #
# The PWR cannot accommodate ZI models.
# As such, they will not be included.
# From Chapter 8 in Mixed Effects Models and Extensions in Ecology with R
# 8.8 Zero Truncated Distributions for Count Data
################# Testing for non-normal distributions #########
# Likelihood ratio test of H0: Poisson, as restricted NB model:
#n.b., the distribution of the test-statistic under H0 is non-standard
# alpha=0.01
odTest(CCLO.glm.abundance.nb, alpha=0.1)#2.2e-16
# NB is a better fit than P
##############################################################################
############################## Clutch Size ##################################
```

```
###############################################################################
# Import Clutch Size Data
ClutchSize <- read.delim("~/OneDrive/Documents/Master's Thesis/
                Inputs for Statistical Software/Text/ClutchSize(edited).txt")
#Creating subsets#
CCLO.ClutchSize<-subset(ClutchSize, Species=="CCLO")
#Histogram to look at the spread of the data
hist(CCLO.ClutchSize$Clutch.Size)
##Data appears non-normal
###### TEST FOR NORMALITY- Shapiro–Wilk test #####
# If the p-value is less than alpha, then we reject the null hypothesis
# The null hypothesis is that the population is normally distributed
shapiro.test(CCLO.ClutchSize$Clutch.Size)#p-value < 2.2e-16
# The population is not normally distributed #
####### Likelihood Ratio Tests for Non-Normal Distributions ########
# Likelihood ratio test of H0: Poisson, as restricted NB model:
#n.b., the distribution of the test-statistic under H0 is non-standard
# alpha=0.05
odTest(CCLO.glm.cs.nb)# 0.04542
# NB is a better fit


###############################################################################
###############################################################################
###### Assessing the fit of the NULL, GLM and PWR models for Abundance ###########
###############################################################################
###############################################################################
############# NULL ##########
# Running the NULL Model
CCLO.null.abundance<-glm.nb(CCLO~1, data=Abundance)
# Idenitfying the AIC for the NULL model
AIC(CCLO.null.abundance)
########## GLM ###############
# Running the GLMs for Distance to Oil Well, Shallow Gas Well, Road and
# Shallow Gas Well Density
## Running Distance to Oil Well ##
CCLO.abundance.glm.ow<-glm.nb(CCLO~DtoOW, data= Abundance.DtoOW)
## Identifying the AIC for DtoOW
AIC(CCLO.abundance.glm.ow)
#  Running Distance to Shallow Gas Well
CCLO.abundance.glm.sgw<-glm.nb(CCLO~DtoSGW, data= Abundance.DtoSGW)
#  Identifying the AIC for DtoSGW
AIC(CCLO.abundance.glm.sgw)
# Running Distance to Road
CCLO.abundance.glm.rd<-glm.nb(CCLO~DtoRoad, data= Abundance.DtoRoad)
```

# Identifying the AIC for DtoRoad
AIC(CCLO.abundance.glm.rd)
# Running Shallow Gas Well Density
CCLO.abundance.glm.den<-glm.nb(CCLO~SGWDensity, data= Abundance.SGWDensity)
# Identifying the AIC for SGWDensity
AIC(CCLO.abundance.glm.den)
############ **PWR** ###########
Running the PWR for Distance to Oil Well, Shallow Gas Well, Road and
Shallow Gas Well Density, where K is the number of breakpoints,
#seg.Z is the predictor variable and psi is the starting point
the model could use to search for the breakpoint. Psi is not required
when K=1. The object in the segmented statement (CCLO.abundance.glm.ow, for instance)
#is the GLM relating to that predictor, which was created when the GLM models were run
# Running Distance to Oil Well
CCLO.abundance.pwr.ow<-segmented(CCLO.abundance.glm.ow, seg.Z=~DtoOW,
                    psi=NA, control=seg.control(K=1))
Identifying the AIC for DtoOW
AIC(CCLO.abundance.pwr.ow)
# Running Distance to Shallow Gas Well Model
CCLO.abundance.pwr.sgw<-segmented(CCLO.abundance.glm.sgw, seg.Z=~DtoSGW,
                    psi=NA, control=seg.control(K=1))
# Identifying the AIC for DtoSGW
AIC(CCLO.abundance.pwr.sgw)
# Running Distance to Road Model
CCLO.abundance.pwr.rd<-segmented(CCLO.abundance.glm.rd, seg.Z=~DtoRoad,
                    psi=NA, control=seg.control(K=1))
# Identifying the AIC for DtoRoad
AIC(CCLO.abundance.pwr.rd)
# Running Shallow Gas Well Density Model
CCLO.abundance.pwr.den<-segmented(CCLO.abundance.glm.den, seg.Z=~SGWDensity,
                    psi=NA, control=seg.control(K=1))
# Identifying the AIC for SGWDensity
AIC(CCLO.abundance.pwr.den)

###
###
Assessing the fit of the NULL, GLM and PWR models for Clutch Size
###
###
NULL
# Running NULL model
CCLO.cs.null<-glm(Clutch.Size~1, data= CCLO.ClutchSize,family= poisson)
# Identifying AIC for NULL Model
AIC(CCLO.cs.null)

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GLM
# Running Distance to Oil Well Model
CCLO.cs.glm.ow<-glm(Clutch.Size~DtoOW, data= CCLO.ClutchSize,family= poisson)
# Identifying AIC for Distance to Oil Well Model
AIC(CCLO.cs.glm.ow)
# Running Distance to Shallow Gas Well Model
CCLO.cs.glm.sgw<-glm(Clutch.Size~DtoSGW, data= CCLO.ClutchSize,family= poisson)

# Identifying AIC for Distance to Shallow Gas Well Model
AIC(CCLO.cs.glm.sgw)
# Running Distance to Road Model
CCLO.cs.glm.rd<-glm(Clutch.Size~DtoRoad, data= CCLO.ClutchSize,family= poisson)
# Identifying AIC for Distance to Road Model
AIC(CCLO.cs.glm.rd)
# Running Shallow Gas Well Density Model
CCLO.cs.glm.den<-glm.(Clutch.Size~SGWDensity, data= CCLO.ClutchSize,family= poisson)
# Identiying AIC for Shallow Gas Well Density Model
AIC(CCLO.cs.glm.rd)
####### **PWR** #########
Running the PWR for Distance to Oil Well, Shallow Gas Well, Road and
Shallow Gas Well Density, where K is the number of breakpoints,
#seg.Z is the predictor variable and psi is the starting point
the model could use to search for the breakpoint. Psi is not required
when K=1. The object in the segmented statement (CCLO.cs.glm.ow, for instance)
#is the GLM relating to that predictor, which was created when the GLM models were run

# Running Distance to Oil Well Model
CCLO.cs.pwr.ow<-segmented(CCLO.cs.glm.ow, seg.Z=~DtoOW,
                psi=NA, control=seg.control(K=1))
# Identifying AIC for Distance to Oil Well Model
AIC(CCLO.cs.pwr.ow)
# Running Distance to Shallow Gas Well Model
CCLO.cs.pwr.sgw<-segmented(CCLO.cs.glm.sgw, seg.Z=~DtoSGW,
                psi=NA, control=seg.control(K=1))
# Identifying AIC for Distance to Shallow Gas Well Model
AIC(CCLO.cs.pwr.sgw)
# Running Distance to Road Model
CCLO.cs.pwr.rd<-segmented(CCLO.cs.glm.rd, seg.Z=~DtoRoad,
                psi=NA, control=seg.control(K=1))
# Identifying AIC for Distance to Road Model
AIC(CCLO.cs.pwr.rd)
# Running Shallow Gas Well Density Model
CCLO.cs.pwr.den<-segmented(CCLO.cs.glm.den, seg.Z=~SGWDensity,
                psi=NA, control=seg.control(K=1))

```
# Identifying AIC for Shallow Gas Well Density Model
AIC(CCLO.cs.pwr.den)


###############################################################################
###############################################################################
##### Assessing the fit of the NULL, GLM and PWR models for Nesting Success #########
###############################################################################
###############################################################################

# Because nesting success is binomial (only 0 or 1 as an outcome) and the time a nest
# is exposed affects the probability of nesting success, I will use the logistic exposure
#code from Shaffer 2003.
######### Logistic Exposure#####################
#Begin Shaffer's code for GLM logistic Exposure link function
logexp = function(Expos = 1)
{
 linkfun = function(mu) qlogis(mu^(1/Expos))
 linkinv = function(eta)  plogis(eta)^Expos
 mu.eta = function(eta) Expos * plogis(eta)^(Expos-1) *
  .Call(stats:::C_logit_mu_eta, eta, PACKAGE = "stats")
 valideta <- function(eta) TRUE
 link = paste("logexp(", deparse(substitute(Expos)), ")",
          sep="")
 structure(list(linkfun = linkfun, linkinv = linkinv,
           mu.eta = mu.eta, valideta = valideta,
           name = link),
       class = "link-glm")
}
#End Shaffer's link code
####################################################################
# The logistic exposure code gave problems when there was missing data "NA"
# Each column was edited separately. When there was not an observation per 100m
# All observations were removed above that point. As such, text files were created
# for each predictor and since the null model does not require predictor varibles
# (which would have NAs), the file used for the NULL model contains all the predictors
# with NAs for removed observations

#### Importing nesting success data for NULL Model
Exposure <- read.delim("~/OneDrive/Documents/Master's Thesis/
                Inputs for Statistical Software/Text/Exposure(Edited).txt")
#### Importing nesting success data for GLM and PWR Models
Exposure.DtoOW <- read.delim("~/OneDrive/Documents/Master's Thesis
                /Inputs for Statistical Software/Text/Exposure(DtoOW).txt")
Exposure.DtoSGW <- read.delim("~/OneDrive/Documents/Master's Thesis
```

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```
                        /Inputs for Statistical Software/Text/Exposure(DtoSGW).txt")
Exposure.DtoRoad <- read.delim("~/OneDrive/Documents/Master's Thesis/
                        Inputs for Statistical Software/Text/Exposure(DtoRoad).txt")
Exposure.SGWDensity <- read.delim("~/OneDrive/Documents/Master's Thesis/
                        Inputs for Statistical Software/Text/Exposure(SGWDensity).txt")
####### Creating Subsets ########
# NULL Model
CCLO.Exposure<-subset(Exposure, Species=="CCLO")
### Data used for GLM and PWR
CCLO.Exposure.DtoOW<-subset(Exposure.DtoOW, Species=="CCLO")
CCLO.Exposure.DtoSGW<-subset(Exposure.DtoSGW, Species=="CCLO")
CCLO.Exposure.DtoRoad<-subset(Exposure.DtoRoad, Species=="CCLO")
CCLO.Exposure.SGWDensity<-subset(Exposure.SGWDensity, Species=="CCLO")
# Running NULL Model
#Trials=1, Expos is the number of days between observations
CCLO.exp.null <- glm(Survive/Trials ~ 1,
            family = binomial(logexp(CCLO.Exposure$Expos)),
            data=CCLO.Exposure)
# Identifying AIC for NULL Model
AIC(CCLO.exp.null)
##### GLM #######
#Trials=1, Expos is the number of days between observations
# Running Distance to Oil Well Model
CCLO.exp.glm.ow <- glm(Survive/Trials ~ DtoOW,
              family = binomial(logexp(CCLO.Exposure.DtoOW$Expos)),
              data=CCLO.Exposure.DtoOW)
# Identifying AIC for Distance to Oil Gas Well Model
AIC(CCLO.glm.ow)
# Running Distance to Shallow Gas Well Model
CCLO.exp.glm.sgw <- glm(Survive/Trials ~ DtoSGW,
               family = binomial(logexp(CCLO.Exposure.DtoSGW$Expos)),
               data=CCLO.Exposure.DtoSGW)
# Identifying AIC for Distance to Shallow Gas Well Model
AIC(CCLO.exp.glm.sgw)

# Running Distance to Road Model
CCLO.exp.glm.rd <- glm(Survive/Trials ~ DtoRoad,
              family = binomial(logexp(CCLO.Exposure.DtoRoad$Expos)),
              data=CCLO.Exposure.DtoRoad)
# Identifying AIC for Distance to Road Model
AIC(CCLO.glm.rd)
# Running Shallow Gas Well Density Model

CCLO.exp.glm.den <- glm(Survive/Trials ~ SGWDensity,
```

```
                    family = binomial(logexp(CCLO.Exposure.SGWDensity$Expos)),
                    data=CCLO.Exposure.SGWDensity)
# Identifying AIC Shallow Gas Well Density Model
AIC(CCLO.glm.den)
```

PWR

```
# Running the PWR for Distance to Oil Well, Shallow Gas Well, Road and
# Shallow Gas Well Density, where K is the number of breakpoints,
#seg.Z is the predictor variable and psi is the starting point
# the model could use to search for the breakpoint. Psi is not required
# when K=1. The object in the segmented statement (CCLO.exp.glm.ow, for instance)
#is the GLM relating to that predictor, which was created when the GLM models were run
#Trials=1, Expos is the number of days between observations
# Running Distance to Oil Well Model
CCLO.exp.pwr.ow<-segmented(CCLO.exp.glm.ow, seg.Z=~DtoOW,
                    psi=NA, control=seg.control(K=1))
# Identifying AIC for Distance to Oil Well Model
AIC(CCLO.exp.pwr.ow)
# Running Distance to Shallow Gas Well Model
CCLO.exp.pwr.sgw<-segmented(CCLO.exp.glm.sgw, seg.Z=~DtoSGW,
                    psi=NA, control=seg.control(K=1))
# Identifying AIC for Distance to Shallow Gas Well Model
AIC(CCLO.exp.pwr.sgw)
# Running Distance to Road Model
CCLO.exp.pwr.rd<-segmented(CCLO.exp.glm.rd, seg.Z=~DtoRoad,
                    psi=NA, control=seg.control(K=1))
# Identifying AIC for Distance to Road Model
AIC(CCLO.exp.pwr.rd)
# Running Shallow Gas Well Density Model
CCLO.exp.pwr.den<-segmented(CCLO.exp.glm.den, seg.Z=~SGWDensity,
                    psi=NA, control=seg.control(K=1))
# Identifying AIC for Shallow Gas Well Density
AIC(CCLO.exp.pwr.den)


##############################################################################
##############################################################################
```

Graphs for best-fitting models when the slope was different from zero

```
##############################################################################
##############################################################################
require(extrafont)# Times New Roman
require(ggplot2)# To create graphs
require(segmented)#To attain CI for breakpoints, where applicable
```

Abundance

```
## Distance to Road(PWR) #
```

```r
confint.segmented (CCLO.abundance.pwr.rd, type="response", level=0.90)#CI for breakpoint
#47.89    -758.5    854.3


CCLO.Abundance.DtoRoad<-data.frame(DtoRoad = Abundance.DtoRoad$DtoRoad) #Create a
data frame with xvalues
CCLO.ab.rd.pred <- predict(CCLO.abundance.pwr.rd,
                newdata = CCLO.Abundance.DtoRoad, type = 'response',se = TRUE) #predicted
values
CCLO.Abundance.DtoRoad$fit <- CCLO.ab.rd.pred$fit #add predicted values to dataframe for
DtoRoad


CCLO.Abundance.DtoRoad$ymax <- CCLO.ab.rd.pred$fit+ 1.645*CCLO.ab.rd.pred$se.fit
#calculate UCL
CCLO.Abundance.DtoRoad$ymin <- CCLO.ab.rd.pred$fit - 1.645 *CCLO.ab.rd.pred$se.fit
#calculate LCL


ggplot(Abundance.DtoRoad,aes(x = DtoRoad, y = CCLO)) +  #calls dataframe with rawdata
  geom_point() + #puts in raw data
  geom_ribbon(data = CCLO.Abundance.DtoRoad,aes(y = fit, ymin = ymin, ymax = ymax),alpha
= 0.25) + #plot CI
  geom_line(data = CCLO.Abundance.DtoRoad,aes(y = fit),colour = "black")+ #plots fitted line
  ggtitle("Chestnut-collared Lonspur")+ #title
  scale_size_area() +
  xlab("Distance to Road (m)") +
  ylab("Predicted Abundance")+
  theme(plot.title = element_text(hjust = 0),
      text=element_text(family="Times New Roman", face="bold", size=12))


# Distance to Shallow Gas Well (PWR) #
confint.segmented (CCLO.abundance.pwr.sgw, type="response", level=0.90)#CI for breakpoint
# 247    152.3    341.7
CCLO.Abundance.DtoSGW<-data.frame(DtoSGW = Abundance.DtoSGW$DtoSGW) #Create a
data frame with xvalues
CCLO.ab.sgw.pred <- predict(CCLO.abundance.pwr.sgw,
                newdata = CCLO.Abundance.DtoSGW, type = 'response',se = TRUE)
#predicted values
CCLO.Abundance.DtoSGW$fit <- CCLO.ab.sgw.pred$fit #add predicted values to dataframe for
DtoSGW


CCLO.Abundance.DtoSGW$ymax <- CCLO.ab.sgw.pred$fit+ 1.645*CCLO.ab.sgw.pred$se.fit
#calculate UCL
CCLO.Abundance.DtoSGW$ymin <- CCLO.ab.sgw.pred$fit - 1.645 *CCLO.ab.sgw.pred$se.fit
#calculate LCL
```

```
ggplot(Abundance.DtoSGW,aes(x = DtoSGW, y = CCLO)) +  #calls dataframe with rawdata
  geom_point() + #puts in raw data
  geom_ribbon(data = CCLO.Abundance.DtoSGW,aes(y = fit, ymin = ymin, ymax = ymax),alpha
= 0.25) + #plot CI
  geom_line(data = CCLO.Abundance.DtoSGW,aes(y = fit),colour = "black")+ #plots fitted line
  geom_vline(xintercept=c(152.3 ,341.7), linetype="dashed")+ #plots CI around breakpoint
  ggtitle("Chestnut-collared Lonspur")+ #title
  scale_size_area() +
  xlab("Distance to Shallow Gas Well (m)") +
  ylab("Predicted Abundance")+
  theme(plot.title = element_text(hjust = 0),
      text=element_text(family="Times New Roman", face="bold", size=12))


# Shallow Gas Well Density (GLM) #
CCLO.Abundance.SGWDensity<-data.frame(SGWDensity =
Abundance.SGWDensity$SGWDensity) #Create a data frame with xvalues
CCLO.ab.den.pred <- predict(CCLO.abundance.glm.den,
                newdata = CCLO.Abundance.SGWDensity, type = 'response',se = TRUE)
#predicted values
CCLO.Abundance.SGWDensity$fit <- CCLO.ab.den.pred$fit #add predicted values to dataframe
for SGWDensity

CCLO.Abundance.SGWDensity$ymax <- CCLO.ab.den.pred$fit+
1.645*CCLO.ab.den.pred$se.fit #calculate UCL
CCLO.Abundance.SGWDensity$ymin <- CCLO.ab.den.pred$fit - 1.645
*CCLO.ab.den.pred$se.fit #calculate LCL

ggplot(Abundance.SGWDensity,aes(x = SGWDensity, y = CCLO)) +  #calls dataframe with
rawdata
  geom_point() + #puts in raw data
  geom_ribbon(data = CCLO.Abundance.SGWDensity,aes(y = fit, ymin = ymin, ymax =
ymax),alpha = 0.25) + #plot CI
  geom_line(data = CCLO.Abundance.SGWDensity,aes(y = fit),colour = "black")+ #plots fitted
line
  ggtitle("Chestnut-collared Lonspur")+ #title
  scale_size_area() +
  xlab("Shallow Gas Well Density (#/2.56 square kilometer)") +
  ylab("Predicted Abundance")+
  theme(plot.title = element_text(hjust = 0),
      text=element_text(family="Times New Roman", face="bold", size=12))
################### Clutch Size #################
# Distance to Shallow Gas Well(PWR) #
confint.segmented (CCLO.cs.pwr.sgw, type="response", level=0.90) # To attain CI around
breakpoint
```

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# 35 -2821   2891
CCLO.cs.DtoSGW<-data.frame(DtoSGW =CCLO.ClutchSize.DtoSGW$DtoSGW) #Create a data frame with xvalues
CCLO.cs.sgw.pred <- predict(CCLO.cs.pwr.sgw,
                 newdata = CCLO.cs.DtoSGW, type = 'response',se = TRUE) #predicted values
CCLO.cs.DtoSGW$fit <- CCLO.cs.sgw.pred$fit #add predicted values to dataframe for DtoSGW

CCLO.cs.DtoSGW$ymax <- CCLO.cs.sgw.pred$fit+ 1.645*CCLO.cs.sgw.pred$se.fit #calculate UCL
CCLO.cs.DtoSGW$ymin <- CCLO.cs.sgw.pred$fit - 1.645 *CCLO.cs.sgw.pred$se.fit #calculate LCL

ggplot(CCLO.ClutchSize.DtoSGW,aes(x = DtoSGW, y = Clutch.Size)) + #calls dataframe with rawdata
  geom_point() + #puts in raw data
  geom_ribbon(data = CCLO.cs.DtoSGW,aes(y = fit, ymin = ymin, ymax = ymax),alpha = 0.25) + #plot CI
  geom_line(data = CCLO.cs.DtoSGW,aes(y = fit),colour = "black")+ #plots fitted line
  ggtitle("Chestnut-collared Lonspur")+ #title
  scale_size_area() +
  xlab("Distance to Shallow Gas Well (m)") +
  ylab("Predicted Clutch Size")+
  theme(plot.title = element_text(hjust = 0),
      text=element_text(family="Times New Roman", face="bold", size=12))
#################### **Nesting Success** ################
Distance to Shallow Gas Well(PWR)
confint.segmented (CCLO.exp.pwr.sgw, type="response", level=0.90) # To attain CI around breakpoint
#209.6   109.4   309.8
CCLO.exp.DtoSGW<-data.frame(DtoSGW =CCLO.Exposure.DtoSGW$DtoSGW) #Create a data frame with xvalues
CCLO.exp.sgw.pred <- predict(CCLO.exp.pwr.sgw,
                 newdata = CCLO.exp.DtoSGW,se = TRUE) #predicted values
CCLO.exp.DtoSGW$fit <- 1/(1+exp(-CCLO.exp.sgw.pred$fit)) #add predicted values to dataframe for DtoSGW

CCLO.exp.DtoSGW$ymax <- 1/(1+(exp(-(CCLO.exp.sgw.pred$fit+ 1.645*CCLO.exp.sgw.pred$se.fit)))) #calculate UCL
CCLO.exp.DtoSGW$ymin <- 1/(1+(exp(-(CCLO.exp.sgw.pred$fit - 1.645 *CCLO.exp.sgw.pred$se.fit)))) #calculate LCL
CCLO.exp.DtoSGW$fit <- 1/(1+exp(-CCLO.exp.sgw.pred$fit)) #add predicted values to dataframe for DtoSGW
CCLO.Exposure.DtoSGW$Success<-ifelse(CCLO.Exposure.DtoSGW$Survive == 0,0,0.0000000001)

```
ggplot(CCLO.Exposure.DtoSGW,aes(x = DtoSGW, y = Success)) + #calls dataframe with
rawdata
  geom_point(shape="|") + #puts in raw data
  geom_ribbon(data = CCLO.exp.DtoSGW,aes(y = fit, ymin = ymin, ymax = ymax),alpha = 0.25)
+ #plot CI
  geom_line(data = CCLO.exp.DtoSGW,aes(y = fit),colour = "black")+ #plots fitted line
  geom_vline(xintercept=c(109.4,309.8), linetype="dotted")+ #plots CI around breakpoint
  ggtitle("Chestnut-collared Lonspur")+ #title
  scale_size_area() +
  xlab("Distance to Shallow Gas Well (m)") +
  ylab("Probability of Nesting Sucess")+
  theme(legend.position = "none", plot.title = element_text(hjust = 0),
      text=element_text(family="Times New Roman", face="bold", size=12))

# Shallow Gas Well Density (GLM) #
CCLO.exp.SGWDensity<-data.frame(SGWDensity =
CCLO.Exposure.SGWDensity$SGWDensity) #Create a data frame with xvalues
CCLO.exp.den.pred <- predict(CCLO.exp.glm.den,
                newdata = CCLO.exp.SGWDensity,se = TRUE) #predicted values
CCLO.exp.DtoSGW$fit <- 1/(1+exp(-CCLO.exp.sgw.pred$fit)) #add predicted values to
dataframe for DtoSGW

CCLO.exp.SGWDensity$fit <- 1/(1+exp(-(CCLO.exp.den.pred$fit))) #add predicted values to
dataframe for SGWDensity

CCLO.exp.SGWDensity$ymax <- 1/(1+exp(-(CCLO.exp.den.pred$fit+
1.645*CCLO.exp.den.pred$se.fit))) #calculate UCL
CCLO.exp.SGWDensity$ymin <- 1/(1+exp(-(CCLO.exp.den.pred$fit -
1.645*CCLO.exp.den.pred$se.fit))) #calculate LCL
CCLO.Exposure.SGWDensity$Success<-ifelse(CCLO.Exposure.SGWDensity$Survive ==
0,0,0.0000000001)
ggplot(CCLO.Exposure.SGWDensity,aes(x = SGWDensity, y = Success)) + #calls dataframe
with rawdata
  geom_point(shape="|") + #puts in raw data
  geom_ribbon(data = CCLO.exp.SGWDensity,aes(y = fit, ymin = ymin, ymax = ymax),alpha =
0.25) + #plot CI
  geom_line(data = CCLO.exp.SGWDensity,aes(y = fit),colour = "black")+ #plots fitted line
  ggtitle("Chestnut-collared Lonspur")+ # title
  scale_size_area() +
  xlab("Shallow Gas Well Density (#/2.56 square kilometer)") +
  ylab("Probability of Nesting Sucess")+
  theme(plot.title = element_text(hjust = 0),
      text=element_text(family="Times New Roman", face="bold", size=12))
```

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Appendix 2 Parameters used to create geostatistical layer in ArcMap 10.2.1 using Ordinary Krigging from observed data. For each layer, the maximum number of neighbour to include was five, the minimum number of neighbours was two, the sector type was four and 45 degrees, the number of lags was 12, the model type was stable and no anisotropy was used.

		Variogram					Model Type	
Response	Species	Major Semiaxis	Minor Semiaxis	Lag Size	Nugget	Parameter	Range	Partial Sill
Nesting Success	WEME	9.26E+03	9.26E+03	1.11E+03	1.99E-01	2.00	9,260.03	5.41E-02
Nesting Success	VESP	11,78.478	11,78.478	1.27E+03	1.49E-01	2.00	11,78.478	1.53E-02
Nesting Success	SPPI	1.25E+05	1.25E+05	1.04E+04	1.58E-01	0.20	124,891.51	0.00E+00
Nesting Success	SAVS	1.65E+04	1.65E+04	1.88E+03	2.10E-01	2.00	16,547.20	5.91E-03
Nesting Success	CCLO	1.41E+05	1.41E+05	1.17E+04	2.19E-01	2.00	140,533.59	1.17E-02
Clutch Size	VESP	1.23E+03	1.23E+03	1.38E+02	1.29E+00	1.11	1,194.40	1.56E+00
Clutch Size	SPPI	3.87E+03	3.87E+03	4.49E+02	2.03E+00	2.00	3,873.65	6.80E+00
Clutch Size	SAVS	1.38E+03	1.38E+03	1.03E+02	9.90E-03	0.43	919.05	3.46E+00
Clutch Size	CCLO	1.41E+03	1.41E+03	1.86E+01	1.48E+00	2.00	119.43	2.36E+00
Abundance	WEME	1.16E+04	1.16E+04	1.36E+03	2.91E+00	2.00	11,597.41	4.32E-01
Abundance	VESP	1.68E+04	1.68E+04	2.54E+03	7.23E-01	2.00	16,819.64	1.01E-01
Abundance	SPPI	2.29E+04	2.29E+04	3.36E+03	3.24E+00	2.00	22,939	6.67E-01
Abundance	SAVS	3.54E+04	3.54E+04	4.24E+03	1.14E+01	2.00	35,438.17	1.38E+00
Abundance	CCLO	8.12E+03	8.12E+03	9.53E+02	1.17E+01	2.00	8,119.87	7.76E+00