Duck Populations and the Oil and Gas Industry in the Boreal Plains of Alberta

By

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ABSTRACT

The boreal forest of northern Alberta supports a large portion of North America's breeding duck population in addition to being an area of importance to the petroleum industry. Breeding duck surveys in the Boreal Plains ecozone show several ground nesting species are in decline while cavity and over-water nesters are showing both positive and negative population trends since the 1970s. Industry has been identified as a limiting factor that may be influencing duck populations and species composition in the region, but there has been limited empirical research to test this assertion. The objectives of this research were to (1) assess the hypothesis that as aerial extent and activity associated with industry increases, breeding waterfowl populations will decrease over the same time period and (2) determine the best climate data aggregations when modelling industrial effects on duck populations.

Mixed effects logistic regression models were used to analyse relationships between breeding duck pair counts and a combination of climate, environmental, landscape, and industry variables. Top models showed consistent results across nesting guilds, including a small, negative relationship between breeding pairs and cumulative areas of petroleum infrastructure, and a positive relationship between both cumulative infrastructure edge and industrial activity with breeding pairs.

The impact of using different seasonal classifications for understanding relationships between breeding duck populations and industrial development was examined using no climate data (null), and annual, two, four, and five seasons. Predictions of duck densities across gradients of oil and gas infrastructure and activity were generated using models fit with different seasonal aggregations. Different seasonal aggregations showed similar patterns for relationships between industry variables and breeding duck density but the presence of industry variables in models did vary by seasonal classification. Variation was also observed between nesting guild and industry measure for predicted duck pair densities.

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CHAPTER 1. INTRODUCTION

1.1 WATERFOWL AND INDUSTRY IN THE WESTERN BOREAL FOREST

Each spring, over 12 million waterfowl migrate to the western boreal forest (WBF) of Canada making it a priority area for wetland and waterfowl conservation (Prairie Habitat Joint Venture 2008, Slattery, Morissette et al. 2011, Prairie Habitat Joint Venture 2014). The timing of migration and arrival to the breeding grounds of the WBF are determined largely by climate cues which can differ among species (Murphy-Klassen, Underwood et al. 2005, Yali, Qinchuan et al. 2015). Breeding pairs arrive to the WBF and disperse in low densities over a mosaic of forest and wetland habitats (Downing and Pettapieve 2006, Fast, Collins et al. 2011, Alberta NAWMP Partnership 2013). Wetlands of varying size and type, and surrounding uplands provide the necessary habitat to support the millions of arrivals (Smith, Smith et al. 2007). However, some duck species' populations are in decline, while others are showing modest increases relative to long-term averages (Haszard and Clark 2007, Prairie Habitat Joint Venture 2008, Fast, Collins et al. 2011, Nummi, Paasivaara et al. 2013).

It is theorized that the changing composition and declining populations of ducks in the region is due to climate change and industrial development (Fast, Collins et al. 2011, Slattery, Morissette et al. 2011, Prairie Habitat Joint Venture 2014). The oil and gas industry is hypothesised to be impacting breeding waterfowl by reducing habitat and degrading habitat by altering hydrological flow and wetland connectivity which might have negative consequences on waterfowl populations (Prairie Habitat Joint Venture 2008, Graf 2009, Prairie Habitat Joint Venture 2014). Anthropogenic noise and activity may also be negatively impacting waterfowl but there has been limited studies on breeding waterfowl's response to these types of disturbances (Borgmann 2011).

The boreal plains region of Alberta includes the Western Canadian Sedimentary Basin (WCSB) where rich deposits of crude oil and natural gas are found. Oil and gas have been part of Alberta's economy since the early 1900s, but it wasn't until technological advances developed in the early 1990s, coupled with increasing demand and prices that the oil and gas industry saw considerable growth and development (Dusseault 2002, Government of Canada 2006). The WCSB contains bitumen, a heavy crude oil product mixed with varying amounts of clay and sand, found at different depths beneath the earth's surface. Only a small fraction is mined at the surface (3%), with the majority extracted *in-situ* using either horizonal wells and steam assisted gravity drainage, or cyclic steam simulation (Dusseault 2002). In addition to the oil and gas industry, other anthropogenic disturbances in the region include foresty, mining, and agriculture (Schindler 1998, Schindler 2001, Schneider, Stelfox et al. 2003, Alberta Biodiversity Monitoring Institute 2007, Schindler and Lee 2010). Yet, despite the prevalence of industry in the region and its importance to waterfowl populations, little is known about how industry and waterfowl interact (Slattery, Morissette et al. 2011). With several species of ducks in decline in the region, an understanding of how petroleum infrastructure and activity relates to waterfowl populations becomes increasingly important with forecasted industry expansion (Schneider, Stelfox et al. 2003, Slattery, Morissette et al. 2011).

Attention to the relationship between industry and ducks is also important for the development of more effective conservation strategies. Currently, waterfowl conservation in the WBF emphasises large scale protectionist policy initiatives, wetland mapping, and developing best management practices with a focus on road construction, wetland crossings, and wetland reclamation (Prairie Habitat Joint Venture 2008, Partington and Gillies 2010, Ducks Unlimited Canada 2014, Prairie Habitat Joint Venture 2014, Partington, Gillies et al. 2016). This focus of conservation efforts on industry is guided by assumptions that industry is limiting duck populations. This research was undertaken to better understand the relationships between industry and duck populations to enable effective, and efficient waterfowl conservation to be applied in the region. Understanding how industry is impacting breeding ducks is important in developing best management practices, mitigating the effects of industry, and targeting conversation (Prairie Habitat Joint Venture 2008, Prairie Habitat Joint Venture 2014, Alberta Government and Environment and Climate Change Canada 2016).

In addition to industry, climate change is theorized to be impacting some species of ducks in a negative way. The phenological mismatch hypothesis, where a changing climate can throw off the synchronisation of peak food supplies and favourable habitat conditions for some species of ducks is believed to a factor contributing to downward population trends (Drever, Clark et al. 2012, Guillemain, Pöysä et al. 2013). However, there are a number of complex ecological relationships that are poorly understood relating to how climate can change duck behaviour and breeding success, which can vary be species and geography (for a review see Guillemain, Pöysä et al. 2013). Climate change could also be negatively impacting duck populations in the WBF by changing habitat conditions as a result of reduced precipitation and snow accumulation (Drever, Clark et al. 2012). Drier conditions could also result in an increase of forest fires, which have the potential to reduce food availability in wetland habitats by changing nutrient compositions (Schindler 2001, Haszard and Clark 2007).

It is important to understand how climate and weather influence populations, as climate can account for a large portion (75-98%) of population variability for some waterfowl species (Forcey, Thogmartin et al. 2011, Börger and Nudds 2014). Waterfowl studies often include climate data (e.g. Drever, Clark et al. 2012, Barker, Cumming et al. 2014, Ross, Hooten et al. 2015, Roy, McIntire et al. 2015), but the way in which climate data are aggregated has not been examined. So to better understand how industry is related to duck populations, I tested the implications of using different seasonal aggregations of local climate data in models that examine relationships between industry and breeding duck populations. This is important because controlling for climate supports better parametrized models to better understand industrial effects. Understanding how climate and anthropogenic impacts relate to duck populations has been identified as a key area of research (Holopainen, Arzel et al. 2015).

1.2 THESIS OBJECTIVES AND ORGANIZATION

The overall objective of this research is to determine how the petroleum industry is related to breeding duck populations in the boreal plains of Alberta. The following research questions were formed to meet this objective:

1. How does increasing oil and gas infrastructure and activity relate to breeding duck populations?

2. Does the treatment of climate data influence model performance and predicted outcomes when exploring the relationship between oil and gas infrastructure and activity and duck populations?

To address question (1) general linear mixed models were fit to breeding pair counts with a combination of landscape, climate, and industry measures (Chapter 2). For question (2), different seasonal classifications were used in the best models developed for question (1) to see if how climate data was classified changed the results (Chapter 3). Chapter 4 summarizes the information presented in chapters 2 and 3 and concludes with this study's findings, management implications and recommendations for future research.

CHAPTER 2. OIL AND GAS INFRASTRUCTURE EXTENT AND ACTIVITY IN THE BOREAL PLAINS OF ALBERTA: IMPACT ON BREEDING DUCKS 1980 - 2010

2.1 ABSTRACT

The boreal forest of northern Alberta supports a large portion of North America's breeding duck population in addition to being an area of importance to the petroleum industry. The boreal forest has been experiencing increased levels of petroleum extraction since the 1990s but little is understood how this increase relates to duck populations. Breeding duck surveys in the Boreal Plains ecozone show several ground nesting species are in decline while cavity and over-water nesters are showing both positive and negative population trends since the 1970s. Despite the importance of the boreal forest to breeding duck populations and the petroleum industry, impacts of the industry on ducks has not been well researched. Our objective was to assess how the aerial extent of infrastructure and activity associated with the petroleum industry are related to breeding duck populations over a 30 year time period. Using mixed effects logistic regression, we modelled breeding duck pair counts by nesting guild, using a combination of climate, environmental, landscape, and petroleum industry measures as explanatory variables. Top models showed consistent results across nesting guilds, including a small, negative relationship between breeding pairs and cumulative area of infrastructure, and a positive relationship between both cumulative infrastructure edge and petroleum industrial activity with breeding pairs. Based on our results, we conclude that not all petroleum infrastructure and activity are having a negative impact on breeding duck populations. We recommend that conservation policies and industry practices designed to increase or sustain duck populations should limit cumulative industrial area. However, the positive and negative effects of industry on duck populations observed in our models suggest that additional factors are impacting populations in the region that are not captured in this analysis. Future research should explore how landscape composition changes with increased industry, and how that may be impacting breeding, nest success, and brood rearing for ducks in the boreal plains of northern Alberta.

2.2 INTRODUCTION

2.2.1 BACKGROUND

The boreal plains is important to continental waterfowl populations with millions of breeding ducks found in low densities over large areas (Fast, Collins et al. 2011, Slattery, Morissette et al. 2011, Alberta NAWMP Partnership 2013). However, long-term waterfowl surveys show some species' populations are declining in the boreal forest, while some species are showing modest increases (Haszard and Clark 2007, Prairie Habitat Joint Venture 2008, Fast, Collins et al. 2011, Nummi, Paasivaara et al. 2013). Several ground nesting species are of concern with declining populations since the 1970s (e.g. Mallard (*Anas platyrhynchos*), American Wigeon (*Anas americana*), Lesser (*Aythya affinis*) and Greater Scaup (*Aythya marila*) (Fast, Collins et al. 2011). The region also lies within the Western Canadian Sedimentary Basin where rich deposits of crude oil and natural gas are found. Here we use the term petroleum (or oil and gas) to refer to naturally occurring hydro-carbons that include crude oil, natural gas, natural gas liquids, and bitumen. Our focus is on *in-situ* extraction of crude oil conducted with horizontal wells and steam assisted gravity drainage or vertical wells and cyclic steam stimulation. In addition to the petroleum industry, forestry, mining, and agriculture all contribute to the anthropogenic footprint in the region (Figure 1).

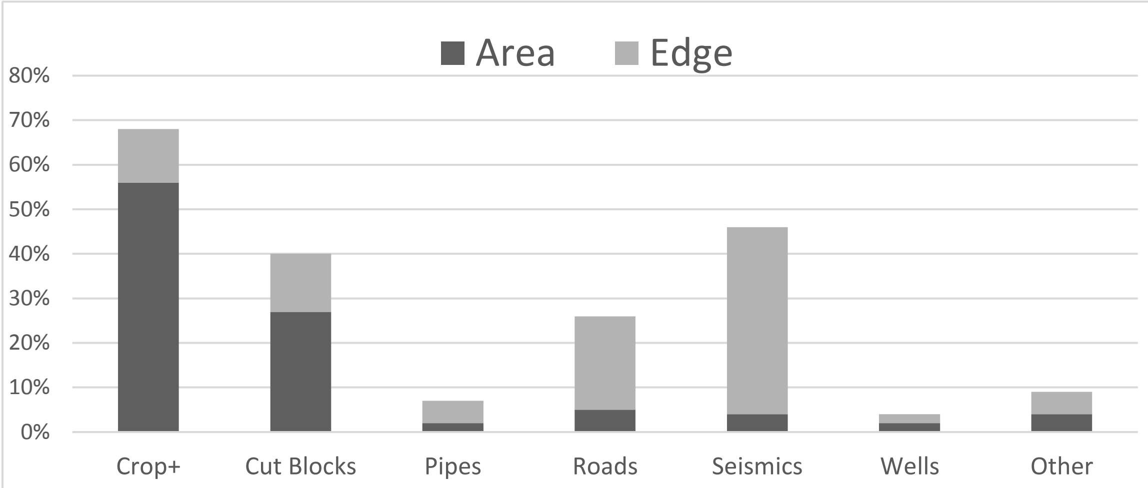

Figure 1 Summary of anthropogenic features in the Boreal Plains ecozone. The most predominant land use in the region is agriculture (Crop (+) includes cultivation, pasture, and bare ground), followed by forestry (Cut Blocks). Features associated with the oil and gas industry contribute to a small portion of overall anthropogenic area, but a large portion of anthropogenic edge. Source: AMBI 2010

The overall areal extent of agriculture and forestry (cut blocks) is larger than the extent of petroleum features, but linear features of industry, especially seismic and roads, create a significantly larger amount of anthropogenic edge compared to other land uses (Figure 1). The impact of increased habitat edge from anthropogenic activity adds to habitat fragmentation, a component of landscape change that has become an important area of study within conservation biology (Lindenmayer and Fischer 2006). Linear features that contribute to this anthropogenic edge include roads, pipelines, and cut-lines (2 - 8 metre swaths cut for seismic surveys) that fragment and reduce natural habitats. Additional infrastructure of the petroleum industry include facility processing sites and well pads that require regular maintenance and can produce anthropogenic noise.

Industrial activity and anthropogenic disturbances has been increasing in the boreal forest of Alberta (Schindler 1998, Schindler 2001, Schneider, Stelfox et al. 2003, Alberta Biodiversity Monitoring Institute 2007, Schindler and Lee 2010). Yet, despite the prevalence of petroleum activity in the region and its importance to duck populations, little is known about how industry and ducks interact (Slattery, Morissette et al. 2011). With several species of ducks in decline in the region, an understanding of how industrial infrastructure and activity relates to duck populations becomes increasingly important with forecasted industry expansion (Schneider, Stelfox et al. 2003, Slattery, Morissette et al. 2011).

In the WBF, studies on the impacts of the oil and gas industry has been focused on other taxa, namely songbird and mammalian species. Oil and gas infrastructure can have negative impacts on songbird communities but the degree of impact can vary considerably by species and spatial scale (Bayne, Habib et al. 2008, Van Wilgenburg, Hobson et al. 2013, Thomas, Brittingham et al. 2014, Bayne, Leston et al. 2016). The noise from facility processing sites (e.g. compressor stations) may be negatively impacting species that rely on auditory communication, resulting in reduced songbird abundance and species diversity (Bayne, Habib et al. 2008). Grizzly bears (*Ursus arctos*) have been found to avoid oil and gas infrastructure, but avoidance can vary by season and feature type (Laberee, Nelson et al. 2014). Declining caribou (*Rangifer tarandus*) in the WBF has been attributed to industrial activity that has increased habitat fragmentation and stressed levels (Sorensen, McLoughlin et al. 2008).

Research on how industry is related to waterfowl species in the WBF is limited, but anthropogenic factors are hypothesized to be limiting duck populations by degrading habitat quality or changing predator communities (Slattery, Morissette et al. 2011). Industry has the potential to change hydrological flow in and through wetlands with the construction of linear features such as roads or pipelines, but how this might impact the quality of duck habitats is unclear (Graf 2009). Linear features also increase habitat fragmentation which could increase predator efficiency, and change predator communities which may be negatively impacting duck populations (Slattery, Morissette et al. 2011).

Increasing industrial development and the changing composition of duck populations in the region is of particular interest for the North American Waterfowl Management Plan (NAWMP). One of NAWMP's primary mandates is to increase or maintain waterfowl populations based on long-term averages (Alberta NAWMP Partnership 2013). The Prairie Habitat Joint Venture, in partnership with NAWMP, work to guide conservation programs in the region to protect waterfowl habitat. In the WBF, this conservation work is done under an assumption that industry and climate change are the main factors limiting duck populations (Prairie Habitat Joint Venture 2014). However, these assumptions have not been validated.

This research addressed this information gap by assessing relationships between breeding duck populations and industrial infrastructure and activity related to the petroleum industry. If the oil and gas industry is negatively impacting duck populations as postulated by Slattery, Morissette et al 2011, either by degrading habitat or increasing predation, it is predicted that as industry increases, duck populations will decrease. To test this prediction, two categories of industrial development were defined. Industrial extent was defined based on the aerial extent (area) and total edge (edge) of oil and gas infrastructure (Dyer, O'Neill et al. 2002, Walker, Naugle et al. 2007, Copeland, Pocewicz et al. 2011, Stewart, Heim et al. 2016). In addition to the aerial extent of industry, information on the number and portion of active well pads was used to quantify industrial activity or intensity (Copeland, Doherty et al. 2009, Christie, Jensen et al. 2015).

2.2.2 STUDY AREA

The boreal plains of Alberta (Figure 2) is a sparsely populated northern region (Statistics Canada 2017). The boreal plains is primarily forested, comprising of a mix of deciduous species such as Aspen (*Populus tremuloides)* and balsam poplar (*Populus balsamifera*) and coniferous species (e.g. white spruce (*Picea glauca)*, black spruce (*Picea mariana)*, jack pine (*Pinus banksiana)*) (Downing and Pettapieve 2006). Much of the soil in the area is poorly drained, resulting in wetlands, particularly fen and bog peatlands in the lowlands (Schneider, Devito et al. 2016). The wetland habitat of the region is also influenced by surficial geology (Devito, Creed et al. 2005) where post-glacial moraine dominates followed by glaciolacustrine deposits, organic deposits, and stagnant ice moraine (Fenton, Waters et al. 2013). The climate of the boreal plains is characterized by short summers and long winters with most precipitation received between April and August (Downing and Pettapieve 2006). Of the upland areas, almost half is open mixed forest and grasses (44%), followed by closed forests (22%) (Latifovic, Olthof et al. 2008).

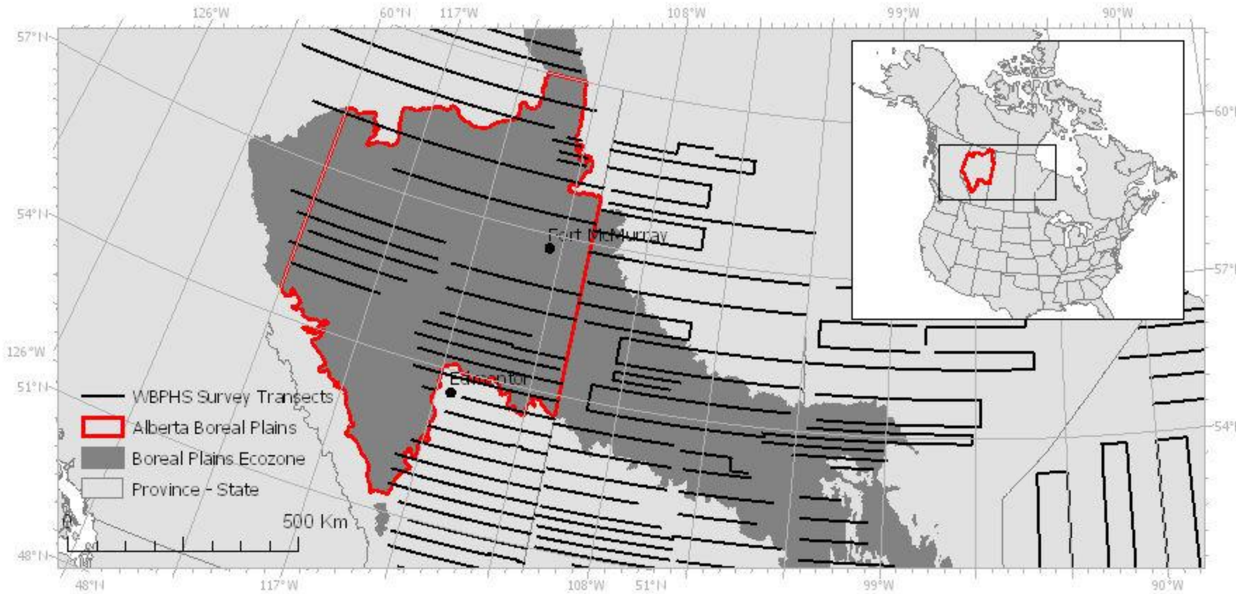

Figure 2. Boreal Plains ecozone of Alberta (outlined in red). The Waterfowl Breeding Population and Habitat Survey (WBPHS) is conducted every spring along survey transects found throughout Canada and the United States. There are 145 survey transects within the study area that range from 53.9°N to 59.5°N latitude.

2.3 METHODS

2.3.1 BREEDING WATERFOWL POPULATION DATA

The United States Fish and Wildlife Service (USFWS) and the Canadian Wildlife Service (CWS) have been conducting waterfowl surveys since 1955 (Smith 1995). Aerial surveys are conducted every spring along 29.9 km (18 mile) segments that are linked end to end into transects. Observers count the waterfowl within 200 meters on either side of segments and recorded by species. The timing of survey can vary depending on habitat conditions (e.g. spring ice break up), but typically the boreal forest surveys take place mid-May to mid-June (Smith 1995). Survey counts are used to estimate the total number of indicated breeding pairs (IBP) using visibility correction factors that are modeled using data collected from aerial and ground surveys to account for observation bias, birds missed during the survey, and birds double counted (Smith 1995). The adjusted IBP counts were pooled by nesting guild categorized as cavity nesters (generic goldeneye, bufflehead), overwater nesters (redhead, canvasback, ring-necked duck, ruddy duck), or ground nesters (mallard, gadwall, American wigeon, green-winged teal, blue-winged teal, northern shoveler, northern pintail, generic scaup). See Appendix A, Table 1 for duck species' common and scientific names. Using guild populations for modeling accounts for the low densities of breeding waterfowl in the study area that are difficult to model with many segments having zero counts for several species (i.e. zero inflated data). Community-level modelling is commonly used in studies to deal with species having zero counts, which allows for the inclusion of all species (even those species with low counts) and is often applied to analysis for data that contains a large number of species (Ferrier and Guisan 2006). There are 145 survey segments in the study area, and over 70% have been surveyed at least 25 of the 30 year study period (1980 – 2010; Table 1). The petroleum industry in Alberta goes back to the 1940s and has experienced several boom-bust cycles relating to global market, industry trends, and technological advances (Bott 2004). The study period was chosen to capture long-term duck population trends beginning with the development of economically feasible *in-situ* extraction techniques in 1980 (Shah, Fishwick et al. 2010).

Table 1.The number of years that segments were surveyed (1980 – 2010).

Total Segments	Year Count	% Years Surveyed
3	18	58
25	19	61
3	21	68
10	22	71
6	25	81
31	26	84
1	27	87
7	28	90
51	29	94
8	31	100

2.3.2 CLIMATE DATA

Climate data produced by Natural Resources Canada were obtained in ESRI® raster grid format at a 300 metre resolution for North America for the period 1980 - 2010 (McKenney, Hutchinson et al. 2011). Five climate variables were chosen based on waterfowl ecology literature (e.g. Barker, Cumming et al. 2014, Ross, Hooten et al. 2015) and expert knowledge (S. Slattery, personal communication, January 2017). The climate variables included in this analysis were determined *a priori* based on species-specific variables identified as important for breeding duck to minimize 'over-fitting' the population models (Knape and de Valpine 2011). To account for the influence temperature has on the timing of duck migration and nest initiation, monthly minimum and maximum temperatures (degrees Celsius) were included in the analysis. The measures of wetness, which influence habitat conditions and wetland availability, are monthly precipitation (millimetres), climate moisture index (which accounts for precipitation and potential evapotranspiration (Hogg 1996)), and snow depth (centimetres) (Drever, Clark et al. 2012, Finger, Afton et al. 2016). Each monthly dataset was averaged over the survey segments to give a monthly mean of the climate variable which was then aggregated into seasonal averages and totals. We constructed models using IBP counts (by nesting guild) as a response variable and different seasonal classifications as explanatory variables to determine the best seasonal aggregation of monthly climate data. A four season classification (spring, summer, autumn, winter) was found to have the best fit for the cavity and overwater nesting guild models, and a five season classification (early spring, spring, high summer, late summer-fall, winter) best fit the ground nesting guild population data.

2.3.3 LANDSCAPE AND DUCK HABITAT

Landscape characteristics and wetland data were selected for inclusion in the analysis based on previous use in waterfowl studies and availability (e.g. Fast, Clark et al. 2004, Lemelin, Darveau et al. 2010, Barker, Cumming et al. 2014, Holopainen, Nummi et al. 2014). NRCan's CanVec hydrology and saturated soils vector GIS data was used to calculate wetland area (km^2), wetland edge (km), and number of wetlands per survey segment (Fast, Clark et al. 2004, Government of Canada 2008, Kuczynski, Paszkowski et al. 2012, Barker, Cumming et al. 2014).

A 250 m resolution land cover raster (circa 2005) produced by NRCan was used to capture land cover characteristics of the survey segments (Latifovic, Olthof et al. 2008). The 39 classes of land cover were objectively reclassed (see Table 2 for reclassification of land cover data) based on earlier work that identified important land classes for waterfowl in the region (Slattery, Devries et al. 2007). The portion of each of the 10 generalized classes within a survey segment was used to capture overall land cover of the survey segments (Barker, Cumming et al. 2014).

Table 2. Land cover classes were consolidated into more general classes. Some of the original 39 land cover classes were not represented within the survey transects (e.g. ice-snow) or were not well represented. For example, most of the transects have less than 5 % of High-low shrub dominated, Grassland, Herb-shrub-bare cover so these classes were collapsed into a Mixed shrub and grass class. Other land cover classes not well represented were grouped into an 'other' category.

Land Cover Description	Reclass Description	Land Cover Description	Reclass Description
Temperate or subpolar needle-leaved evergreen closed tree canopy	Evergreen deciduous low density	Polar grassland, herb-shrub	Other
Cold deciduous closed tree canopy	Evergreen deciduous low density	Shrub-herb-lichen-bare	Other
Mix needle-leaved evergreen cold deciduous closed tree canopy	Mix-needle leaved closed canopy	Herb-shrub poorly drained	Other
Mix needle-leaved evergreen cold deciduous closed young tree canopy	Mix-needle leaved closed canopy	Lichen-shrub-herb-bare soil	Other
Mix cold deciduous needle-leaved evergreen closed tree canopy	Mix-needle leaved closed canopy	Low vegetation cover	Other
Temperate or subpolar needle-leaved evergreen med. density, moss-shrub understory	Evergreen medium density	Cropland-woodland	Cropland - woodland
Temperate or subpolar needle-leaved evergreen med. density, lichen-shrub understory	Evergreen deciduous low density	High biomass cropland	Crop
Temperate or subpolar needle-leaved evergreen low density, shrub-moss understory	Evergreen deciduous low density	Medium biomass cropland	Crop
Temperate or subpolar needle-leaved evergreen low density, lichen (rock) understory	Evergreen deciduous low density	Low biomass cropland	Crop
Temperate or subpolar needle-leaved evergreen low density, poorly drained	Evergreen low density poorly drained	Lichen barren	Other
Cold deciduous broad-leaved, low to medium density	Broad leafed low to medium density	Lichen-sedge-moss-low shrub wetland	Other
Cold deciduous broad-leaved, medium density, young regenerating	Broad leafed low to medium density	Lichen-spruce bog	Other
Mix needle-leaved evergreen cold deciduous, low to medium density	Other	Rock outcrops	Other
Mix cold deciduous - needle-leaved evergreen, low to medium density	Other	Recent burns	Other
Low regenerating young Mix cover	Low regenerating young Mix cover	Old burns	Other
High-low shrub dominated	Mix shrub and grass	Urban and Built-up	Other
Grassland	Mix shrub and grass	Water bodies	Other
Herb-shrub-bare cover	Mix shrub and grass	Mixes of water and land	Other
Wetlands	Other	Snow/ ice	NA
Sparse needle-leaved evergreen, herb-shrub cover	Other		

Landform is an important factor in influencing wetland distribution in the boreal forest (Devito, Creed et al. 2005, Ménard, Darveau et al. 2013). To capture landform, 1M scale surficial geology vector GIS data from the Alberta Geological Survey was intersected with the survey segments to get the portion of the major surficial geology classes within each segment (Fenton, Waters et al. 2013). Topography is another measure of landform that has been used in population models that we included using the coefficient of variation in topological ruggedness for each survey segment (Doherty, Naugle et al. 2008, Integrated Remote Sensing Studio 2010, Barker, Cumming et al. 2014).

Table 3.Surficial geology classes were reclassed based on representation of the classes in the survey transects.

Surficial Geology	General Class
Eolian Deposits	Other
Fluvial Deposits	Other
Glaciofluvial Deposits	Other
Glaciolacustrine Deposits	Glaciolacustrine Deposits
Moraine	Moraine
Fluted Moraine	Fluted Moraine
Stagnant Ice Moraine	Stagnant Ice Moraine
Ice-Thrust Moraine	Other
Organic Deposits	Organic Deposits
Colluvial Deposits	Other
Lacustrine Deposits	Other
Lake	Other
Bedrock	Other

2.3.4 INDUSTRIAL EXTENT & ACTIVITY

We included variables in the analysis to quantify industrial aerial extent and activity (Dyer, O'Neill et al. 2002, Walker, Naugle et al. 2007, Copeland, Doherty et al. 2009, Copeland, Pocewicz et al. 2011, Stewart, Heim et al. 2016). Infrastructure associated with petroleum activity include roads, pipelines, cut lines (2 - 8 metre swaths cut for seismic surveys), facility processing sites, and well pads (about 1 hectare in size). Unfortunately data representing all the various types of industrial features are not readily available. In Alberta, anthropogenic footprint GIS data sources are available from AMBI and Global Forest Watch Canada, and more recently from Environment and Climate Change Canada, but these data do not provide any temporal information, only the cumulative footprint of various anthropogenic disturbances (Hird, Collingwood et al. 2009, Government of Canada 2013, Lee 2014). Global Forest Watch released aggregated petroleum tenures data (February 2017) with temporal information, unfortunately too late for inclusion in our analysis. To overcome the lack of a comprehensive data for petroleum infrastructure and activity at the time of analyses, we used a combination of three vector GIS data sets that included temporal and spatial representations of pipelines, well pads, and industrial dispositions to quantify industrial extent and activity.

2.3.5 INDUSTRIAL DISPOSITIONS

Alberta Energy Regulator and Alberta Environment and Parks administer industrial activity on provincial lands with industrial dispositions. Industrial dispositions include geospatial data attached to permitting and licensing information relating to mineral surface leases, license of occupancy, and vegetation control easements. Industrial dispositions are dated (e.g. date activity is approved) enabling spatial and temporal representation of the industry footprint. Industrial dispositions in GIS vector format were licensed from Alberta Environment and Parks by Ducks Unlimited. All industrial disposition types (Figure 3) were used in the analysis except those specific to habitat development (e.g. marsh/wetland habitat development) as it is assumed that these

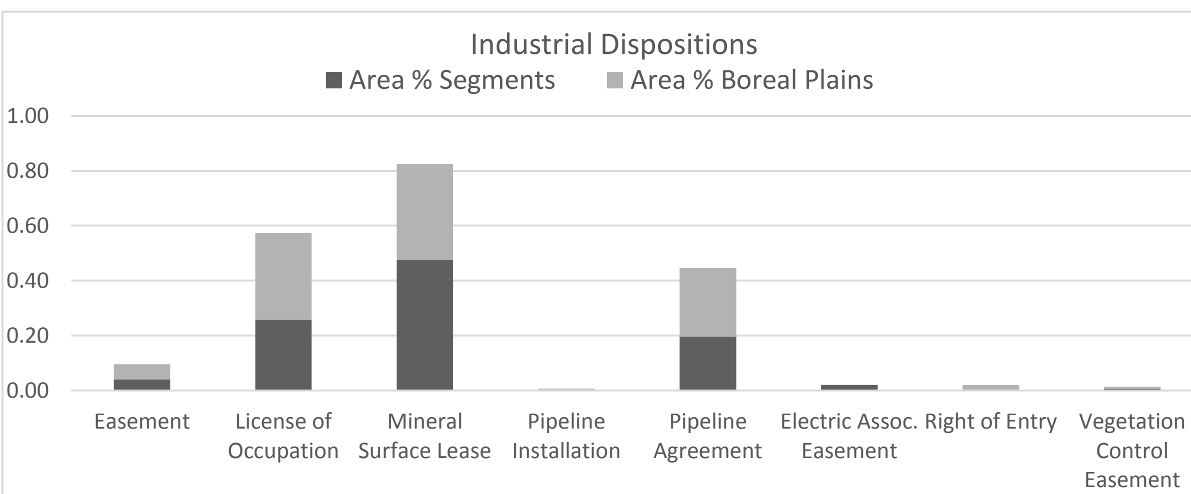

Figure 3. Industrial disposition types administered in Alberta, shown by portion within Boreal Plains and portion within breeding waterfowl survey transects. License of occupation, mineral surfaces leases, and pipeline agreements make up the majority of industrial dispositions in the study area.

activities would have been carried out with minimum detrimental effects to breeding ducks.

2.3.6 PIPELINES & WELL PADS

GIS vector data representing well pads and pipelines dated with licensing and permitting information was licensed by Ducks Unlimited from IHS Markit®. A 12 metre buffer was applied to the pipelines, and the well pad points were buffered to be one hectare in size. Buffers were used so that the full extent of the industrial footprint was captured and based on recommendations for the study area (Alberta Biodiversity Monitoring Institute 2007).

2.3.7 INDUSTRIAL EXTENT

We calculated two measures of industrial extent, one for total aerial extent, and another for total edge using the industrial dispositions, pipelines, and well pad GIS data. Using year of infrastructure license/permit dates, we quantified cumulative area (cum_area) and edge (cum_edge) as the accumulated total industrial footprint and edge for each year (1980 – 2010). Well pads are usually constructed within a year (Canadian Association of Petroleum Producers 2014), so if we assume that year of construction is the same as year of operation we can derive a measure of industrial development that can be characterized as a construction phase. This phase might have a greater negative impact on breeding ducks due to increased activity and disturbance (Canadian Association of Petroleum Producers 2014). However, because the breeding season coincides with 'spring break-up', a period from April to June when frost thaws from underground and road access and weight restrictions limit industrial activity, we suspect that the construction phase will not negatively impact IBP. To test this we included covariates for annual amount of industrial development as the amount of footprint or area (add_area) and edge (add_edge) added each year. The GIS polygons of the different types of infrastructure often overlap, thus to prevent overestimating the amount of additive infrastructure, we excluded the overlap of features in the additive totals (Figure 4).

2.3.8 INDUSTRIAL ACTIVITY

The IHS Markit® well pad data was used to quantify the ongoing industrial activity on survey segments. A total of 189 different status types of the well pad data were used to characterize each well pad as either active or inactive. If the well status description contained terms ‘abandon’, ‘closed’ or ‘canceled’, the well was considered inactive, otherwise, the well status was classified as active which included status descriptions such as ‘drilling’, ‘flowing’, and ‘pumping’. The active, inactive status and license and permit dates were used to characterize industrial activity over time for each survey segment (Copeland, Doherty et al. 2009). We totaled the number of active wells (cnt_active), and the portion of active wells (per_active) for each survey segment for inclusion in the models.

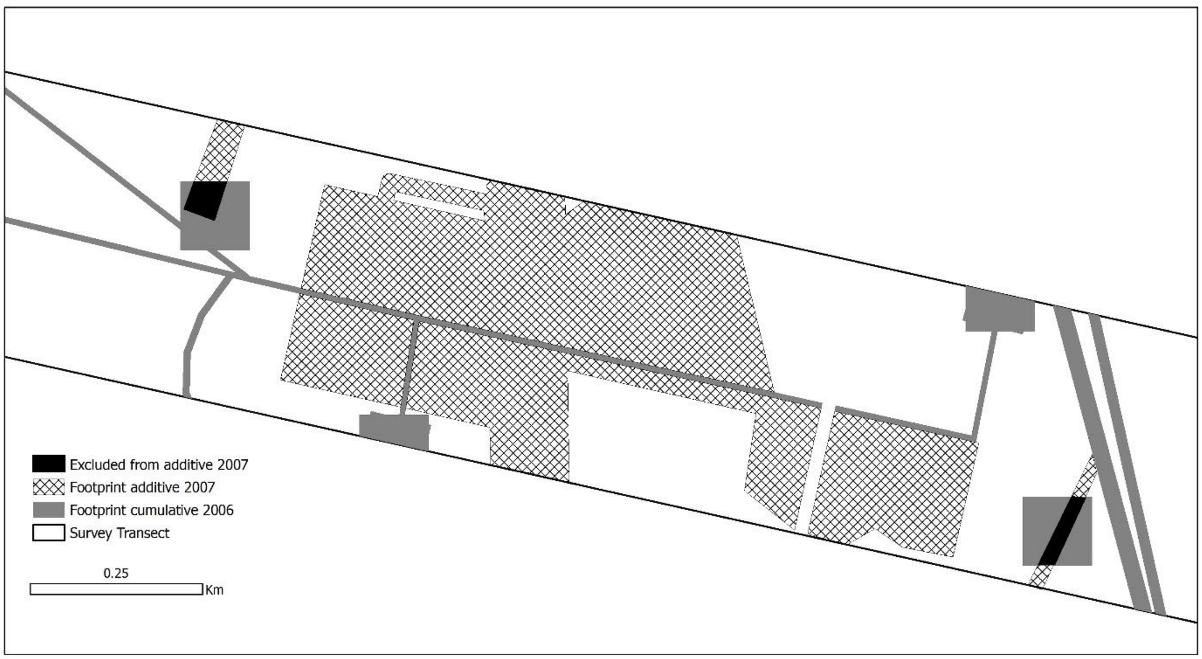

Figure 4. Vector GIS data was used to create measures of cumulative and additive industry area and edge. Areas in grey represent the cumulative aerial extent of infrastructure in 2006. In 2007, additional infrastructure was built (hatched areas) which would be added to the cumulative measure in 2007. Areas of overlap between 2006 and 2007 were excluded from the additive totals (black areas).

2.4 ANALYSIS

Collinearity (multicollinearity) of predictor variables used in regression modelling can lead to inaccurate results and decreased statistical power (Graham 2003, Zuur, Leno et al.

2009). To eliminate the potential of predictor variable collinearity we performed a correlation analyses between variables among variable categories of land cover, habitat, landform, industry, and climate (See Appendix A, Table 2 for a full list of variables). There was no correlation detected among the land cover, landform, and industry variables. Wetland edge and wetland area were correlated (r > 0.9) so we removed wetland edge from the analysis (Zuur, Leno et al. 2009). Among the climate variables, high correlation (r > 0.75) was found between minimum (min) and maximum (max) temperature and between climate moisture index (cmi) and precipitation (pcp). Maximum temperature was correlated with climate moisture index for the late summer and autumn periods of the five season classification, so we choose to include minimum temperature over maximum temperature in the analysis. Climate moisture index is the ratio of annual precipitation to annual potential evapotranspiration and provides a more encompassing measure of moisture conditions compared to precipitation alone thus was chosen over precipitation for the analysis (Hogg 1996). All late summer and autumn climate variables were correlated so we averaged these seasons together (Zuur, Leno et al. 2009).

We modeled IBP counts by nesting guild with generalized linear mixed-effects regression models (Zuur, Leno et al. 2009) fit using maximum likelihood using the lme4 package (Bates, Maechler et al. 2015) in the R environment (R Development Core Team 2008). Generalized linear mixed-effects regression modelling is an extension of linear regression analysis that accommodates the Poisson distribution of the duck population counts, allows for the inclusion of fixed and random effects, and handles unbalanced, zero inflated data (Bolker, Brooks et al. 2009). For the study period 1980 – 2010, not all survey segments are counted every year (Table 1), and low densities of nesting ducks in the boreal forest results in many counts of zero (even after pooling species into nesting guild). A survey segment identifier was used as a random effect in the model to reduce the potential of pseudoreplication (Bolker, Brooks et al. 2009). Survey segment area was used as an offset to account for the variation in survey segment size (10.1 km^2 to 12.4 km^2) while converting IBP counts to a density measure.

Land cover, habitat, landform, climate, and industrial variables were used as fixed effects. To ensure model convergence, the scale of predictor variables were standardized by centering values on the mean of each predictors and dividing by the standard deviation of each predictor. Model competitions were run using the full suite of predictor variables. Each nesting guild model was fit using a step-wise reduction technique to determine the most parsimonious model and evaluated with an Akaike Information Criteria (AIC) approach. Based on information theory, AIC is used to rank models using the log-likelihood and number of explanatory variables to measure model fit with consideration to degrees of freedom. The lower the AIC score, the better the model fit (Burnham and Anderson 2003, Zuur, Leno et al. 2009, Arnold 2010). Akaike weights (w_i) were calculated from the difference in AIC values to get a normalized relative likelihood, or a measure of probability for a model being the actual best model (Burnham and Anderson 2003). Model error residuals (Pearson) were plotted using normal quantile-quantile plots (qq plots) to assess how residuals were distributed as a measure of model adequacy (Zuur, Leno et al. 2009). In addition to presenting details of the final models, we provide summaries of industrial area, edge, activity, and duck populations.

2.5 RESULTS

2.5.1 INDUSTRIAL EXTENT & ACTIVITY

In the study area, almost 25% of the 145 survey segments had less than 2% industrial infrastructure prior to 1980 (measured as a portion of total segment area) (Figure 5). Twenty segments (16%) did not have any infrastructure as of 1980, and only five segments had more than 50% infrastructure pre 1980. Activity levels on survey segments increased from an average of 8% in the 1980s, to 16% in the 1990s, increasing to a high of 26% since 2000 (Figure 6).

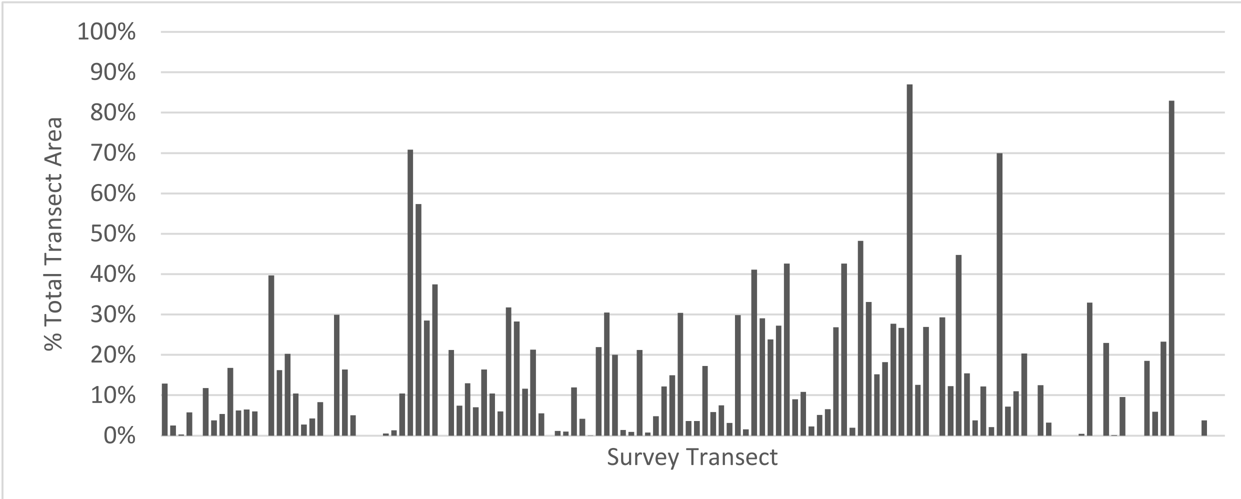

Figure 5. Portion of total segment area that is industrial infrastructure prior to 1980. Total infrastructure area on survey transects before and after 1980. Ordered by increasing transect latitude from right to left.

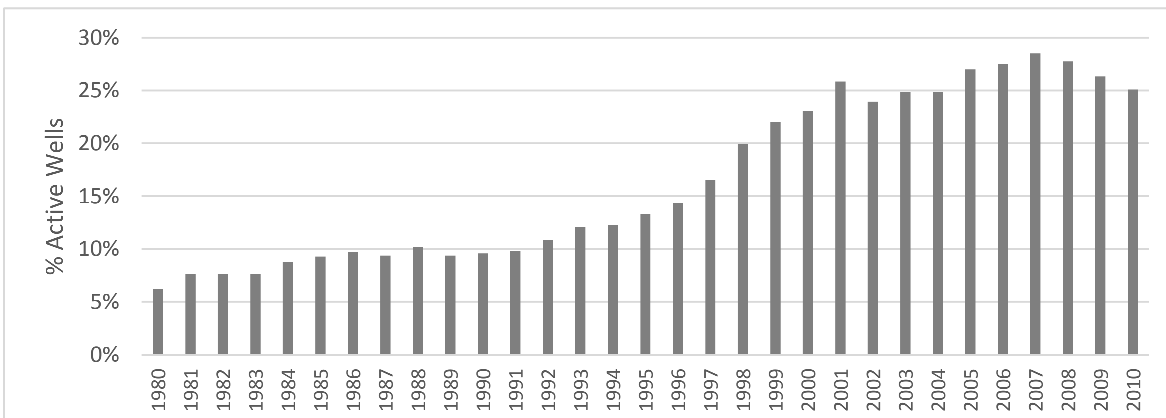

Figure 6. Average % active wells on survey segments 1980 – 2010. Industrial activity in the boreal plains increased in the mid-1990s.

The amount of industrial infrastructure on survey segments has increased steadily over the period (Figure 7). Increases in additive infrastructure occurred in 1985, the mid 1990s, and 2004 – 2007. Between 2006 and 2007 the most infrastructure area was added to the survey segments with an annual increase of between 15% and 20% for that period. Infrastructure edge has also increased annually over time (Figure 8). The growth of infrastructure cumulative edge dropped from a high of 17% in 1985 to a low of 1% in 2010.

Across the boreal plains survey segments, ground nesting ducks are found in greater numbers than cavity and overwater nesters (United States Fish and Wildlife Service and Canadian Wildlife Service 2016)(Figure 9). The total number of cavity and overwater nesting species pairs has remained more constant than the ground nesting guild species but all guilds show periods of increasing and decreasing populations over the study period. Grouping species by nesting guild may mask the declines reported for some species in the WBF where total duck populations have been more stable compared to the PPR (Slattery, Morissette et al. 2011).

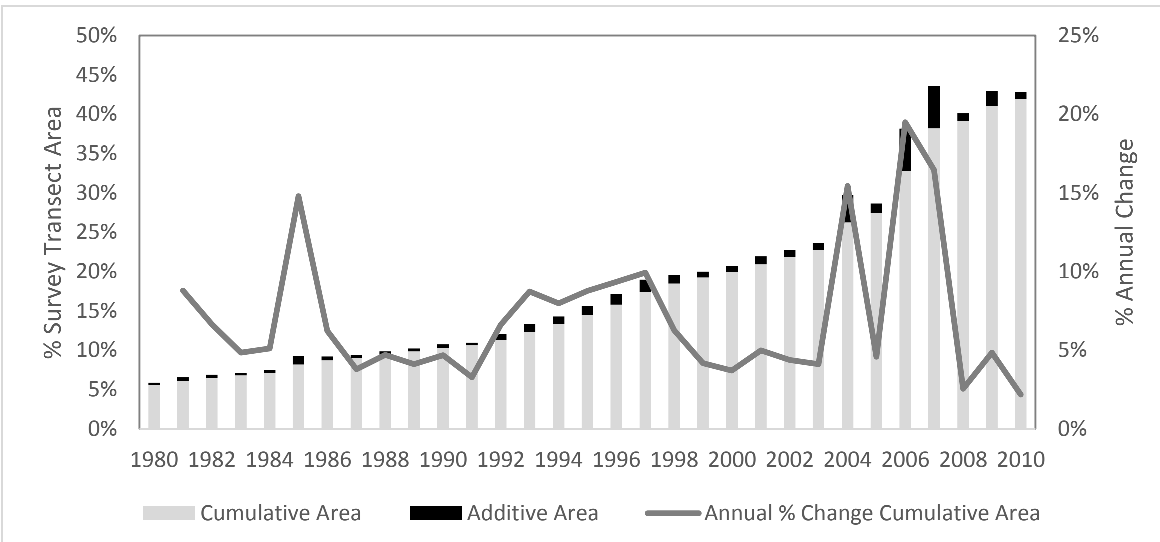

Figure 7. Additive and cumulative infrastructure area (as a portion of survey transect area) on survey segments 1980 – 2010.

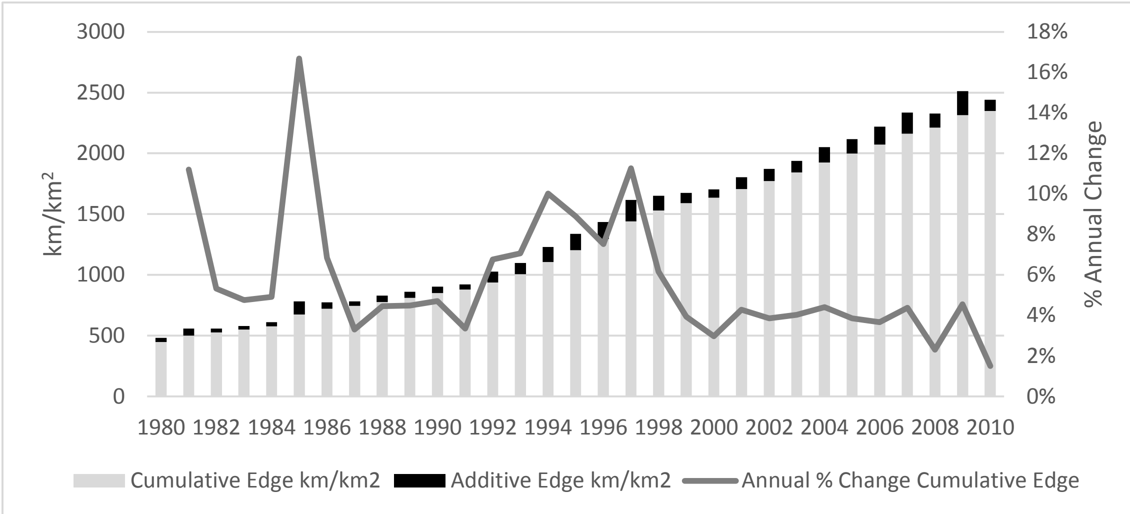

Figure 8. Cumulative and additive infrastructure edge on survey segments 1980 – 2010 measured as total kilometers per total segment area (km/km2). Increases in additive infrastructure edge have occurred annually since 1980.

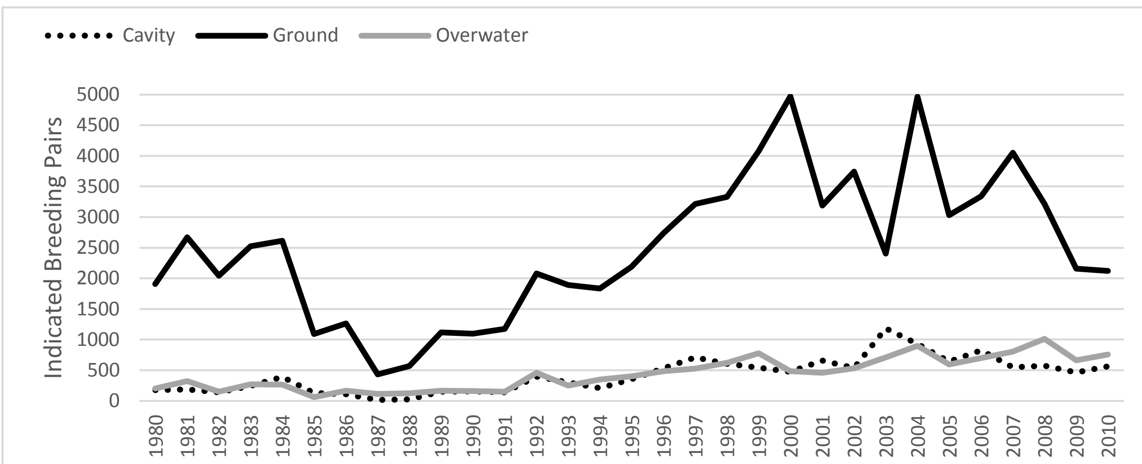

Figure 9. Total indicated breeding pairs (IBP) by nesting guild on all segments in the study area (n=145) for the period 1980 – 2010.

2.5.2 MODELS

Top models, (models within 4 AIC units) accounted for 93 – 98 % of the cumulative model weight (Table 4). The cumulative industry measures (area and edge) and percent active wells were retained in all top guild models. The best model (lowest AIC) coefficient estimates (Figure 10) showed a small negative effect of cumulative area on breeding duck populations across all nesting guilds. A small, well estimated positive effect was observed between percent active wells and IBP for all guilds. Cumulative industrial edge had a modest sized positive effect and was best estimated in the ground nester model. The top model for overwater nesters also included additive edge as a small positive effect. For all guilds, climate coefficients have a mix of positive and negative effects that are well estimated (Figure 10, Appendix A, Table 3). Land cover and land form variables were observed to be both negatively and positively related to breeding ducks, but were not as well estimated as the climate variables (Table 5).

Table 4. Top models (within 4 AIC units) by nesting guild with model degrees of freedom (df), AIC, delta AIC (AIC), AIC weights (W_i), and cumulative AIC weights (Cum.W_i). Industry measure are in bold (per_active = % active wells, area_cum = cumulative industrial area, edge_cum = cumulative industrial edge, edge_add = additive industrial edge). Climate parameters are omitted from model equations for brevity. Complete model parameters are listed on coefficient plots (Figure 10). Top models accounted for 93 – 98 % of the cumulative model weight.

Guild	Model	df	AIC	ΔAIC	W_i	Cum.W_i
Cavity	cnt_wet + rug + mix_close + eg_med_moss + eg_dec_low + low_regen + **per_active + area_cum + edge_cum**	25	22846.66	0	0.27	0.2696
	cnt_wet + rug + mix_close + eg_med_moss + eg_dec_low + low_regen + crop_wood + **per_active + area_cum + edge_cum**	26	22847.01	0.35	0.23	0.4959
	cnt_wet + rug + mix_close + eg_med_moss + eg_dec_low + low_regen + crop_wood + **per_active + cnt_active + area_cum + edge_cum**	27	22847.78	1.12	0.15	0.65
	cnt_wet + rug + mix_close + eg_med_moss + low_regen + **per_active + area_cum + edge_cum**	24	22847.82	1.16	0.15	0.8009
Ground	latitude + cnt_wet + por_M + por_LG + eg_med_moss + eg_dec_low + low_regen + crop_wood + crop + **per_active + area_cum + edge_cum**	29	63393.63	0	0.20	0.1989
	latitude + cnt_wet + por_M + por_LG + eg_med_moss + eg_dec_low + low_regen + crop_wood + crop + **per_active + area_cum + edge_cum**	30	63393.7	0.07	0.19	0.391
	latitude + cnt_wet + por_M + por_LG + eg_med_moss + eg_dec_low + low_regen + shrub_grass + crop_wood + crop + **per_active + area_cum + edge_cum**	31	63393.86	0.23	0.18	0.5684
	latitude + cnt_wet + por_M + por_LG + eg_med_moss + eg_dec_low + low_regen + shrub_grass + crop_wood + crop + **per_active + area_cum + edge_cum + edge_add**	32	63394.84	1.21	0.11	0.677
	latitude + cnt_wet + por_M + por_LG + eg_med_moss + eg_dec_low + low_regen + crop_wood + crop + **per_active + area_cum + edge_cum**	28	63394.84	1.21	0.11	0.7857
Overwater	cnt_wet + wet_area + eg_med_moss + eg_dec_low + low_regen + **per_active + cnt_active + area_cum + edge_cum + edge_add**	26	27541.65	0	0.26	0.2643
	cnt_wet + wet_area + eg_med_moss + low_regen + **per_active + cnt_active + area_cum + edge_cum + edge_add**	25	27541.93	0.28	0.23	0.494
	cnt_wet + wet_area + por_M + eg_med_moss + eg_dec_low + low_regen + **per_active + cnt_active + area_cum + edge_cum + edge_add**	27	27542.49	0.84	0.17	0.6677
	cnt_wet + wet_area + eg_med_moss + low_regen + **per_active + cnt_active + area_cum + edge_cum + edge_add**	24	27543.07	1.42	0.13	0.7976
	cnt_wet + wet_area + por_M + rug + eg_med_moss + eg_dec_low + low_regen + **per_active + cnt_active + area_cum + edge_cum + edge_add**	28	27543.46	1.81	0.11	0.9045

2.5.3 MODEL EVALUATION

Model residuals are well distributed for the cavity and ground nesting guild models, giving us confidence in the overall quality of these models, but the overwater model residuals show deviation from normality and may not be parametrized adequately (Figure 10) (Zuur, Leno et al. 2009). Overwater nesters are found in very low densities across the study area, so even with the ability of GLMMs to handle low counts and zero inflated data, further research that focuses on overwater nesters should consider the use of mixed models that are specifically designed for zero inflated Poisson distributions (Zuur, Leno et al. 2009).

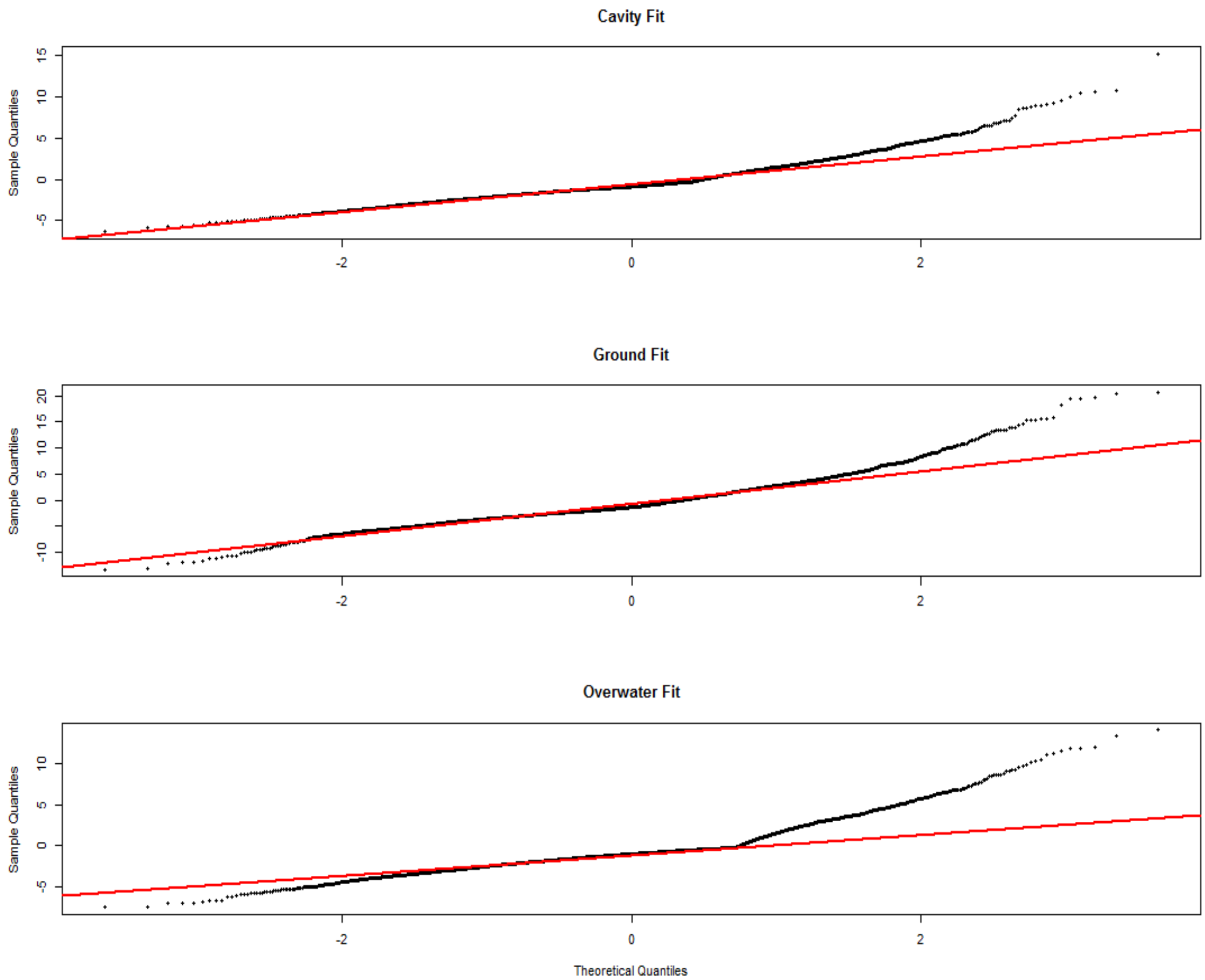

Figure 10. Quantile-quantile plots of top nesting guild models' studentized residuals (shown in black) against a theoretical normal distribution (shown in red). The cavity and ground nesting model residuals show similar distributions. The overwater guild model shows some deviation from normality.

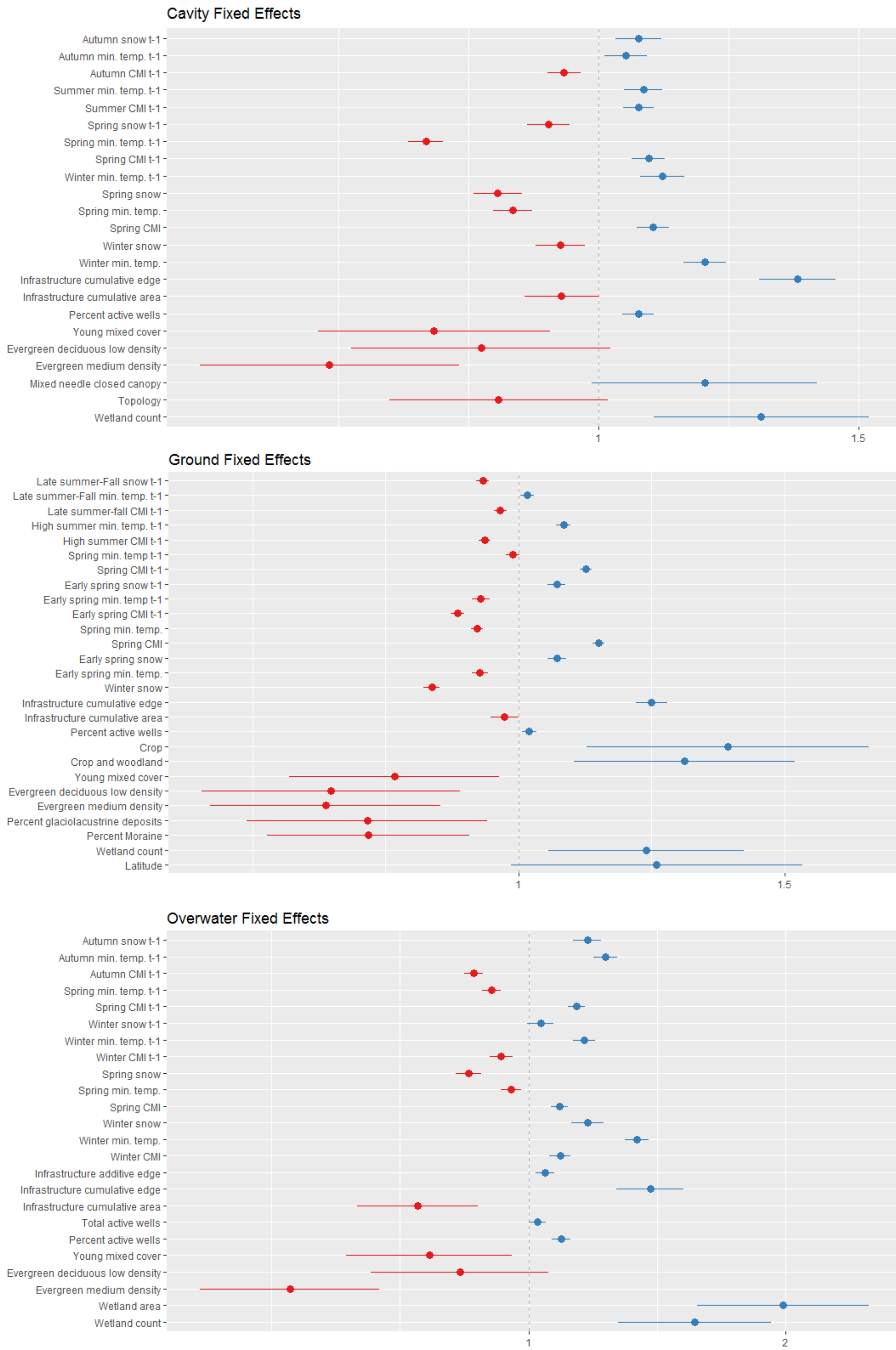

Figure 11. Coefficient Plots of nesting guild models. Estimated coefficients of explanatory variables indicated by dots shown with 95% confidence intervals (lines). Negative effects shown in red, positive in blue. The shorter the confidence interval line, the better the coefficient is estimated in the model.

Table 5. Variables included in the top models indicated as having a positive (+) or negative (-) relationship to guild populations. Table does not include climate variables. For a full list of top guild model variables and coefficients see Appendix A Table 2. The cumulative area and edge measures of industrial infrastructure, and industrial activity were in all nesting guild top models.

Category	Covariate	Cavity	Ground	Overwater	Detail
Industry	per_active	(+)	(+)	(+)	Active wells/Total wells per segment (%)
	cnt_active	.	.	(+)	Total number of active wells
	area_cum	(-)	(-)	(-)	Total cumulative industrial area as a portion of segment area (%)
	edge_cum	(+)	(+)	(+)	Total cumulative industrial edge/total segment area (km/km2)
	edge_add	.	.	(+)	Total additive industrial edge/total segment area (km/km2)
Land Cover	mix_close	(+)			Mixed-needle leaved closed canopy (%)
	eg_med_moss	(-)	(-)	(-)	Evergreen medium density (%)
	eg_dec_low	(-)	(-)	(-)	Evergreen deciduous low density (%)
	low_regen	(-)	(-)	(-)	Low regenerating young mixed cover (%)
	shrub_grass	.	.	.	Mixed shrub and grass (%)
	crop_wood	.	(+)	.	Cropland - woodland (%)
	crop	.	(+)	.	Cropland (%)
Habitat	cnt_wet	(+)	(+)	(+)	Total wetlands per segment
	wet_area	.	.	(+)	Total wetland area per segment
Landform	rug	(-)	.	.	Average topological ruggedness of segment
	por_LG	.	(-)	.	Percent Glaciolacustrine Deposits (%)
	por_M	.	(-)	.	Percent Moraine (%)
	latitude	.	(+)	.	Degrees latitude

2.6 DISCUSSION

Our measures of industry show periods of industrial expansion and contraction, but we do not find much evidence that this is negatively related to changes in duck populations over the same time period. On the contrary, our measures of infrastructure edge and activity show a small, positive relationship to IBP populations for all nesting guilds. We see a spike in infrastructure area added in 2007, which is followed by a decline in the amount of additive and cumulative area. Additive edge shows a similar decline around this same period. This downward trend may be a reflection of reduced petroleum production in the region beginning in the early 2000s (Johnson, Kralovic et al. 2016) and may also be attributed to changing industry practices that focus on wetland restoration, reclamation and remediation (Alberta Environment 2004, Alberta Environment 2011, Canadian Association of Petroleum Producers 2014, Cumulative Environmental Management Association 2014).

The annual percent change in cumulative edge across all survey segments remained fairly consistent, even during periods with increasing cumulative industrial area. It is possible that less infrastructure edge is being added to the landscape as a result of industry practices that emphasise reuse of existing linear features, and reclamation of linear features (Alberta Environment 2011, Canadian Association of Petroleum Producers 2014, Pyper, Nishi et al. 2014, Silvacom 2015). Another explanation of lower rates of industrial edge could be related to increased industrial area that is reducing the amount of overall edge. If additive industrial area encompasses existing infrastructure, it has the potential to reduce the complexity of fragmentation, and measured edge while increasing cumulative industrial area.

The estimated negative coefficients for cumulative industrial area are small across all nesting guilds, which is in contrast to the better estimated, larger positive effect of cumulative industrial edge. Cumulative industrial area may be capturing actual habitat loss that is negatively impacting IBP, whereas the measure of cumulative edge could be capturing components of landscape change that is having a positive effect on duck populations in the region.

We speculate that the positive effect of industrial edge may be related to other factors of landscape change that is favorable for IBP, assuming our measure of industrial edge is an index of fragmentation or correlated with fragmentation (Wang and Cumming 2009, Wang, Blanchet et al. 2014). Increasing fragmentation in forested landscapes can change land cover composition resulting in an increase of mixed, more diverse habitats that can be beneficial to breeding ducks (Slattery, Devries et al. 2007, Nitschke 2008, Copeland, Pocewicz et al. 2011). For example, the clearing of forest areas can increase the amount of herbaceous cover, which has been linked to higher nest success for breeding ducks in the prairie-pothole region (PPR) (Emery, Howerter et al. 2005, Lee and Boutin 2005, Thompson, Arnold et al. 2012). These changes in landscape composition may be what is having a positive effect on breeding duck populations, not increasing industrial edge *per se*.

In the PPR, the planting of herbaceous cover has been used as a management tool to increase duck populations, but this might be creating habitats that increase nest and brood predation (Devries and Armstrong 2011). Mammalian predation is a major limiting factor of duck populations in the PPR, but is not as well studied in the WBF (Pierre, Bears et al. 2001, Phillips, Clark et al. 2003, Stephens, Rotella et al. 2005). The period following disturbance can benefit small mammals that prey on nests, hence industrial development in the WBF could be altering predator composition and populations in a way that is having an overall negative impact on duck populations (Fisher and Wilkinson 2005). However, evidence that some mammalian predators avoid disturbed areas suggests the relationship between industry and predators needs to be evaluated in the WBF (Pierre, Bears et al. 2001). Research currently underway in the study area focused on nest predation, will help to better understand how nest success is related to predation (S. Slattery, personal communication, January 2018). With several species of ground nesting ducks experiencing declining populations in the WBF we do not think that the positive relationship we detected with edge and IBP is having an overall positive impact on populations.

Contrary to our prediction, our measure of industrial activity showed a small positive effect with IBP. Anthropogenic activity has been linked to increased stress levels in caribou populations, and reduced songbird abundance but we did not find evidence that IBP is negatively related to our measure of petroleum activity (Bayne, Habib et al. 2008, Sorensen, McLoughlin et al. 2008). We are uncertain why petroleum activity and IBP are positively associated, but suspect that the biological relevance of this relationship is minor.

We did not find any support that the construction phase or additive infrastructure negatively impacts IBP densities. The overwater model retained additive edge as a small, positive effect which may be related to the construction phase and the creation of ‘borrow-pits’, the excavation of soil for construction that creates open pits that can retain and hold water. No negative relationship was detected between additive measures of industry and IBP, and this is likely related to the timing of construction that is limited during spring break-up from April to June, a period that encompasses the breeding season (May – June). However, nesting and brood rearing periods could be negatively impacted by industrial construction, especially if it were to commence after spring break-up. Our analysis used construction year, but a more thorough look at industrial impacts could use construction month to better understand the ‘seasonality of industry’ and its relationship to breeding ducks and nest success.

This study attempted to capture the total footprint of the oil and gas industry, as well as the intensity of industrial activity temporally. This meant that our research was unable to include seismic lines and roads because data for these features, with temporal information are not available. The results of the analysis may change if all types of features were included as previous research surmises that seismic lines and roads, which are prominent features in the region, may negatively impact wetland habitat (Lee and Boutin 2005, Alberta Biodiversity Monitoring Institute 2007, Graf 2009, van Rensen, Nielsen et al. 2015). Aggregated datasets of industrial development that have been developed since our analysis was completed may be useful for further research into how cumulative industrial area is negatively impacting duck populations (globalforestwatch.org/datasets). Additional industrial stressors affecting duck populations in the region that were not included in our analysis are forestry operations, mining, and agriculture. A more inclusive analysis of the impacts of industry on duck populations would include all types of industry.

The results of this analysis, based on our measures of oil and gas infrastructure and activity, showed that industry does not have a large negative impact on IBP densities in the region. Thus other factors are thought to be influencing IBP densities, especially for those species in the ground nesting guild that are experiencing declining numbers. The coefficients for the land cover classes in our model indicate a strong relationship between land cover and duck populations, but these relationships are not well estimated. Annual change in land cover at a higher spatial resolution would be a valuable addition to the analysis and could help determine how industry is changing landscape composition. The Landsat satellite imagery archive offers 30 m resolution land cover data that is freely available at a fine temporal scale making it well suited to measure landscape change over time (Lillesand, Kiefer et al. 2004).

Wetlands are an important aspect for all breeding waterfowl but the resolution of the wetland data used in the models may not adequately account for this habitat. Higher resolution wetland data could help overcome this but is not available for the entire study area. However, reducing the number of survey segments to only include those covered by the detailed Alberta wetland inventory (geodiscover.alberta.ca) may be a suitable trade-off to incorporate finer scale wetland data in the models.

This analysis has advanced our understanding of how the oil and gas industry interacts with duck populations in the boreal plains of Alberta. The results show that there are both negative and positive impacts of the petroleum industry on breeding duck populations. Cumulative area of infrastructure was found to negatively impact IBPs, so best management practices (BMPs) should focus on reducing the overall area of petroleum infrastructure in order to sustain or increase duck populations. We recommend the development of BMPs that consider cumulative landscape change, with a focus on wetland habitats for effective waterfowl conservation.

The effects of industrial activity on ecosystem function and aquatic environments is not well understood, but is getting increased recognition as a priority for research (Schneider, Stelfox et al. 2003, Kreutzweiser, Beall et al. 2013, Alberta Government and

Environment and Climate Change Canada 2016). Future research that utilizes higher resolution, temporally explicit land cover data, and detailed wetland data could provide further insight into how industry is related to duck populations in the boreal plains of Alberta.

CHAPTER 3. CLIMATE, INDUSTRY, AND DUCKS: HOW SEASONAL AGGREGATION IMPACTS RESULTS

3.1 ABSTRACT

Climate is an important influence on population trends for a number of species, including breeding waterfowl. Therefore, climate is often accounted for when trying to determine the importance of other factors influencing population trends. There are numerous ways in which climate data have been incorporated into waterfowl population models (four seasons, annual averages, 30 year averages, breeding and non-breeding seasons, etc.) but the influence of seasonal aggregation method on results and interpretations for other covariates has not been tested. To assess potential implications of climate aggregation methods, this study examined the impact of different seasonal classifications using no climate data (null), and annual, two, four, and five seasons on relationships between breeding duck populations and measures of petroleum industrial development within the Boreal Plains ecozone of northern Alberta. The measures of oil and gas industrial infrastructure used in this analysis included cumulative and additive area (infrastructure aerial footprint) and infrastructure edge (total perimeter of infrastructure area/total transect area), and activity or intensity (portion of industry active wells on a survey segment and total number of active wells). Also included in the models were environmental variables for land cover, surficial geology, topology, and wetland habitat. We used generalized linear mixed models (GLMM) fit by maximum likelihood to breeding duck pair counts using environmental variables, industrial measures, and climate data (1980 – 2010) aggregated by annual (one), two, four, and five seasons, or excluded (null season). Predictions of duck densities were generated across gradients of oil and gas infrastructure and activity using models fit with different seasonal aggregations. Different seasonal aggregations showed similar patterns for relationships

between industry variables and breeding duck density but the presence of industry variables in models did vary by seasonal classification. Models excluding climate data (null season), and one and two seasonal aggregations retained industry measures that were not retained in the four and five seasonal aggregation models. The precision of model estimates did not change across seasonal aggregations but did vary by nesting guild. The magnitude of change in predicted duck pair density across industrial gradients showed variation by nesting guild and industry measure. Our results demonstrate that how local climate data is summarized can have implications in duck population models, especially if results are used to predict populations or to model scenarios of industrial development.

3.2 INTRODUCTION

Climate has long been regarded as an important influence on ecological processes and has been increasingly incorporated into ecological studies at local and global scales (Knape and de Valpine 2011). The use of large-scale climate data such as the El Nino Southern Oscillation and the North Atlantic Oscillation have been argued to be superior to local scale weather data (Stenseth, Mysterud et al. 2002). Yet, local scale climate data continues to be important in population modelling across a number of taxa (Knape and de Valpine 2011) and within the context of waterfowl population models, has been found to be more important than large-scale climate data (Ross, Hooten et al. 2015) as well as complimentary to large-scale climate data (Börger and Nudds 2014). Regardless of spatial scale, evidence suggests climate data are important to include as climate covariates can account for a large portion (75-98%) of population variability for some waterfowl species (Börger and Nudds 2014).

Climate data are becoming increasingly accessible to researchers as a growing number of climate data resources are made freely available for ecological modelling (e.g. PRISM Climate Group 2004, McKenney, Hutchinson et al. 2011, WorldGrids 2017). However, the use of climate data in ecology poses challenges as historical temporal ranges increase, and spatial extent expands which results in large datasets which are not easily incorporated into population ecology models (Hamann, Wang et al. 2013), and often require advanced data management and processing.

Due to large data challenges, monthly climate data are often aggregated into seasons for use in biological studies. For ecological application, climate data are often aggregated by the metrological definition of season (i.e. in the northern hemisphere: winter (Dec. – Feb), spring (Mar. – May), summer (Jun. – Aug.), autumn (Sept. – Nov.)) which is based on the astronomical progression of the sun. The metrological season is often used, but does not always capture nuances of biological interactions between species and habitat (Basille, Fortin et al. 2013). The fixed periods of metrological seasons do not account for the climatic signals that trigger biological processes such as migration or nesting. Nor does the fixed metrological seasonal classification conform to the changing climate with longer summer periods and shorter winter periods (Kutta and Hubbart 2016). Hartshorne (1938) advocated the use of different seasonal classifications used in population modelling by considering location and the ecological cycles of species. In addition to location, latitudinal differences in climate may not be reflected in a four season aggregation. The Inuit of northern Canada combine the conventional four seasons (spring, summer, fall, winter) with the addition of early spring and early fall season resulting in six seasons that takes into account ice and snow characteristics (Ferguson and Messier 1996, Hay, Aglukark et al. 2000). Similarly, in Australia, six seasons are argued to be more representative of ecological processes related to reproductive cycles and phenology (Entwisle 2014). Other seasonal classifications used to study population trends include biological seasons, such as brood-rearing season, or the regulated hunting and non-hunting seasons (Schooley 1994).

In waterfowl research, several approaches to summarizing climate data for population models have been utilized (Table 6). Barker, Cumming et al. (2014) utilized 30 year means summarized by four seasons of 14 climate and bioclimatic variables for modelling duck populations distributions across Canada. Roy, McIntire et al. (2015) also used the four meteorological seasons and daily averages to assess how precipitation and snow depth accounted for the spatial variability of density dependence of mallard populations in the Prairie Pothole Region (PPR) and Alaska. As an alternative to the four metrological seasons, Ross, Hooten et al. (2015) used annual averages from June to May when modelling climate, density dependence, and predation in lesser and greater scaup (*Aythya* spp) populations in the Northwest Territories. The various aggregation methods presented here demonstrate there is no single approach to the use of climate data in waterfowl research, nor has there been any comparison of different aggregation methods. Something we address here with a focus on the impacts of industry on duck populations in the boreal region of Alberta.

Table 6. Select waterfowl population studies using climate data categorized by different seasonal classification. Studies used local scale climate data focused on all of Canada, the Western Boreal Forest (WBF), the North West Territories (NWT), and the Prairie Pothole Region (PPR).

Climate Variable	Author	Summary Method	Season	Geography
Temperature	Barker et al (2014)	30 yr mean summarized by 4 season	4 season	Canada
	Roy et al (2015)	Spring mean (t)	4 season	WBF/PPR
Precipitation	Barker et al (2014)	30 yr mean summarized by 4 season	4 season	Canada
	Roy et al (2015)	Year t-1 monthly total	Monthly	WBF/PPR
Climate Moisture Index	Barker et al (2014)	30 yr mean summarized by 4 season	4 season	Canada
Snow Extent	Ross et al (2015)	June (t-1) to May (t) average	1 season	NWT
Snow Duration	Drever et al (2012)	Spring: Feb - Aug and Annual: Aug (t-1)- July	1 season	WBF/PPR

3.2.1 BACKGROUND

While it is acknowledged that it is important to include climate data in waterfowl population models (Börger and Nudds 2014, Holopainen, Arzel et al. 2015), and various methods to aggregate climate data have been used, it has not been considered how aggregation method may impact results when modelling for other effects. Climate effects may vary by duck species, or nesting guild, and latitudinal range thus we hypothesize that better parametrization of climate variables in models could better account for these effects. If climate aggregation method is influential, we predict that parameter estimates and effect sizes associated with industry will vary in direction, and magnitude and/or precision across seasonal aggregation. We examined the use of different seasonal aggregations on statistical relationships between breeding duck densities and metrics of industrial development to assess whether our interpretation of relationships varied substantially with seasonal aggregation method.

3.3 METHODS

3.3.1 SEASON AGGREGATIONS

We defined one, two, four, and six season classifications (Table 7). A one season classification (June in year previous to survey to May year of the survey) that was used to model scaup populations in the Northwest Territories was included (Ross, Hooten et al. 2015). A two season classification based on breeding season (May – June) and non-breeding season (July – April) was defined. The four season classification used the conventional meteorological definitions of season, with three months per season. A six season classification was defined using an ecological grouping of months (Hartshorne 1938), meant to characterize the short summers and long winters of the region; this season was modified to monthly breaks because the monthly climate data could not be split at mid-month points.

We consider the survey year as May in the year of the survey to April of the following year. Climate variables for the survey year (t), and for the year prior (t-1) to survey were used to capture conditions during the survey, and previous to the survey (Table 2). Including climate conditions from the year previous (t-1) accounts for wetland productivity in year *t* that is influenced by wet and dry cycles that impact nutrient and vegetation dynamics (Johnson, Werner et al. 2010). We included climate variables for year of survey and year previous to survey that could affect conditions during the survey period. Temperature (minimum and maximum) and climate moisture index were averaged by season (e.g. average of March, April, and May for 4 season spring). Precipitation and snow depth were totalled by season (e.g. November, December, January, and February snow depth measures summed for 6 season winter).

To reduce the impacts of multicollinearity in the models, we conducted a correlation analysis of climate variables within each season (Graham 2003, Zuur, Leno et al. 2009). High correlation ($r > 0.75$) was found between minimum and maximum temperature, and between climate moisture index and precipitation. We choose to exclude maximum temperature because it was also correlated with climate moisture index in the six season aggregation. We included climate moisture index over precipitation because it represents a ratio of annual precipitation to annual potential evapotranspiration, which is argued to be a better measure of moisture than precipitation alone (Hogg 1996). In the six season aggregation, all late summer and autumn climate variables were correlated so we averaged these seasons together, resulting in a five season aggregation (Zuur, Leno et al. 2009).

Table 7. Seasonal aggregations listed with months included for year of survey (t) and year prior to survey (t-1). Temperature and precipitation are available in daily and weekly time periods, but snow depth and climate moisture index are only available monthly so full months were incorporated into the seasons rather than a mid-month break point listed under Period.

Season	Name	Description	Code	Period	Month	t	t-1
1 Season	Annual	Annual	sc	Jun (t-1) - May	Jun (t-1) - May	yes	no
2 Season	Nesting	Nesting	ne	May - Jun	May - Jun	yes	yes
	Non Nesting	Non Nesting	nn	Jul - Apr	Jul - Apr	no	yes
4 Season	Spring	Spring	sp	Mar - May	Mar - May	yes	no
	Summer	Summer	su	Jun - Aug	Jun - Aug	yes	yes
	Autumn	Autumn	au	Sep - Nov	Sep - Nov	no	yes
	Winter	Winter	wi	Dec - Feb	Dec - Feb	no	yes
6 Season	Prevernal	Early Spring	pr	Mar - May	Mar - Apr	yes	no
	Vernal	Spring	ve	May - Mid Jun	May - Jun	yes	yes
	Estival	High Summer	es	Mid Jun - Mid Aug	Jul - Aug	no	yes
	Serotinal	Late Summer	sr (srat)	Mid Aug - Mid Sep	Sep	no	yes
	Autumnal	Fall	at (srat)	Mid Sep - Nov	Oct	no	yes
	Hibernal	Winter	hi	Nov - Mar	Nov- Feb	yes	no

3.3.2 SEASONAL MODELS

To test whether the use of different seasonal aggregations influenced modeled results of industrial effects, we first constructed models to analyze measures of industry and breeding duck populations following methods outlined in Chapter 2. In brief, we examined relationships between industry and duck populations over time (1980 – 2010) with mixed effects logistic regression models using the lme4 package (Bates, Maechler et al. 2015) in the R environment (R Development Core Team 2008). We used a multistage analytical approach where we first fit breeding duck populations to models using just the climate covariates, by each season. A step-wise reduction technique was used to eliminate non-significant climate covariates. Then we added in the environmental and industry measures into competing models, and again employed a step-wise reduction technique to determine the most parsimonious model for each nesting guild and seasonal aggregation. Models were then ranked using Akaike Information Criteria (AIC) (Burnham and Anderson 2003, Zuur, Leno et al. 2009, Arnold 2010).

We then used the best models (lowest AIC) for each seasonal aggregation to make predictions of duck densities using the lme4 package's predict method (Bates, Maechler et al. 2015). The predict method allows us to generate predictions for duck pair densities over the range of industry measures, while setting all other model terms to zero (scaled average of explanatory variables). The resulting predictions are the generalized effect of the industry impacts generated using the competing seasonal aggregations. We also compared the estimated coefficients of the industry effects of the different seasonal aggregations.

3.4 RESULTS

For each nesting guild, one model contained nearly all the model weight (Table 8). Among the different seasonal classifications used in duck population models, there were no competing models ($\Delta AIC < 2$)(Burnham and Anderson 2003, Arnold 2010). In general, the finer resolution seasonal (seasons four and five) classifications outperformed the more broadly defined seasons (seasons one and two). Exclusion of climate data resulted in the lowest ranked models across all guilds. Top model for the overwater and cavity nesting guilds (lowest AIC) contained the four season classification, while top model for the ground nesting guild top model was the five season classification. Details of top models can be found in Appendix A, Table 3.

Relationships between duck densities and industrial development measures were similar across aggregation methods within each nesting guild (Table 8). A positive relationship was detected between IBP densities and industrial activity and edge and a negative relationship observed between cumulative industrial area and IBP densities.

Table 8. Performance of seasonal aggregation models fit to breeding waterfowl densities by nesting guild. Model listed by guild (cavity (cav), ground (grd), overwater (ovw) and seasonal classification (no climate (0), season 1, 2, 4, 5).

Guild	Season	df	AIC	ΔAIC	w_i
Cavity	season 4	25	22846.66	0.00	1
	season 5	26	22897.04	50.38	1.15E-11
	season 2	18	23631.67	785.01	3.5E-171
	season 1	16	23816.54	969.88	2.5E-211
	season 0	13	23988.27	1141.60	1.3E-248
Ground	season 5	29	63393.63	0.00	1
	season 4	27	63910.66	517.03	5.4E-113
	season 2	22	64687.21	1293.58	1.3E-281
	season 1	19	64997.64	1604.01	0
	season 0	13	65973.32	2579.69	0
Overwater	season 4	26	27541.65	0.00	1
	season 5	25	27642.71	101.05	1.14E-22
	season 2	15	28048.83	507.17	7.4E-111
	season 1	14	28467.00	925.35	1.2E-201
	season 0	11	28572.31	1030.65	1.6E-224

3.4.1 INDUSTRIAL COVARIATES

While the industrial effects were consistent across seasonal aggregations, the inclusion of industrial covariates retained in the top models varied with seasonal aggregation (Table 9). The exclusion of climate data (season 0), and the broad seasonal aggregations of season 1 and season 2 result in the inclusion of additive edge in the cavity and ground nesting models. However, additive edge is not retained in the season 4 or season 5 models for these guilds. Similarly, the overwater guild models exclude additive industrial edge as a covariate for all seasonal aggregations except season 4, the top ranked model.

Table 9. *Percent change in predicated pairs across a gradient of industrial area, activity, and edge using different seasonal aggregations (no climate (0), 1, 2, 4, 5), listed by nesting guild (cav - cavity, grd - ground, ovw – overwater). Top models are indicated in bold, and industrial effects not retained in top seasonal models are indicated with 'x'.*

	% Change in Pairs/km^2				
	Cumulative Area	Total Active	Additive Edge	Cumulative Edge	% Active
cav0	-548	72	147	2020	39
cav1	-502	58	112	2027	33
cav2	-425	57	57	1260	34
cav4	**-217**	**x**	**x**	**521**	**22**
cav5	-197	x	x	528	23
grd0	-93	16	52	294	10
grd1	-111	15	49	510	8
grd2	-48	x	41	200	8
grd4	x	x	x	80	5
grd5	**-53**	**x**	**x**	**231**	**5**
ovw0	-21936	34	x	4478	32
ovw1	-29637	29	x	3156	35
ovw2	-35971	31	x	2375	36
ovw4	**-38345**	**34**	**122**	**591**	**32**
ovw5	-32800	31	x	1066	35

3.4.2 PREDICTED PAIR DENSITIES

Predicted pair density changed at different rates across the gradients of industry covariates depending on seasonal aggregation method. Using the gradient of industry measures, and the minimum and maximum predicted pairs we calculated the percent change in pairs/km^2 (Table 9). This is also expressed as the total predicted pairs across the industry gradient (Figures 12). This variation in predicted pairs between seasonal models was especially evident for cumulative edge in the cavity and overwater nesting guilds, cumulative area in the cavity models, and percentage of active wells for the cavity and ground nesting guilds (see Appendix A, Figures 1 - 6 for all industry gradients and model predictions). The exclusion of climate data (season 0) in the population models results in almost four times the number of predicted pairs for cavity nesters, and almost 8 times the number of overwater nesters compared to the four season top models. For the ground nesting guild, the top ranked season 5 model predicts almost half the number of pairs compared to the season 1 model.

For increasing industrial activity, the cavity and ground nesters IBP densities are predicted to be higher using the null climate model, and the season one and season two classifications compared to season four and season five. The overwater guild does not show much variation between predictions generated with the different seasonal classifications. The ground nesting guild models better estimate this positive relationship between industrial activity and IBP populations with 95% confidence intervals almost half that of the cavity and overwater nesting guild (Figures 13 - 15).

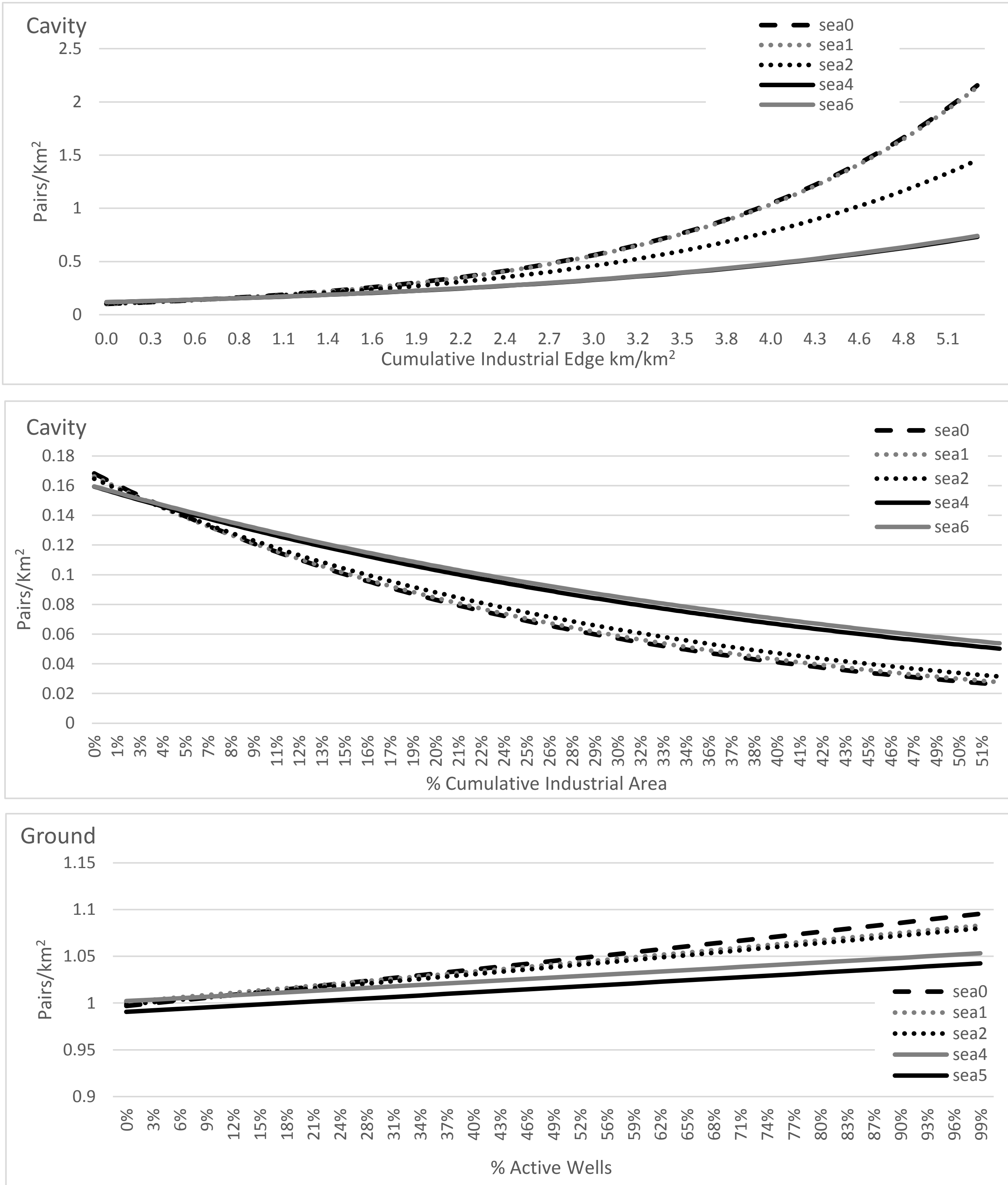

Figure 12. Predicted pairs/km^2 for a gradient of select industrial measures. Top seasonal model is depicted with a solid black line (i.e. season 4 for cavity nesters, and season 5 for ground nesters). For predictions for all guilds and industrial effects see Appendix A, Figures 1 - 6.

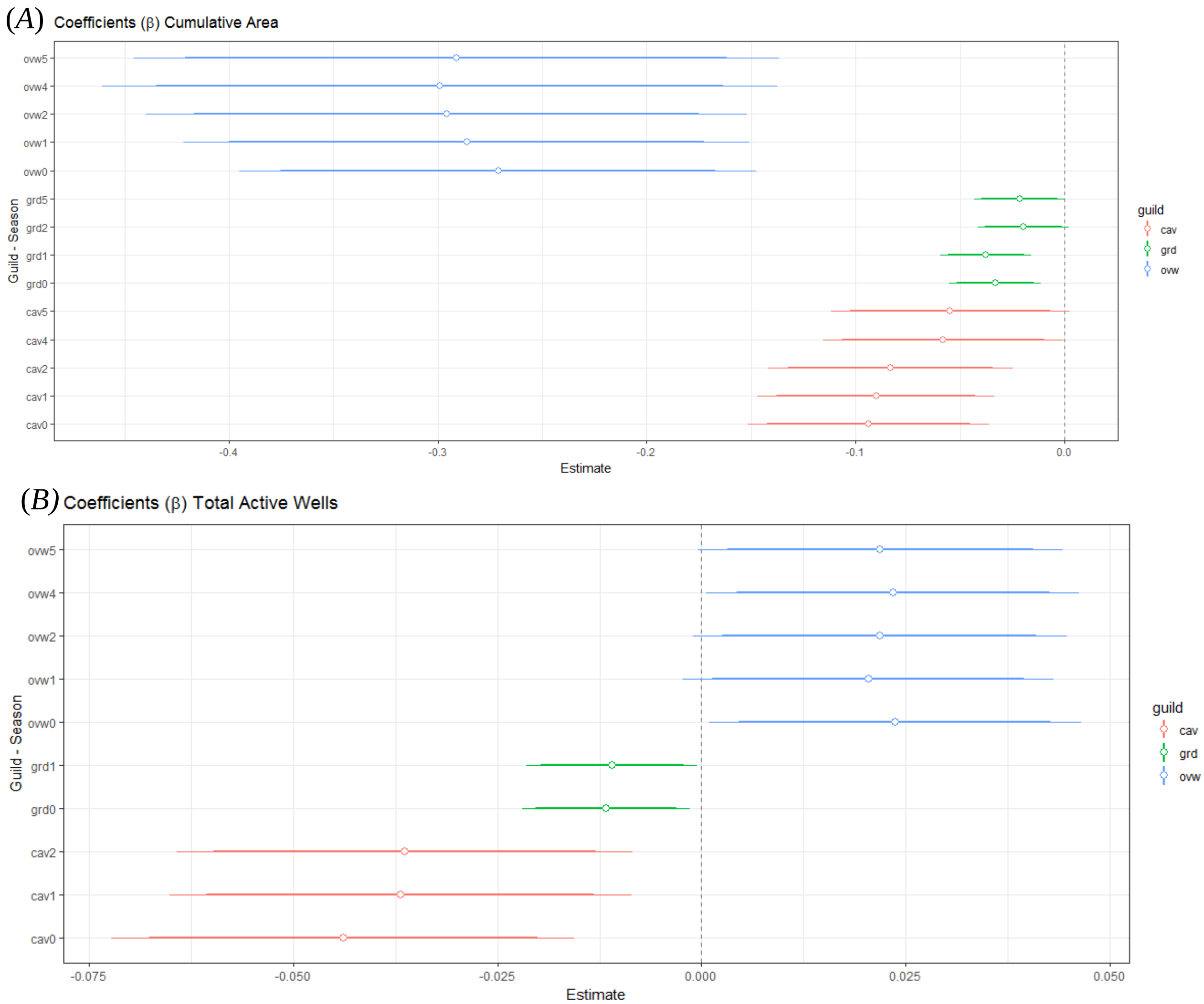

Figure 13. Coefficient estimates of cumulative industrial area (A) and total active wells (B) on IBP densities generated for each nesting guild (ovw – overwater, cav – cavity, grd – ground) with models using different seasonal classifications (no climate (0), season 1, 2, 4, 5). Effects are shown with 95% confidence intervals (thin line), and 50% confidence intervals (thick line).

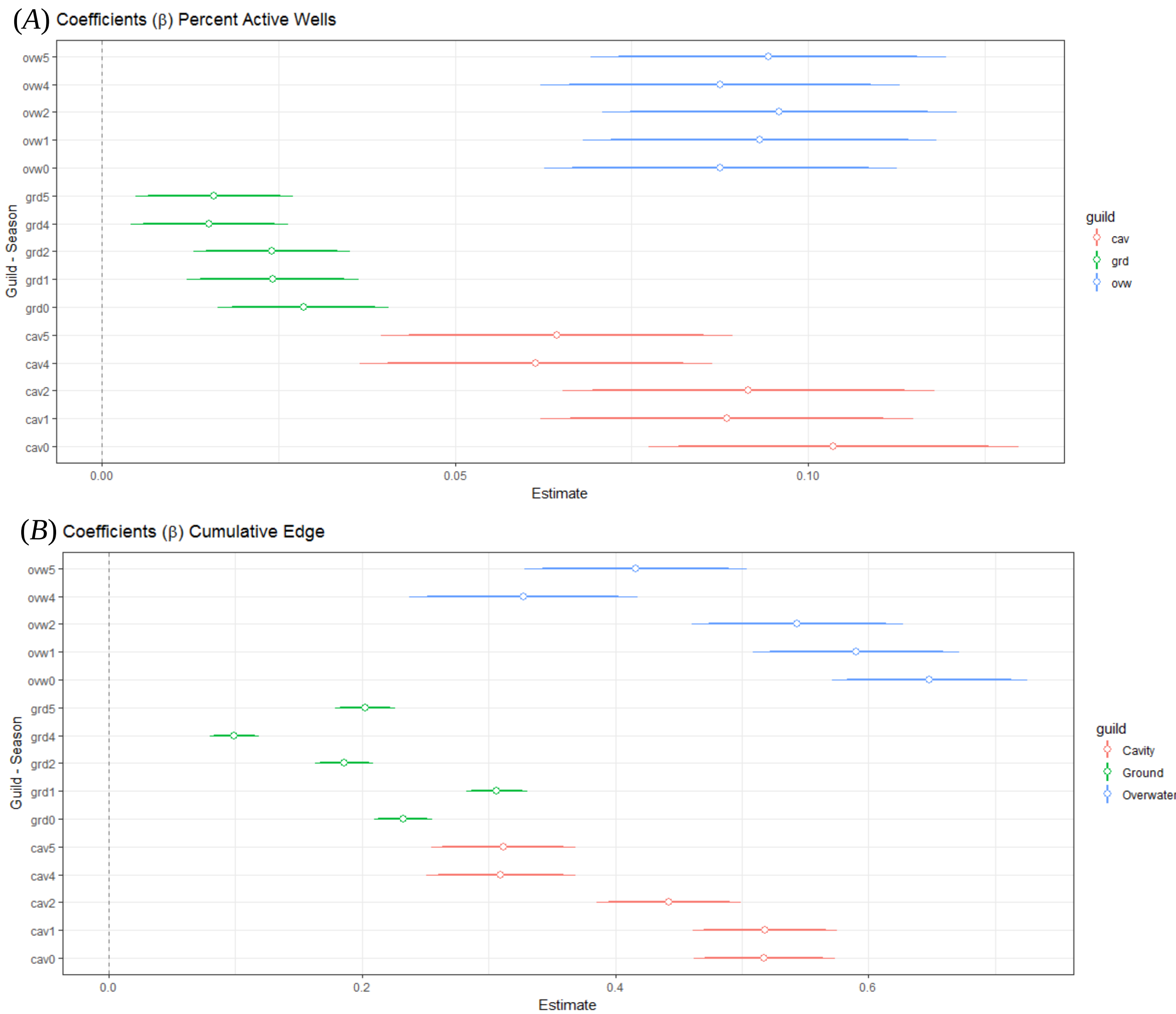

Figure 14. Coefficient estimates of the percentage of active wells (A) and cumulative industrial edge (B) on IBP densities generated for each nesting guild (ovw – overwater, cav – cavity, grd – ground) with models using different seasonal classifications (no climate (0), season 1, 2, 4, 5). Effects are shown with 95% confidence intervals (thin line), and 50% confidence intervals (thick line).

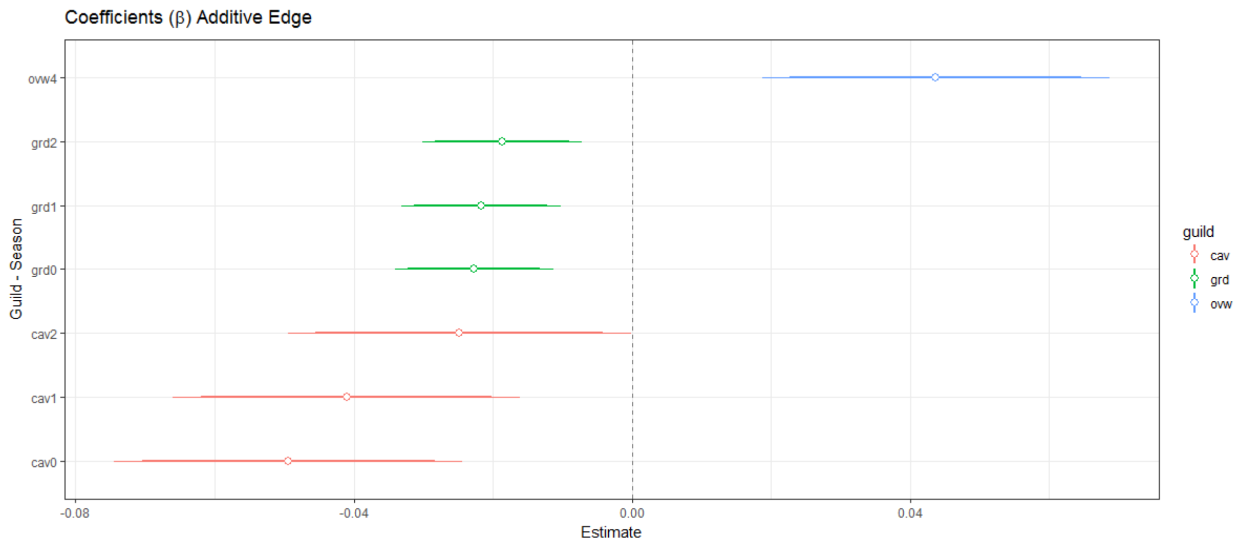

Figure 15. Coefficient estimates of additive industrial edge on IBP densities generated for each nesting guild (ovw – overwater, cav – cavity, grd – ground) with models using different seasonal classifications (no climate (0), season 1, 2, 4, 5). Effects are shown with 95% confidence intervals (thin line), and 50% confidence intervals (thick line).

3.5 DISCUSSION

This work has demonstrated that how local climate data are summarized can vary results when used in GLMMs. Our results show that variable selection and predictions can vary by seasonal aggregation providing support for our hypothesis that the way climate data are aggregated in population models can influence biological interpretation of modelled results. This is important because climate data are often aggregated for use in population models while examining the relationships of other phenomena to duck populations (e.g. Ross, Hooten et al. 2015), as well as the examining the impact of climate itself to populations (e.g. Drever, Clark et al. 2012). As well, understanding how climate effects are related to populations is an important first step to informing decisions related to forming conservation and management strategies to mitigate the impacts of climate change (Jenouvrier 2013).

Using AIC as a measure of model fit, we identified that the optimal seasonal aggregation differs by nesting guild. Studies that attempt to understand waterfowl populations by nesting guild should therefore consider that local climate data should not be treated uniformly for all guilds. Our results suggest that this may be best accomplished using finer temporal resolution climate data.

A comparison of the modelled effect sizes (beta coefficients) for industrial area, edge, and activity using different seasonal aggregation revealed that results vary by seasonal aggregation. The relationships between IBP densities and industrial area, edge, and activity did not change but there were differences in effect size estimated using different seasonal aggregations and the subsequent predictions generated from the effects. Some of the confidence internals of the estimated effects do show overlap, but this does not necessarily mean there is not a statistical difference between the estimates (Ryan and Leadbetter 2002, Payton, Greenstone et al. 2003). A more formalized comparison of the estimated effects is recommended to quantify the magnitude of difference between the seasonal models.

Industrial effect sizes varied by seasonal aggregation but overall industry effects are small compared to the climate and environmental predictors used in the models. Nonetheless, predictions across the gradient of industrial measures show that even these small effects can result in large changes in predicted pairs, especially at higher levels of industrial development.

Predictions generated from modelled effect sizes using different seasonal aggregations could have implications if applied to management or policy decisions. Even with small estimated effects, depending on seasonal aggregation and levels of industry, pair density predictions varied. The variation observed in effect size and predictions has the potential to result in inaccurate conclusions about the effects of industry on duck populations. Simulation modelling has been used to understand the implications of increasing industry development on caribou populations in the boreal (Schneider, Stelfox et al. 2003). A similar approach applied to duck populations and industrial development would need to account for climate covariates judiciously or risk over or under estimating industry effects.

The industrial area, edge, and activity covariates retained in the top models varied by seasonal aggregation. The use of different seasonal aggregation resulted in some industrial effects included or excluded in the top models depending on seasonal aggregation and nesting guild. Cumulative industrial area is only retained in the top ranked season five ground nesters model and omitted from the other seasonal aggregation models. If using the competing seasonal aggregation models, we could conclude that cumulative industrial area does not influence ground nesting species; this is in contrast to the results of the top ranked model where a negative relationship between cumulative industrial area and duck populations was found. This difference in biological interpretation could result in ineffective management strategies that do not consider how cumulative industrial area impacts breeding ground nesters.

3.5.1 MANAGEMENT IMPLICATIONS

Monitoring efforts are on-going in the region to identify areas most important for monitoring, and also to identify what industrial activity should be monitored (Government of Canada and Government of Alberta 2012, Alberta Government and Environment and Climate Change Canada 2016). We have shown that depending on seasonal aggregation, the identification of what industrial activity to monitor could vary. If climate data are omitted from duck population models, or applied in broad seasonal aggregations, some industrial effects on duck populations may not be considered which could have implications if in fact those industrial effects do significantly impact duck populations.

While the PPR is the most productive and important area for breeding waterfowl in North America, interest is shifting to the North American Waterfowl Management Plan (NAWMP) priority areas of WBF (Alberta NAWMP Partnership 2013). As the spatial extent and latitudinal gradient of breeding waterfowl population abundance modelling expands from the PPR to the WBF, and beyond (i.e. national, continental), understanding how climate data can be better utilized in modelling efforts is likely to become increasingly important.

Our analysis in the boreal plains of Alberta demonstrate that decisions on how local climate data is summarized should consider species, nesting guild, and how the results will be utilized. The use of broad definitions of seasons can have implications if generating predictions from models or identifying important relationships between industry and waterfowl populations. Moreover, how climate data are treated in population models warrants attention if climate change impacts are to be better understood or if climate is to be accounted for while examining the importance of other factors influencing population trends (e.g. predation, density dependence). The impacts of climate change could have consequences on breeding ducks' energetic requirements and food availability making the inclusion of climate data in duck population models important (Devink, Clark et al. 2008).

3.5.2 RECOMMENDATIONS

Climate has been found to be an important factor in population trends for a number of waterfowl species (Guillemain, Pöysä et al. 2013, Barker, Cumming et al. 2014, Osnas, Zhao et al. 2016), but the implications of how climate data are aggregated for analysis has not been fully realized. In this study we looked at how the use of different seasonal classifications in GLMMs can influence biological interpretation of population models and predicted duck densities across a gradient of industrial measures. It is recommended that analyses incorporate fine scale climate data to capture the influence of and to control for climate effects on populations. Thoughtful use of local climate data will facilitate the development of better models and lead to an increased understanding of how anthropogenic change may be influencing duck population trends.

CHAPTER 4. OVERVIEW AND CONCLUSIONS

4.1 SUMMARY

This research provides empirical information about how industry and breeding duck populations are related in the WBF. Research into how industrial infrastructure affects wildlife populations in the WBF has focused on large mammals such as caribou and grizzly bears with very limited studies relating to industry and ducks (Sorensen, McLoughlin et al. 2008, Slattery, Morissette et al. 2011, Laberee, Nelson et al. 2014). Petroleum infrastructure has been found to change mammalian behaviour such as avoidance of industrialized areas, increase stress levels, and reduce nutrition levels (Wasser, Keim et al. 2011, Northrup and Wittemyer 2013). However, the positive effect of industrial activity on breeding duck populations suggests that ducks are not avoiding industrial areas or activity. I did find evidence of a small negative relationship with industrial area and IBPs, but this negative effect may be countered by the positive effect detected between IBPs and industrial edge and activity.

This research also provides evidence that the way climate data are aggregated in models that analyse relationships between industry and duck populations has implications for identifying industrial effects and the magnitude of those effects. Given the importance of the inclusion of climate data when researching population trends, and the use of these types of studies to guide monitoring efforts, this is a significant finding (Forcey, Thogmartin et al. 2011, Guillemain, Pöysä et al. 2013, Börger and Nudds 2014, Alberta Government and Environment and Climate Change Canada 2016).

4.2 MANAGEMENT IMPLICATIONS & FUTURE RESEARCH

The negative relationship found between cumulative industrial area and breeding duck populations is an indication that duck conservation efforts that limit cumulative industrial will remain an important mitigation strategy (Northrup and Wittemyer 2013). The reuse of existing infrastructure, the use of less invasive techniques, and avoidance of sensitive areas and wetlands are ways that current practices help limit the growth of industrial area (Alberta Environment 2011, Canadian Association of Petroleum Producers 2014). The development of best management practices (BMPs) by academia, industry, government, conservation groups, and community stakeholders will likely remain an important aspect of conservation in the region (e.g. Cumulative Environmental Management Association 2014, Ducks Unlimited Canada 2014, Silvacom 2015).

The positive effect of additive edge detected for the overwater nesters might be related to construction practices that are creating duck habitat. Understanding the impacts of construction that can occur during different times of the year, with the potential to degrade or enhance duck habitats is necessary for the development of BMPs that can positively influence duck populations. BMPs that focus on road construction and wetland crossings are important conservation tools that engages industry partners and emphasises the importance of wetlands habitats. However, my finding that cumulative edge is positively related to breeding pairs suggests that the edge effect of roads is not as important as the potential hydrological impact of linear features. Roads are known to have impacts on hydrology especially in areas of timber harvesting, but the impact of roads on duck habitat may be less critical with many impacts shown to diminish with increasing distance away from roadway and over time (Forman and Alexander 1998, Lee and Power 2013).

Hydrological impact of resource roads is often evident by a change in vegetation up and down stream of the road crossing (Gillies 2011). However, evidence of hydrological impact at areas where there is no road crossings suggest that additional factors relating to hydrological flow exist that impact hydrology (Gillies 2011). A natural analog of hydrological change in the region is the North American beaver (*Castor canadiensis*). Beaver dams change hydrological flow resulting in changes to vegetation structure in and around wetlands that has been found to be similar to the impacts of road construction (Martell and Foote 2006). Beaver activity has also been associated with increased food availability for ducks and is positively related to brood production (Holopainen, Nummi et al. 2014). Research is recommended that looks beyond the construction phase of roads to longer-term impacts, considers lag-effects on biotic communities, and includes natural processes of hydrological change (Findlay and Houlahan 1997, Findlay and Bourdages 2000, Angermeier, Wheeler et al. 2004, Timoney 2008).

Additionally, the inclusion of all types of infrastructure features (i.e. seismic lines and roads) in future research would enable a more comprehensive look at how different types of features associated with the oil and gas industry might be interacting with duck populations. The infrastructure related to the oil and gas industry can alter hydrological function by wetland drainage and soil compaction during construction but the effect on the quality of wetland habitats is understudied (Foote and Krogman 2006, Graf 2009, Kreutzweiser, Beall et al. 2013, Webster, Beall et al. 2015).

Seismic lines are the most prevalent linear feature in the region and have lower restorative and regenerative capacity in peatland environments (Lee and Boutin 2005, van Rensen, Nielsen et al. 2015). However, seismic lines in marsh habitats have greater natural regenerative capacity, and this naturalized reclamation has been found to be more effective and economic than artificial reclamation processes (Bradshaw 2000, Graf 2009). Marshes offer more suitable habitat for duck populations over peatlands, so could be prioritized for reclamation, but if these habitats have high naturalized restoration capacity, reclamation could be more effective in other types of wetlands (Nummi and Pöysä 1993, Holopainen, Nummi et al. 2014, Holopainen, Arzel et al. 2015).

The protection of natural areas is an important conservation strategy but more research is required to better understand how landscape composition is changing with increasing industry so to better guide policies to conserve and protect duck habitats in the WBF. In my research, relationships between industrial measures and breeding duck populations were observed as both positive and negative, but these relationships may be influenced by additional factors that were not included in the analysis due to the unavailability of industry data with temporal information. For example, the impacts of agriculture and forestry on duck populations are not captured in this work.

I used segment level duck populations and fine scale industrial data (i.e. individual industrial features) for this local scale analysis of industry and ducks on segments that are 400 metre wide and approximately 30 kilometre long. Future research could look to emerging datasets that provide aggregated spatial and temporal representations of petroleum, natural gas, forestry, and mining industrial concessions (Global Forest Watch Canada 2017). Global Forest Watch's industrial concessions, Landsat's satellite imagery archive, and robust imagery segmentation techniques offer an opportunity to learn more how industrial development is related to landscape change over time (Lillesand, Kiefer et al. 2004, Frohn, Reif et al. 2009).

Measures of land cover change (e.g. composition, fragmentation) could be used to look at how industrial development in the WBF of Alberta is changing habitats and how those changes may be related to duck populations. Concerns about caribou populations in the region have prompted studies on land cover change, habitat loss, fragmentation, and predator effects (Sorensen, McLoughlin et al. 2008, Wasser, Keim et al. 2011, Pyper, Nishi et al. 2014). Similar research focused on duck habitats would help increase our understanding how ducks and industry interact in the region. Developing a better understanding of these relationship will be challenged by difficulties in accounting for cumulative and lag effects of industrial activity on wetland habitats, defining characteristics of quality duck habitat that can be detected remotely, and image classification accuracies (Forman and Alexander 1998, Smith, Smith et al. 2007, Zeng, Zhang et al. 2011, Ducks Unlimited Canada 2013).

In Chapter 3, I provide evidence that studies on duck populations and industrial stressors require the judicious use of climate data. For this study, I relied on climate averages, but climate data measured as deviation from averages provides a measure of weather events which can have a significant impact on nesting success (Börger and Nudds 2014). Experimentation with deviations from climate averages, bioclimatic variables, and statistical methods could reveal novel ways to include the influences of climate and weather, while improving model fit. Models that are better parametrized could increase model accuracies and predictive power, which will likely remain important for guiding monitoring activities and assessing environmental impacts in the region (Alberta NAWMP Partnership 2013, Alberta Government and Environment and Climate Change Canada 2016).

Even with recent declines in the petroleum industry, this sector is expected to remain an important contributor to the local and national economy for many years (Canadian Association of Petroleum Producers 2015, Howard 2015, Howard 2015). Threatened caribou populations have lead to the development of policies and industry practices that reduce fragmentation and anthropognic impacts, which may be benefiting other species, including ducks (Alberta Environment 2011, Silvacom 2015). The impacts of climate change and the role of forest ecosystems in regulating green house gases, and the ability of wetlands to store carbon are drawing increased interest and research to the region (Roulet 2000, Yu 2012). My research provides insight on how ducks and industry are interacting in Alberta's WBF, but further consideration to industrial impacts on ecosystem function and aquatic environments is required (Schneider, Stelfox et al. 2003, Kreutzweiser, Beall et al. 2013, Alberta Government and Environment and Climate Change Canada 2016). With increasing industrial development, and threats related to climate change, insight to how duck populations are changing in the WBF will remain an important area of research.

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APPENDIX A

Table 1. Duck species listed by common name, nesting guild, and scientific name

Common Name	Nesting Guild	Scientific Name
Mallard	ground	*Anas platyrhynchos*
Gadwall	ground	*Anas strepera*
American wigeon	ground	*Anas americana*
American green-winged teal	ground	*Anas carolinensis*
Blue-winged teal	ground	*Anas discors*
Northern shoveler	ground	*Anas clypeata*
Northern pintail	ground	*Anas acuta*
Redhead	overwater	*Aythya americana*
Canvasback	overwater	*Aythya valisineria*
Generic scaup	ground	*Aythya affinis* (Lesser)/*Aythya marila* (Greater)
Ring-necked duck	overwater	*Aythya collaris*
Generic goldeneye	cavity	*Bucephala clangula* (Common)/*Bucephala islandica* (Barrow's)
Bufflehead	cavity	*Buchephala albeola*
Ruddy duck	overwater	*Oxyura jamaicensis*

Table 2. Model covariates listed by category.

Category	Covariate	*Description*	Value
Land Cover			
	mix_close	*Mixed-needle leaved closed canopy*	Portion of segment area (%)
	eg_med_moss	*Evergreen medium density*	Portion of segment area (%)
	eg_dec_low	*Evergreen deciduous low density*	Portion of segment area (%)
	eg_low_poor	*Evergreen deciduous low density poorly drained*	Portion of segment area (%)
	broad_low_med	*Broad leafed low to medium density*	Portion of segment area (%)
	low_regen	*Low regenerating young mixed cover*	Portion of segment area (%)
	shrub_grass	*Mixed shrub and grass*	Portion of segment area (%)
	crop_wood	*Cropland - woodland*	Portion of segment area (%)
	crop	*Cropland*	Portion of segment area (%)
	other	*Other*	Portion of segment area (%)
Habitat			
	cnt_wet	*Wetland count*	Total wetlands per segment
	wet_area	*Wetland area*	Total wetland area per segment (km^2)
Landform			
	por_LG	*Percent Glaciolacustrine Deposits*	Portion of segment area (%)
	por_M	*Percent Moraine*	Portion of segment area (%)
	por_MS	*Stagnant Ice Moraine*	Portion of segment area (%)
	por_O	*Organic Deposits*	Portion of segment area (%)
	other	*Other*	Portion of segment area (%)
	rug	*Topological ruggedness*	Average topological ruggedness of segment
	latitude	*Latitude*	Degrees latitude

Category	Covariate	*Description*	Value
Industry			
	per_active	*Percent active wells*	Active wells/Total wells per segment (%)
	cnt_active	*Total active wells*	Total number of active wells
	area_cum	*Cumulative industrial area*	Total cumulative industrial area as a portion of segment area (%)
	area_add	*Additive industrial area*	Total additive industrial area as a portion of segment area (%)
	len_cum	*Cumulative industrial edge*	Total cumulative industrial edge/total segment area (km/km2)
	len_add	*Additive industrial edge*	Total additive industrial edge/total segment area (km/km2)
Climate			
	wi_cmi	*Winter climate moisture index*	Dec - Feb (average) – 4 season
	wi_min	*Winter minimum temperature*	Dec - Feb (average) – 4 season
	wi_snwd	*Winter snow depth*	Dec - Feb (total) – 4 season
	sp_cmi	*Spring climate moisture index*	Mar - May (average) – 4 season
	sp_min	*Spring minimum temperature*	Mar - May (average) – 4 season
	sp_snwd	*Spring snow depth*	Mar - May (total) – 4 season
	wi_cmi_t_1	*Winter climate moisture index t-1*	Dec - Feb (average) – 4 season
	wi_min_t_1	*Winter minimum temperature t-1*	Dec - Feb (average) – 4 season
	wi_snwd_t_1	*Winter snow depth t-1*	Dec - Feb (average) – 4 season
	sp_cmi_t_1	*Spring climate moisture index t-1*	Mar - May (average) – 4 season
	sp_min_t_1	*Spring minimum temperature t-1*	Mar - May (average) – 4 season
	sp_snwd_t_1	*Spring snow depth t-1*	Mar - May (total) – 4 season
	su_cmi_t_1	*Summer climate moisture index t-1*	Jun - Aug (average) – 4 season
	su_min_t_1	*Summer minimum temperature t-1*	Jun - Aug (average) – 4 season
	au_cmi_t_1	*Autumn climate moisture index t-1*	Sep - Nov (average) – 4 season
	au_min_t_1	*Autumn minimum temperature t-1*	Sep - Nov (average) – 4 season
	au_snwd_t_1	*Autumn snow t-1*	Sep - Nov (total) – 4 season
	hi_cmi	*Winter climate moisture index*	Nov- Feb (average) – 5 season

Category	Covariate	*Description*	Value
	hi_snwd	*Winter snow depth*	Nov- Feb (total) – 5 season
	hi_min	*Winter minimum temperature*	Nov- Feb (average) – 5 season
	pr_cmi	*Early spring climate moisture index*	Mar - Apr (average) – 5 season
	pr_min	*Early spring minimum temperature*	Mar - Apr (average) – 5 season
	pr_snwd	*Early spring snow depth*	Mar - Apr (total) – 5 season
	ve_cmi	*Spring climate moisture index*	May - Jun (average) – 5 season
	ve_min	*Spring minimum temperature*	May - Jun (average) – 5 season
	pr_cmi_t_1	*Early spring climate moisture index t-1*	Mar - Apr (average) – 5 season
	pr_min_t_1	*Early spring minimum temperature t-1*	Mar - Apr (average) – 5 season
	pr_snwd_t_1	*Early spring snow depth t-1*	Mar - Apr (total) – 5 season
	ve_cmi_t_1	*Spring climate moisture index t-1*	May - Jun (average) – 5 season
	ve_min_t_1	*Spring minimum temperature t-1*	May - Jun (average) – 5 season
	es_cmi_t_1	*High summer climate moisture index t-1*	Jul - Aug (average) – 5 season
	es_min_t_1	*High summer minimum temperature t-1*	Jul - Aug (average) – 5 season
	srat_cmi_t_1	*Late summer - autumn climate moisture index t-1*	Sep - Oct (average) – 5 season
	srat_min_t_1	*Late summer - autumn minimum temperature t-1*	Sep - Oct (average) – 5 season
	srat_snwd_t_1	*Late summer - autumn snow depth t-1*	Sep - Oct (total) – 5 season

Table 3. Top guild model coefficient estimates with standard errors, z values, and probabilities (Pr(>|z|).

>|z|)
2e-16
27E-05
56E-09
30E-07
129009

Table 3. Top guild model coefficient estimates with standard errors, z values, and probabilities (Pr(>|z|).

eg_dec_low	-0.18715	0.10329	-1.812	7.00E-02	eg_med_moss	-0.2946371	0.0894156	-3.295	0.000984	low_regen	-0.26803	0.1139	-2.353	0.018608
low_regen	-0.26336	0.09259	-2.844	4.45E-03	eg_dec_low	-0.2866131	0.1004119	-2.854	0.004312	per_active	0.08754	0.013	6.732	1.67E-11
per_active	0.06109	0.01273	4.797	1.61E-06	low_regen	-0.1897409	0.0814565	-2.329	0.01984	cnt_active	0.02343	0.01165	2.01	0.044383
area_cum	-0.05793	0.02938	-1.972	4.86E-02	crop_wood	0.2530297	0.0862058	2.935	0.003334	area_cum	-0.29909	0.08248	-3.626	0.000288
edge_cum	0.3095	0.03013	10.272	< 2e-16	crop	0.3190334	0.1098595	2.904	0.003684	edge_cum	0.32758	0.04589	7.138	9.44E-13
wi_min	0.16628	0.01688	9.851	< 2e-16	per_active	0.0159015	0.0056856	2.797	0.005161	edge_add	0.04366	0.01274	3.427	0.000609
wi_snwd	-0.05995	0.01976	-3.035	2.41E-03	area_cum	-0.0215007	0.0109951	-1.955	0.050526	wi_cmi	0.08494	0.01496	5.677	1.37E-08
sp_cmi	0.08707	0.01285	6.776	1.24E-11	edge_cum	0.2030249	0.0120665	16.825	< 2e-16	wi_min	0.29182	0.0159	18.358	< 2e-16
sp_min	-0.13372	0.01565	-8.546	< 2e-16	hi_snwd	-0.1322131	0.0063113	-20.949	< 2e-16	wi_snwd	0.15855	0.02224	7.129	1.01E-12
sp_snwd	-0.15649	0.01942	-8.058	7.77E-16	pr_min	-0.0593776	0.0062738	-9.464	< 2e-16	sp_cmi	0.08251	0.01181	6.985	2.84E-12
wi_min_t_1	0.09735	0.01754	5.551	2.85E-08	pr_snwd	0.058641	0.0073347	7.995	1.30E-15	sp_min	-0.04768	0.01403	-3.398	0.000678
sp_cmi_t_1	0.07687	0.01314	5.848	4.96E-09	ve_cmi	0.1220702	0.0047031	25.955	< 2e-16	sp_snwd	-0.16147	0.018	-8.969	< 2e-16
sp_min_t_1	-0.26955	0.01405	-19.187	< 2e-16	ve_min	-0.0635427	0.0046502	-13.665	< 2e-16	wi_cmi_t_1	-0.07372	0.01573	-4.688	2.76E-06
sp_snwd_t_1	-0.07962	0.01687	-4.72	2.36E-06	pr_cmi_t_1	-0.0928069	0.0053196	-17.446	< 2e-16	wi_min_t_1	0.14989	0.015	9.993	< 2e-16
su_cmi_t_1	0.06242	0.01215	5.137	2.79E-07	pr_min_t_1	-0.0575988	0.0066784	-8.625	< 2e-16	wi_snwd_t_1	0.03226	0.01793	1.799	0.07197
su_min_t_1	0.07332	0.0153	4.792	1.65E-06	pr_snwd_t_1	0.0582015	0.0070478	8.258	< 2e-16	sp_cmi_t_1	0.12852	0.01186	10.839	< 2e-16
au_cmi_t_1	-0.05403	0.01309	-4.129	3.65E-05	ve_cmi_t_1	0.1022915	0.0045208	22.627	< 2e-16	sp_min_t_1	-0.09966	0.01264	-7.884	3.17E-15
au_min_t_1	0.03933	0.01709	2.301	2.14E-02	ve_min_t_1	-0.0093763	0.0052319	-1.792	0.07311	au_cmi_t_1	-0.14854	0.01295	-11.474	< 2e-16
au_snwd_t_1	0.05872	0.01837	3.197	1.39E-03	es_cmi_t_1	-0.051403	0.0046466	-11.063	< 2e-16	au_min_t_1	0.20616	0.01641	12.561	< 2e-16
					es_min_t_1	0.0685124	0.0058112	11.79	< 2e-16	au_snwd_t_1	0.15854	0.01936	8.188	2.65E-16
					srat_cmi_t_1	-0.0278623	0.0048604	-5.733	9.89E-09					
					srat_min_t_1	0.0130268	0.0053959	2.414	1.58E-02					
					srat_snwd_t_1	-0.0548224	0.0051597	-10.625	< 2e-16					

APPENDIX B

Table 1. The NRCan land cover product was used to capture land cover characteristics of the survey segments (Latifovic, Olthof et al 2008). The 250 m resolution raster contains 39 classes that were objectively reclassed based on a combination of how well each class was represented in the study area and previous waterfowl modeling work by DUC that identified important land classes to waterfowl (Slattery, Devries et al 2007).

Land Cover Description	Reclass Description
Temperate or subpolar needle-leaved evergreen closed tree canopy	Evergreen deciduous low density
Cold deciduous closed tree canopy	Evergreen deciduous low density
Mixed needle-leaved evergreen â€“ cold deciduous closed tree canopy	Mixed-needle leaved closed canopy
Mixed needle-leaved evergreen â€“ cold deciduous closed young tree canopy	Mixed-needle leaved closed canopy
Mixed cold deciduous â€“ needle-leaved evergreen closed tree canopy	Mixed-needle leaved closed canopy
Temperate or subpolar needle-leaved evergreen medium density, moss-shrub understory	Evergreen medium density
Temperate or subpolar needle-leaved evergreen medium density, lichen-shrub understory	Evergreen deciduous low density
Temperate or subpolar needle-leaved evergreen low density, shrub-moss understory	Evergreen deciduous low density
Temperate or subpolar needle-leaved evergreen low density, lichen (rock) understory	Evergreen deciduous low density
Temperate or subpolar needle-leaved evergreen low density, poorly drained	Evergreen low density poorly drained
Cold deciduous broad-leaved, low to medium density	Broad leafed low to medium density
Cold deciduous broad-leaved, medium density, young regenerating	Broad leafed low to medium density
Mixed needle-leaved evergreen â€“ cold deciduous, low to medium density	Other
Mixed cold deciduous - needle-leaved evergreen, low to medium density	Other
Low regenerating young mixed cover	Low regenerating young mixed cover
High-low shrub dominated	Mixed shrub and grass
Grassland	Mixed shrub and grass
Herb-shrub-bare cover	Mixed shrub and grass
Wetlands	Other
Sparse needle-leaved evergreen, herb-shrub cover	Other
Polar grassland, herb-shrub	Other
Shrub-herb-lichen-bare	Other
Herb-shrub poorly drained	Other
Lichen-shrub-herb-bare soil	Other
Low vegetation cover	Other
Cropland-woodland	Cropland - woodland
High biomass cropland	Crop
Medium biomass cropland	Crop
Low biomass cropland	Crop
Lichen barren	Other
Lichen-sedge-moss-low shrub wetland	Other
Lichen-spruce bog	Other
Rock outcrops	Other
Recent burns	Other
Old burns	Other
Urban and Built-up	Other
Water bodies	Other
Mixes of water and land	Other
Snow/ ice	NA

Table 2. Summary of top seasonal guild models.

Table 2. Summary of top seasonal guild models.

Cavity

Covariate	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	-1.85091	0.08494	-21.791	< 2e-16
cnt_wet	0.23892	0.08581	2.784	5.36E-03
rug	-0.15594	0.08673	-1.798	7.22E-02
mix_close	0.16006	0.08985	1.781	7.48E-02
eg_med_moss	-0.42305	0.10302	-4.106	4.02E-05
eg_dec_low	-0.18715	0.10329	-1.812	7.00E-02
low_regen	-0.26336	0.09259	-2.844	4.45E-03
per_active	0.06109	0.01273	4.797	1.61E-06
area_cum	-0.05793	0.02938	-1.972	4.86E-02
len_cum	0.3095	0.03013	10.272	< 2e-16
wi_min	0.16628	0.01688	9.851	< 2e-16
wi_snwd	-0.05995	0.01976	-3.035	2.41E-03
sp_cmi	0.08707	0.01285	6.776	1.24E-11
sp_min	-0.13372	0.01565	-8.546	< 2e-16
sp_snwd	-0.15649	0.01942	-8.058	7.77E-16
wi_min_t_1	0.09735	0.01754	5.551	2.85E-08
sp_cmi_t_1	0.07687	0.01314	5.848	4.96E-09
sp_min_t_1	-0.26955	0.01405	-19.187	< 2e-16
sp_snwd_t_1	-0.07962	0.01687	-4.72	2.36E-06
su_cmi_t_1	0.06242	0.01215	5.137	2.79E-07
su_min_t_1	0.07332	0.0153	4.792	1.65E-06
au_cmi_t_1	-0.05403	0.01309	-4.129	3.65E-05
au_min_t_1	0.03933	0.01709	2.301	2.14E-02
au_snwd_t_1	0.05872	0.01837	3.197	1.39E-03

Ground

Covariate	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	0.0001713	0.0695415	0.002	0.998034
latitude	0.2106507	0.1135219	1.856	0.063511
cnt_wet	0.1951743	0.0761071	2.564	0.010333
por_M	-0.2294977	0.0785484	-2.922	0.003481
por_LG	-0.2310644	0.0936409	-2.468	0.013604
eg_med_moss	-0.2946371	0.0894156	-3.295	0.000984
eg_dec_low	-0.2866131	0.1004119	-2.854	0.004312
low_regen	-0.1897409	0.0814565	-2.329	0.01984
crop_wood	0.2530297	0.0862058	2.935	0.003334
crop	0.3190334	0.1098595	2.904	0.003684
per_active	0.0159015	0.0056856	2.797	0.005161
area_cum	-0.0215007	0.0109951	-1.955	0.050526
len_cum	0.2030249	0.0120665	16.825	< 2e-16
hi_snwd	-0.1322131	0.0063113	-20.949	< 2e-16
pr_min	-0.0593776	0.0062738	-9.464	< 2e-16
pr_snwd	0.058641	0.0073347	7.995	1.30E-15
ve_cmi	0.1220702	0.0047031	25.955	< 2e-16
ve_min	-0.0635427	0.0046502	-13.665	< 2e-16
pr_cmi_t_1	-0.0928069	0.0053196	-17.446	< 2e-16
pr_min_t_1	-0.0575988	0.0066784	-8.625	< 2e-16
pr_snwd_t_1	0.0582015	0.0070478	8.258	< 2e-16
ve_cmi_t_1	0.1022915	0.0045208	22.627	< 2e-16
ve_min_t_1	-0.0093763	0.0052319	-1.792	0.07311
es_cmi_t_1	-0.051403	0.0046466	-11.063	< 2e-16
es_min_t_1	0.0685124	0.0058112	11.79	< 2e-16
srat_cmi_t_1	-0.0278623	0.0048604	-5.733	9.89E-09
srat_min_t_1	0.0130268	0.0053959	2.414	1.58E-02
srat_snwd_t_1	-0.0548224	0.0051597	-10.625	< 2e-16

Overwater

Covariate	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	-2.1177	0.10552	-20.069	< 2e-16
cnt_wet	0.44736	0.10559	4.237	2.27E-05
wet_area	0.68517	0.1181	5.802	6.56E-09
eg_med_moss	-0.64355	0.12332	-5.219	1.80E-07
eg_dec_low	-0.18518	0.12199	-1.518	0.129009
low_regen	-0.26803	0.1139	-2.353	0.018608
per_active	0.08754	0.013	6.732	1.67E-11
cnt_active	0.02343	0.01165	2.01	0.044383
area_cum	-0.29909	0.08248	-3.626	0.000288
len_cum	0.32758	0.04589	7.138	9.44E-13
len_add	0.04366	0.01274	3.427	0.000609
wi_cmi	0.08494	0.01496	5.677	1.37E-08
wi_min	0.29182	0.0159	18.358	< 2e-16
wi_snwd	0.15855	0.02224	7.129	1.01E-12
sp_cmi	0.08251	0.01181	6.985	2.84E-12
sp_min	-0.04768	0.01403	-3.398	0.000678
sp_snwd	-0.16147	0.018	-8.969	< 2e-16
wi_cmi_t_1	-0.07372	0.01573	-4.688	2.76E-06
wi_min_t_1	0.14989	0.015	9.993	< 2e-16
wi_snwd_t_1	0.03226	0.01793	1.799	0.07197
sp_cmi_t_1	0.12852	0.01186	10.839	< 2e-16
sp_min_t_1	-0.09966	0.01264	-7.884	3.17E-15
au_cmi_t_1	-0.14854	0.01295	-11.474	< 2e-16
au_min_t_1	0.20616	0.01641	12.561	< 2e-16
au_snwd_t_1	0.15854	0.01936	8.188	2.65E-16

Table 3. AIC scores for guild models for all seasonal classifications. Top models for cavity and ground nesting guilds used the 4 season classification. Ground nesters were best modeled with the 5 season classification.

Table 3. AIC scores for guild models for all seasonal classifications. Top models for cavity and ground nesting guilds used the 4 season classification. Ground nesters were best modeled with the 5 season classification.

	Cavity				Ground				Overwater			
	Model	df	AIC	ΔAIC	Model	df	AIC	ΔAIC	Model	df	AIC	ΔAIC
Season 1	sea1_cav	6	24444.69	0	sea1_grd	6	66099.47	0	sea1_ovw	6	29130.99	0
	sea1_cav_i	5	24447.36	2.67	sea1_grd_i	5	66103.24	3.77	sea1_ovw_i	5	29141.93	10.94
	sea1_cav_ii	4	24501.69	57	sea1_grd_ii	4	66122.56	23.09	sea1_ovw_ii	4	29175.65	44.66
	sea1_cav_iii	3	24529.35	84.66	sea1_grd_iii	3	66559.45	459.98	sea1_ovw_iii	3	29258.75	127.76
	sea1_cav_iv	2	24728.35	283.66	sea1_grd_iv	2	66716.93	617.46	sea1_ovw_iv	2	29417.78	286.79
Season 2	sea2_cav_i	9	24103.86	0	sea2_grd	10	65183.29	0	sea2_ovw_i	9	28628.37	0
	sea2_cav	10	24105.54	1.68	sea2_grd_i	9	65186.68	3.39	sea2_ovw	10	28630.1	1.73
	sea2_cav_ii	8	24105.69	1.83	sea2_grd_ii	8	65197.69	14.4	sea2_ovw_ii	8	28633.58	5.21
	sea2_cav_iii	7	24115.28	11.42	sea2_grd_iii	7	65241.86	58.57	sea2_ovw_iii	7	28645.44	17.07
	sea2_cav_iv	6	24368.11	264.25	sea2_grd_iv	6	65255.88	72.59	sea2_ovw_iv	6	28680.45	52.08
	sea2_cav_v	5	24389.83	285.97	sea2_grd_v	5	65627.65	444.36	sea2_ovw_v	5	28737.94	109.57
	sea2_cav_vi	4	24426.9	323.04	sea2_grd_vi	4	65947.21	763.92	sea2_ovw_vi	4	29011.22	382.85
	sea2_cav_vii	3	24474.74	370.88	sea2_grd_vii	3	66553.67	1370.38	sea2_ovw_vii	3	29363.36	734.99
	sea2_cav_viii	2	24728.35	624.49	sea2_grd_viii	2	66716.93	1533.64	sea2_ovw_viii	2	29417.78	789.41
Season 4	sea4_cav_iii	17	23076.34	0	sea4_grd_iii	17	64098.46	0	sea4_ovw_iii	17	27812.03	0
	sea4_cav_ii	18	23078.01	1.67	sea4_grd_ii	18	64099.54	1.08	sea4_ovw_iv	16	27812.14	0.11
	sea4_cav_i	19	23079.04	2.7	sea4_grd_i	19	64101.01	2.55	sea4_ovw_ii	18	27812.86	0.83
	sea4_cav_iv	16	23080.32	3.98	sea4_grd_iv	16	64101.45	2.99	sea4_ovw_v	15	27813.76	1.73
	sea4_cav	20	23080.65	4.31	sea4_grd	20	64102.82	4.36	sea4_ovw_i	19	27814.32	2.29
	sea4_cav_v	15	23103.81	27.47	sea4_grd_v	15	64107.52	9.06	sea4_ovw	20	27816.15	4.12
	sea4_cav_vi	14	23112.35	36.01	sea4_grd_vi	14	64147.18	48.72	sea4_ovw_vi	14	27827.82	15.79
	sea4_cav_vii	13	23121.11	44.77	sea4_grd_vii	13	64157.08	58.62	sea4_ovw_vii	13	27849.95	37.92
	sea4_cav_viii	12	23151.64	75.3	sea4_grd_viii	12	64187.43	88.97	sea4_ovw_viii	12	27885.19	73.16
	sea4_cav_ix	11	23164.71	88.37	sea4_grd_ix	11	64259.38	160.92	sea4_ovw_ix	11	27935.55	123.52
	sea4_cav_x	10	23203.87	127.53	sea4_grd_x	10	64462.34	363.88	sea4_ovw_x	10	27978.14	166.11
Season 5	sea6_cav_iii	18	23156.02	0	sea6_grd_i	20	63891.67	0	sea6_ovw	21	27989.45	0
	sea6_cav_ii	19	23156.03	0.01	sea6_grd	21	63893.52	1.85	sea6_ovw_i	20	27989.61	0.16
	sea6_cav_i	20	23157.76	1.74	sea6_grd_ii	19	63906.31	14.64	sea6_ovw_ii	19	27990.91	1.46
	sea6_cav	21	23159.28	3.26	sea6_grd_iii	18	63924.65	32.98	sea6_ovw_iii	18	27993.21	3.76
	sea6_cav_iv	17	23174.03	18.01	sea6_grd_iv	17	63940.39	48.72	sea6_ovw_iv	17	27996.22	6.77
	sea6_cav_v	16	23190.55	34.53	sea6_grd_v	16	63964.03	72.36	sea6_ovw_v	16	28000.52	11.07
	sea6_cav_vi	15	23210.31	54.29	sea6_grd_vi	15	63990.49	98.82	sea6_ovw_vi	15	28003.39	13.94
	sea6_cav_vii	14	23230.24	74.22	sea6_grd_vii	14	64079.92	188.25	sea6_ovw_vii	14	28005.66	16.21
	sea6_cav_viii	13	23244.37	88.35	sea6_grd_viii	13	64225.68	334.01	sea6_ovw_viii	13	28013.51	24.06
	sea6_cav_ix	12	23272.09	116.07	sea6_grd_ix	12	64325.19	433.52	sea6_ovw_ix	12	28029.78	40.33
	sea6_cav_x	11	23304.88	148.86	sea6_grd_x	11	64378.61	486.94	sea6_ovw_x	11	28071.82	82.37

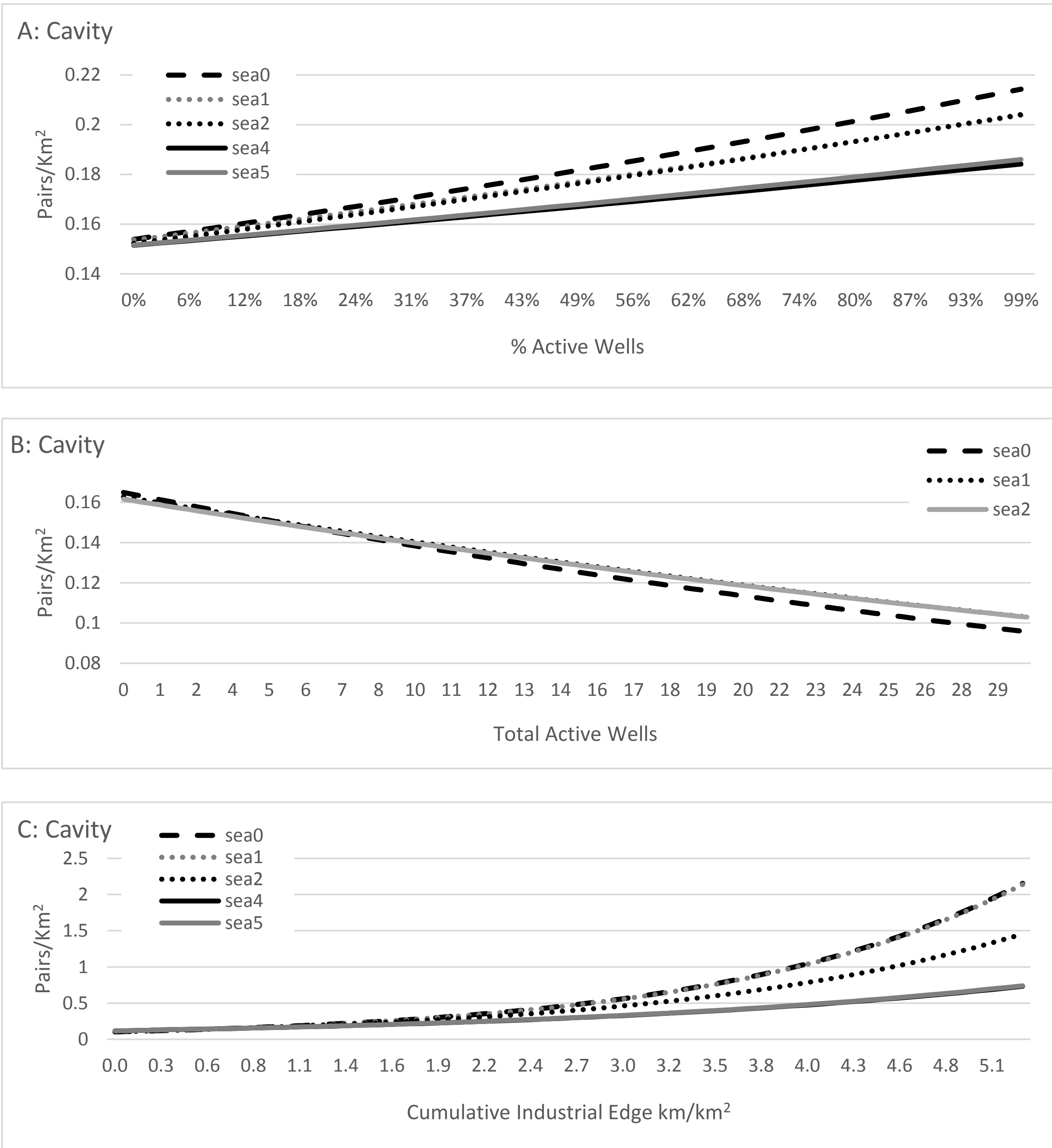

Figure 1. Predicted pairs/km^2 of cavity nesters for a gradient of industrial measures. Top seasonal model is depicted with a solid black line (i.e. season 4).

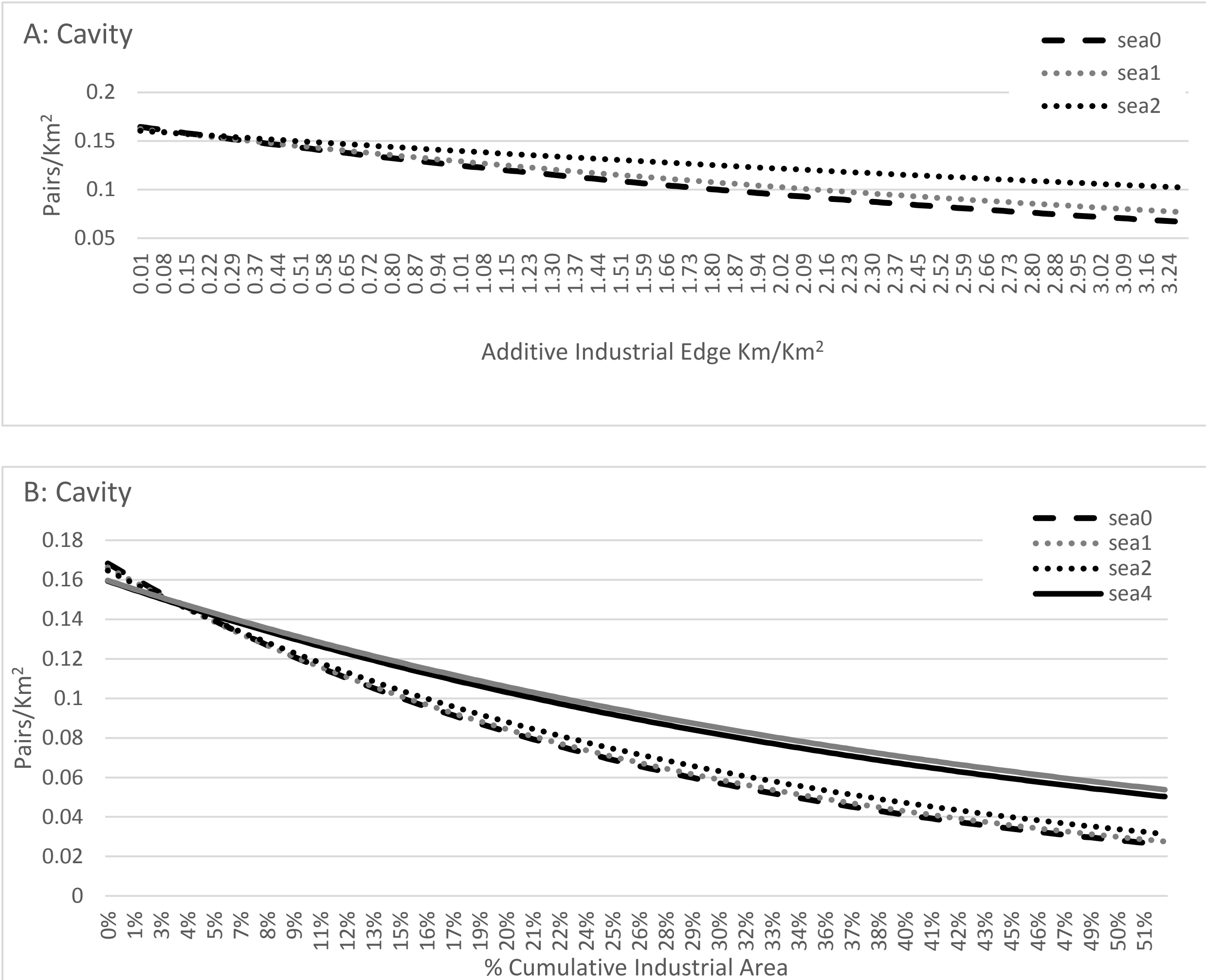

Figure 2. Predicted pairs/km^2 of cavity nesters for a gradient of industrial measures. Top seasonal model is depicted with a solid black line (i.e. season 4).

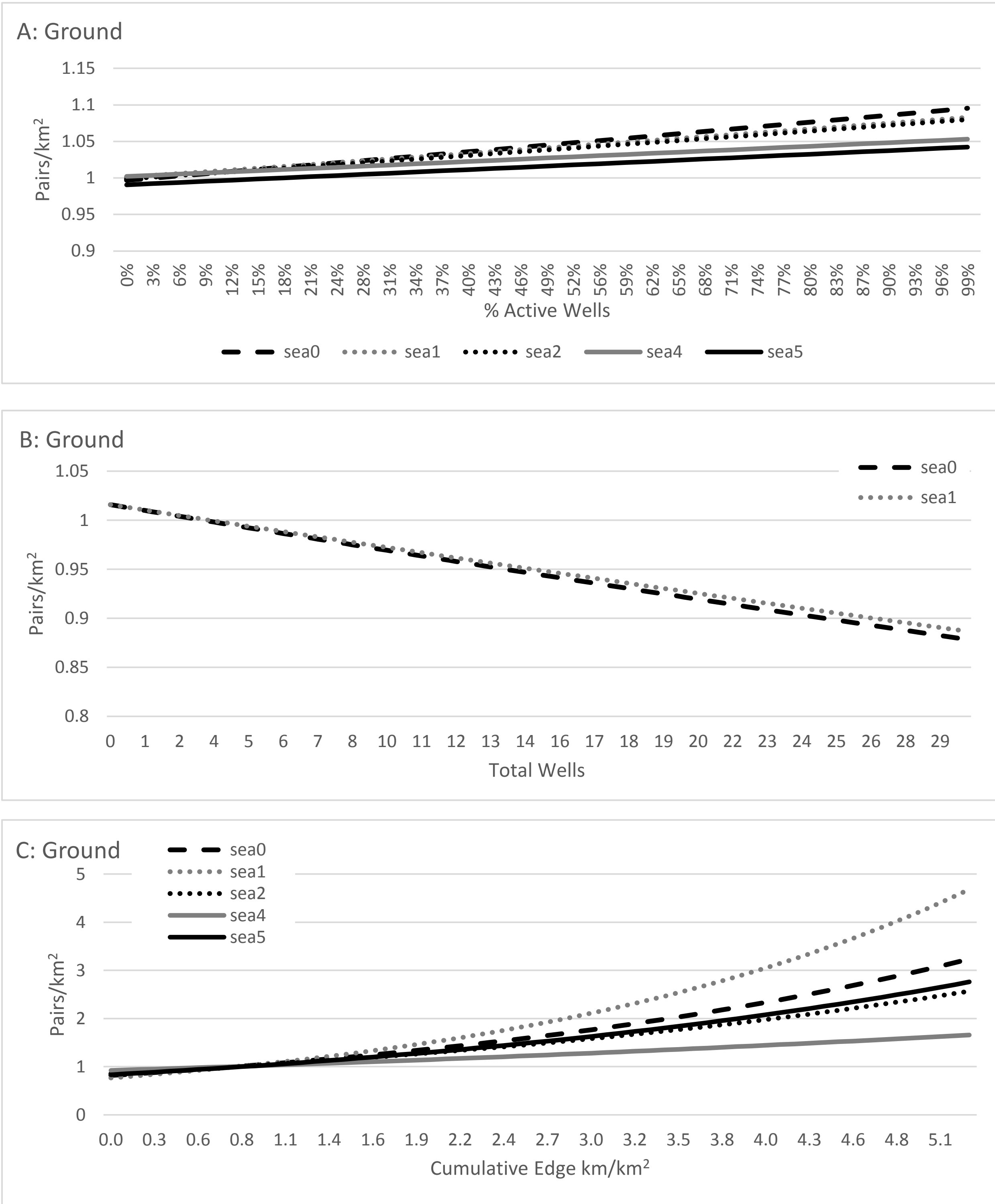

Figure 3. Predicted pairs/km^2 of ground nesters for a gradient of industrial measures. Top seasonal model is depicted with a solid black line (i.e. season 5).

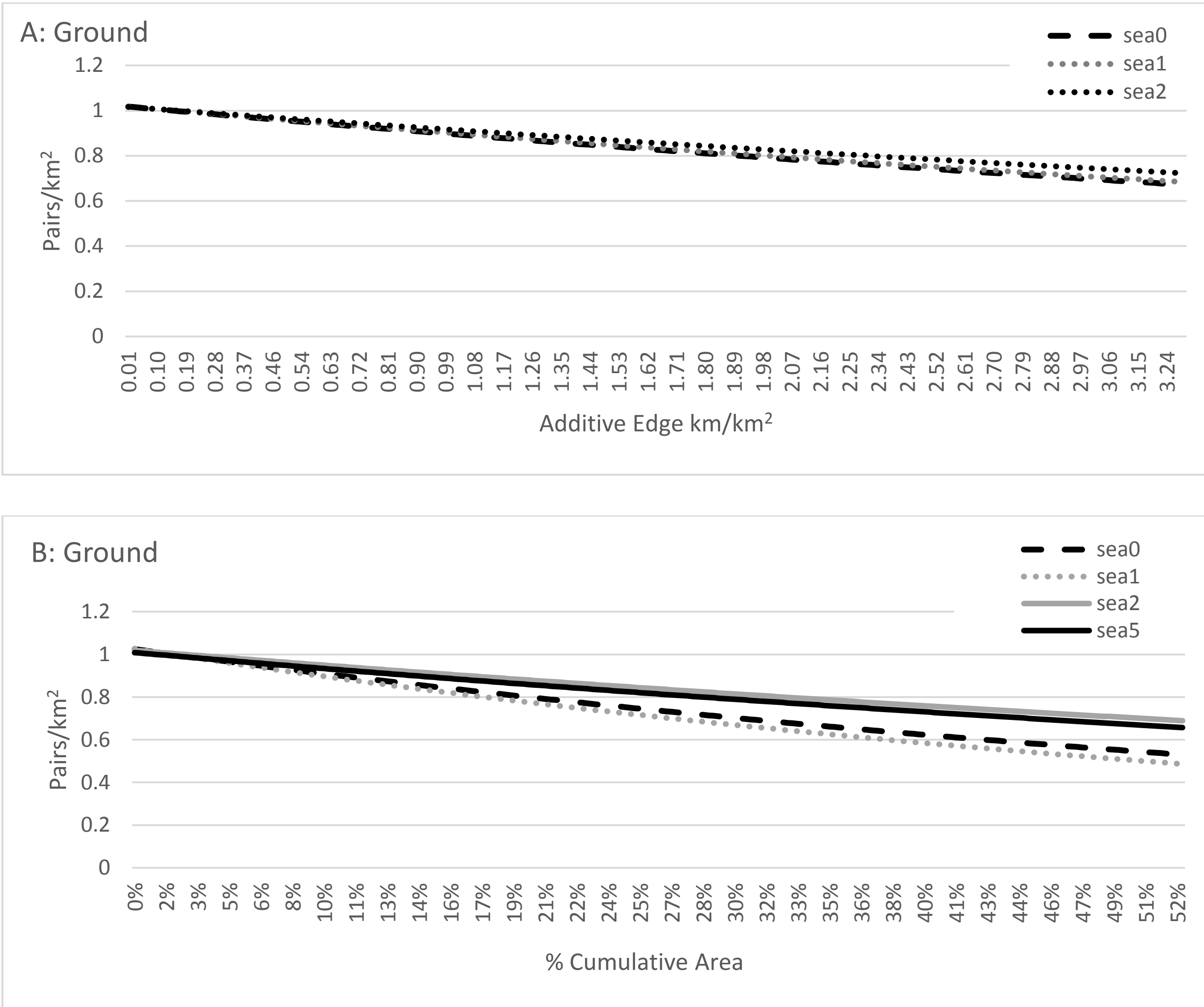

Figure 4. Predicted pairs/km^2 of ground nesters for a gradient of industrial measures. Top seasonal model is depicted with a solid black line (i.e. season 5).

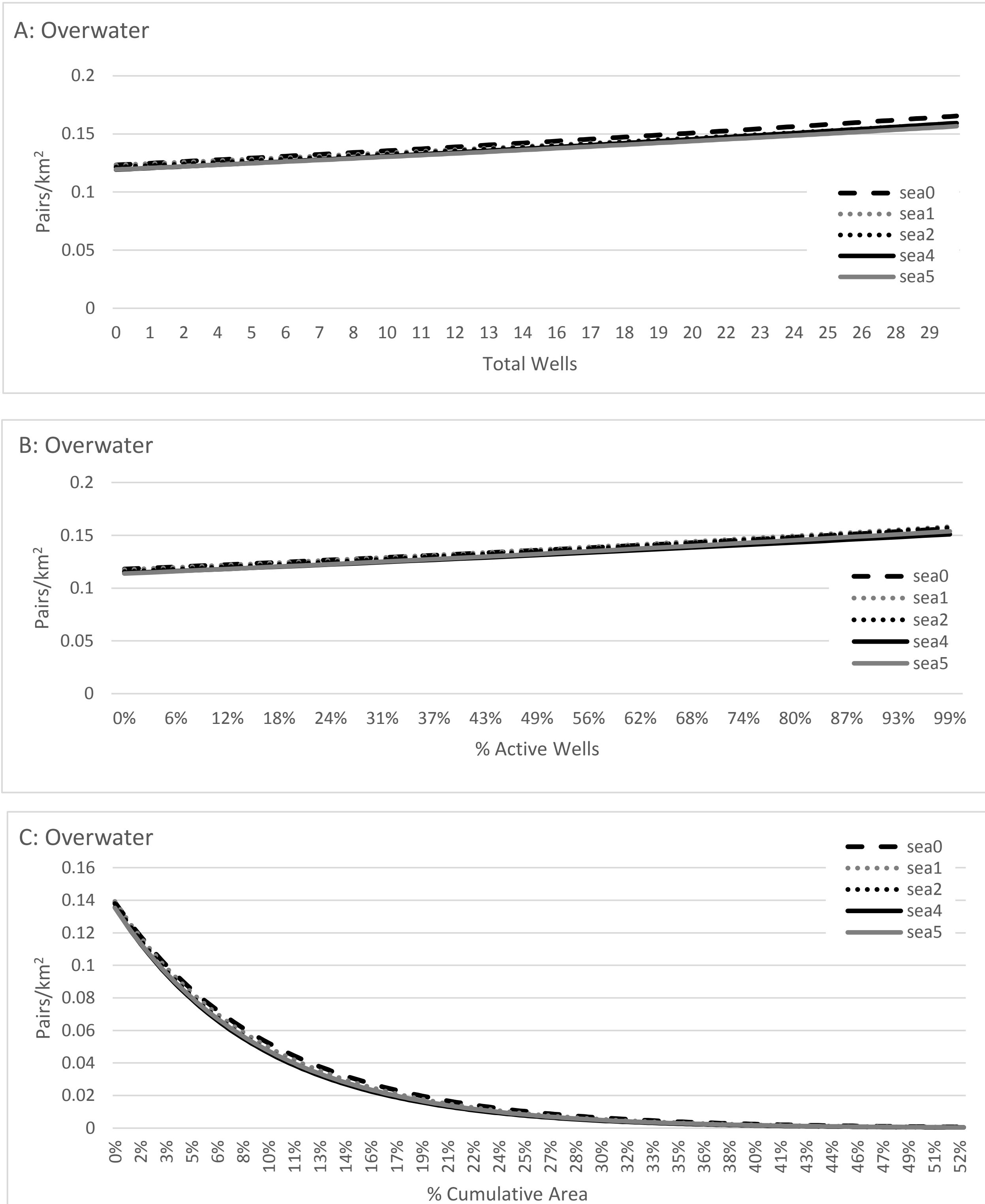

Figure 5. Predicted pairs/km^2 of overwater nesters for a gradient of industrial measures. Top seasonal model is depicted with a solid black line (i.e. season 4).

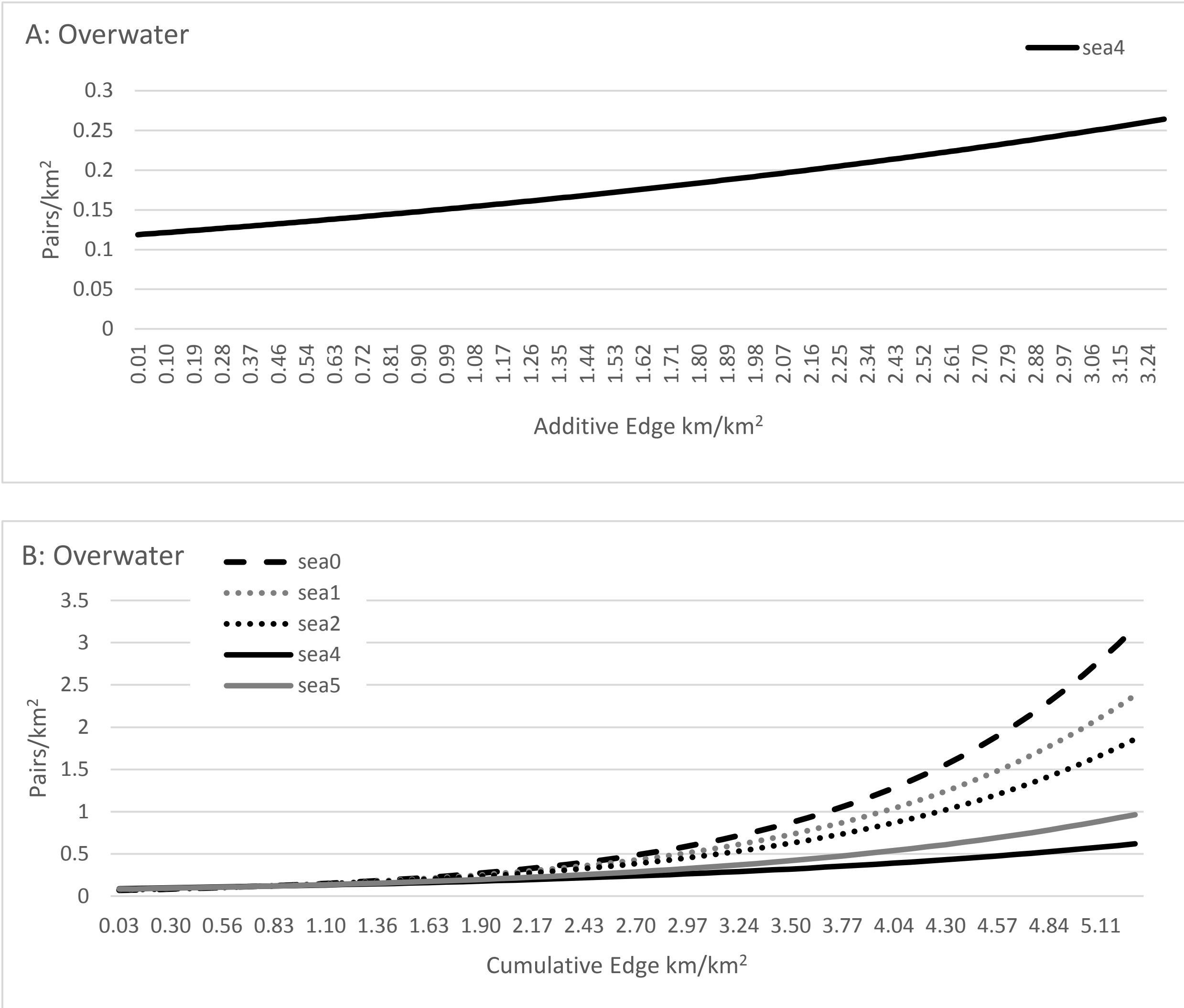

Figure 6. Predicted pairs/km^2 of overwater nesters for a gradient of industrial measures. Top seasonal model is depicted with a solid black line (i.e. season 4).