RELATIONSHIPS BETWEEN BIRD DENSITIES AND DISTANCE TO MINES IN NORTHERN CANADA

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Abstract

Relationships Between Bird Densities and Distance to Mines in Northern Canada

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Increased mining activity in the Canadian Arctic has resulted in significant changes to the environment that may be influencing some tundra-nesting bird populations. In this thesis I examine the direct and indirect effects of mining on birds nesting in the Canadian Arctic. I first perform a literature review of the effects that mining in the Arctic has on northern environments and wildlife and outline several ways in which mines affect Arctic-breeding birds. By using the Program for Regional and International Shorebird Monitoring (PRISM) Arctic plot-based bird survey data from across the Canadian Arctic, collected from 1995 to 2018, I identify the effects of distance to mining operations on the occupancy patterns of Arctic-breeding bird species. Six species' densities were significantly impacted by mine proximity (Canada/Cackling Goose, Long-tailed Duck, Long-tailed Jaeger, Pectoral Sandpiper, Savannah Sparrow, and Rock Ptarmigan) across five major mine sites. Each species has its own unique relationship to distance from mining activity.

Keywords: Canadian Arctic, mining, bird populations, mining activities, tundra-nesting birds, PRISM

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CHAPTER 1: General Introduction

1.0 Arctic Changes

An increase in demand for natural resources including gas, oil and minerals has affected wildlife populations throughout North America, including in the Arctic (Gill et al. 1996, Abbitt et al. 2000, Underhill and Angola 2000, Johnson et al. 2005a). For example, habitat fragmentation from roads and infrastructure leads some mammal species such as wolves (*Canis lupus*) and grizzly bears (*Ursus arctos*), to avoid diamond mines in the Northwest Territories and Nunavut (i.e., Diavik and Ekati diamond mines; Johnson et al. 2005a). Dust, noise, subsidized predators, and other direct and indirect effects of mines operate alone or in interactive ways to influence biodiversity at local to regional scales (reviewed in Chapter 2; Knutsen 2014, Smith et al. 2005, Liebezeit et al. 2009).

Concurrently, rapid anthropogenic climate change is altering Arctic ecosystems. Increases in Arctic temperatures coupled with earlier snow melt can lead to northward expansion of shrub-dominated ecosystems (Sturm et al. 2001, Myers-Smith et al. 2011), alter invertebrate phenology (Høye et al. 2007, Høye and Forchhammer 2008, Shaftel et al. 2021), and impact invertebrate communities and densities (Bowden et al. 2018, Robinson et al. 2018, Markkula et al. 2019). Individually, these factors of land-use and climate change are of concern, but when combined, they could have profound negative effects on Arctic breeding birds (Saalfeld et al. 2013b), their preferred lowland habitats, or their predictable and abundant invertebrate prey items (Meltofte et al. 2007b, McKinnon et al. 2013).

Arctic terrestrial bird species can be best represented in two groups that could be impacted by mining operations due to their greater species richness: shorebirds and passerines (i.e., songbirds). Shorebirds are the most species-rich group of birds in many Arctic locations, followed by passerines (Lindström and Agrell 1999, Liebezeit et al. 2009) and both groups are in a state of decline (Bart et al. 2007, Andres et al. 2012b, North American Bird Conservation Initiative Canada 2019, Rosenberg et al. 2019). It is therefore important to understand how environmental changes and human activities impact the breeding ecology of birds, for both current and future management considerations.

Mining operations have a long-term tenancy and typically remain operational for many years. For example, the Diavik diamond mine in the Northwest Territories began mining operations in 2003 and was originally scheduled to remain open until 2024 before beginning closure procedures, which is estimated to take a year (Shigley et al. 2016, Yip and Pollock 2017). However, the Diavik mine closure schedule plans changed to extend its life expectancy by approximately 10 years by expanding its footprint with the Jay Project where operations are expected to occur from 2019-2029. These expanded operations include creating a new open-pit mine in Lac du Sauvage (Mackenzie Valley Review Board 2016). As seen with the Diavik mine, neither the mine footprint nor the timeline for mine activity is fixed.

Several programs actively monitor the densities of birds that breed in the Arctic, including the Program for Regional and International Shorebird Monitoring (PRISM), the Atlantic Canada Shorebird Survey (ACSS), the International Shorebird Survey (ISS), the

Christmas Bird Count (CBC), and the North American Breeding Bird Survey (BBS) (Niven et al. 2004, Bart et al. 2007, Bart and Johnston 2012). For shorebird species, most programs (i.e., ACSS and ISS) rely on surveys during fall and spring migration, or in winter non-breeding grounds (i.e., CBC) (Niven et al. 2004, Bart et al. 2007). While these programs provide a variety of important insights into the population status of birds, surveys on the Canadian Arctic breeding grounds like PRISM, provide the clearest assessment of abundance for birds in Canada, because these surveys occur during the breeding season when birds are stationary.

1.1 Thesis Objectives

The objectives of this thesis are to a) conduct a review of published and unpublished (grey) literature on the potential impacts of mines in the Arctic and sub-Arctic on tundra-breeding birds and their environments and b) study, using data from a broad-scale bird monitoring scheme, the relationship between Arctic bird densities and the proximity to active mining operations. My central questions are:

1) What does previous literature demonstrate or suggest about the impacts of mining activities on tundra-breeding birds?
2) Does the presence of mines impact the regional distribution and density of birds?

1.2 Thesis Structure

To address my objectives and answer the questions above, I first (Chapter 2) review the literature on mining operations in the Canadian Arctic and the direct and indirect mechanisms through which mine infrastructure and activities may influence tundra-breeding birds. In Chapter 3, I analyze Program for Regional and International Shorebird Monitoring (PRISM) data collected across the Canadian Arctic from 1999 to 2018 to identify the relationships between mines and breeding bird densities. In the final chapter (Chapter 4), I summarize the findings of Chapters 2 and 3 and suggest directions for future research.

CHAPTER 2: Cumulative Effects of Arctic Mines and Their Influence On Bird Densities – A Review

Abstract

Mining activities in the North offer economic benefits for local communities but can have significant negative effects on fragile tundra environments. I reviewed the literature for studies that examine the potential interactions between mining activities in the Canadian Arctic and tundra-breeding birds and suggest additional future research that could help to fill knowledge gaps. Mine infrastructure (roads, waste rock piles, water management structures, buildings) has a direct effect on birds and other wildlife through the removal of habitat. Indirect effects, for example, noise, road dust, snow melt, altered hydrology, or collisions with infrastructure, have widely varying degrees of impact and can alter habitat quality, reproductive success, or birds' survival, thus expanding the potential direct effects on habitat. The level of knowledge of impacts varies widely as well. Some impacts, such as the links between road dust, earlier snow melt, earlier emergence and greater abundance of insects, and earlier bird nesting, are well documented. Other impacts, such as collisions or adverse effects of noise, are poorly documented or have been shown to have mixed effects. Comparatively few studies have examined the potential effects of mines in the Canadian Arctic on tundra-breeding birds, and no comprehensive evidence syntheses have yet been carried out. Based on the fragmentary information available, the population-level impact of mining on tundra birds appears to be small, in large part because the footprint of mining in the Canadian Arctic covers a small (< 0.001%) proportion of the total available Arctic habitat.

2.0 Introduction

Mining is an important and growing industry in northern Canada, representing nearly a quarter of the Gross Domestic Product of Nunavut in 2018 (Statistics Canada 2019). The significant economic opportunities brought about by resource development projects are not without costs, however, as mines bring intensive industrial development to otherwise intact tundra ecosystems. The environmental impacts of individual mines can be magnified at a regional scale through cumulative effects. Understanding the nature and extent of the impacts of mines on wildlife and ecosystems is crucial to balance environmental protection with economic development. Despite their economic importance, and their increasing prevalence in Northern Canada, the impacts of mines and their associated infrastructure on bird communities are not well understood. In this review paper, I examine the evidence for the impacts of mines on birds.

Mines are scattered across Canada's Arctic and sub-Arctic, and vary in what minerals are targeted and their stage of development (NWT & Nunavut Chamber of Mines 2016). For example, examples of active mines in the Canadian Arctic include Hope Bay, Meadowbank, Whale Tail Lake/Amaruq, and Meliadine targeting gold in Nunavut (Figure 2.1; Larouche et al. 2015, Bilodeau et al. 2018, TMAC Resources Inc. 2019), and Diavik, in the Northwest Territories, targeting diamonds (see Chapter 3 Appendix Table S3.1). Regardless of the target mineral, all mines have large footprints consisting of roads, buildings, pits, waste rock piles, and in some cases, waterway ports (Coulton et al. 2013, Larouche et al. 2015, Baffinland 2018). Further, all mines create a wide variety of disturbances such as noise, dust, water management and myriad others.

The environmental impacts of mines can arise through direct and indirect pathways and can act individually or through “cumulative effects”. The term ‘cumulative effects’ has numerous definitions, but here I adopt the definition set by Environment and Climate Change Canada: cumulative effects are the change to the environment from human actions that occurred in the past, present, and foreseeable future (Environment Canada 2016). This broad definition encompasses the common uses in contemporary literature (Crain et al. 2008, Houle et al. 2010), which emphasize the interactive nature of many environmental impacts. Mining impacts can accumulate in different ways, such as additive, synergistic, multiplicative, masking, and compensatory interactions (Department of Environmental Affairs and Tourism (DEAT) 2004, Environment Canada 2016, David Tàbara et al. 2018, Government of Canada 2019b).

In many cases, it is hard to distinguish the various forms of cumulative effect because there simply is not enough information about how different mechanisms of effect interact. For example, mining roads cause direct habitat loss, but also exert a broader influence on some wildlife species through avoidance behaviours (e.g., wolf avoidance of human development). They can also lead to increased vehicle traffic which increases collision risks, can cause road dust which can potentially make the habitat less usable by wildlife species, or even allow hunters to access wildlife more efficiently. Each of these effects operate in addition to the overall loss of habitat, but we do not know, and it is difficult to determine, whether these effects are strictly additive or whether they are synergistic in nature. In this chapter, I explore the potential individual and cumulative effects of mining activities on breeding birds in the Canadian Arctic.

Birds are a common ‘valued ecosystem component’ in environmental assessments of mining activities because they play important functional roles in Arctic ecosystems, and because they are easily monitored in comparison to many other Arctic ecosystem components (Baffinland 2020, Smith et al. 2020). Bird densities and nest success may be impacted by mining activities through direct and indirect effects. Many other disturbances, such as direct or indirect effects of climate change, may also interact with the impacts of mines but these pathways of effect are not the focus of this review. I first address the direct effects of the mine footprint and the associated physical alterations to the local environment. I then address the indirect effects of mine infrastructure and activities, including issues such as road dust or noise disturbance. I then explore the impacts of these effects on tundra-breeding birds, for example through habitat loss, direct mortality of adult birds or altered occupancy or reproductive success. I conclude with a discussion of what is known about the degree to which these effects interact as cumulative effects, and the further research required to clarify these interactions.

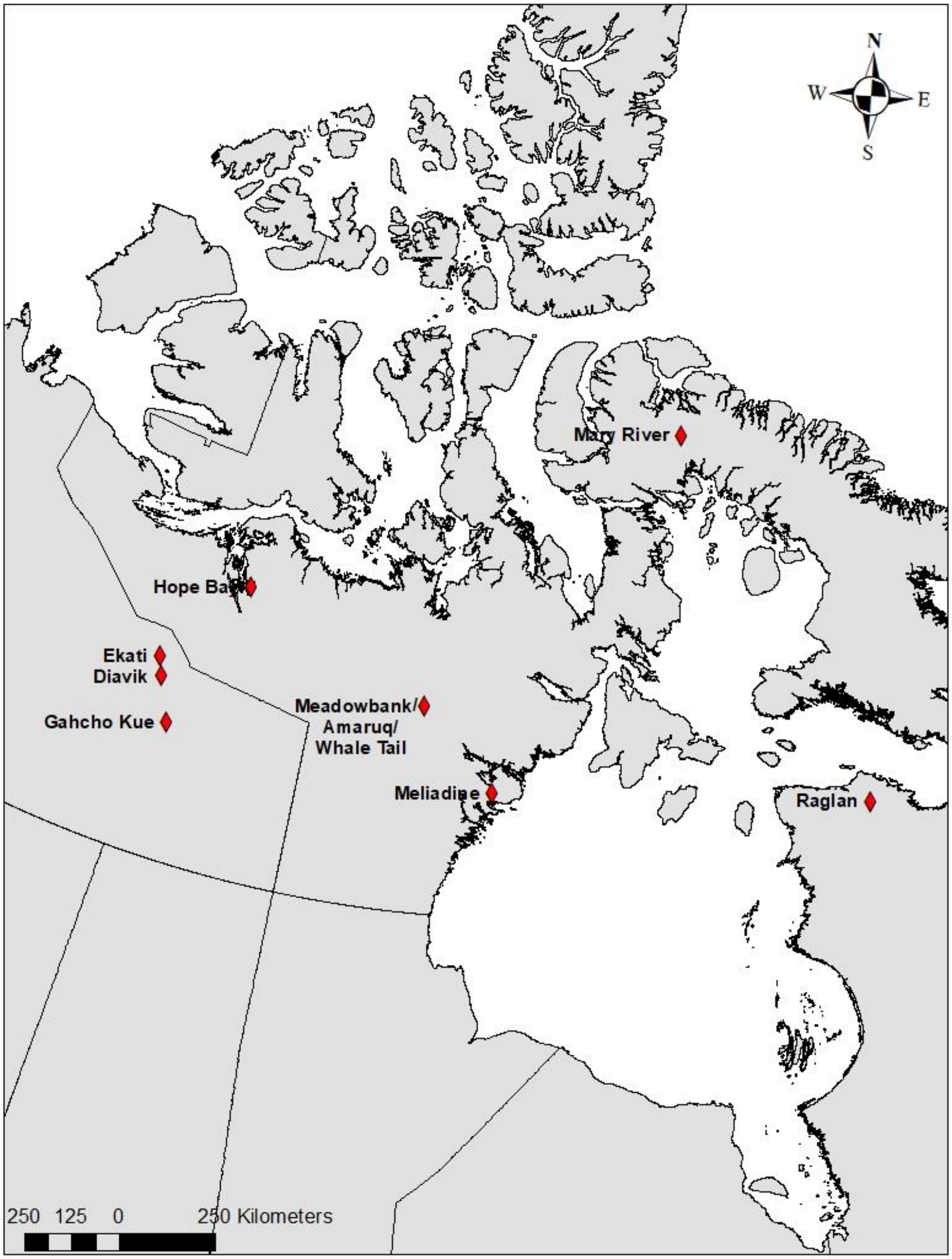

Figure 2.1. Map of Northern Canada, with the locations of active mines, 2020.

2.1 Direct Effects of Mines on Arctic Environments

2.11 Mining Footprint

The development of mine infrastructure results in a direct loss of habitat. This infrastructure, collectively referred to as the mine's "footprint", includes pits, roads, buildings, waste rock piles, and potentially even railways and ports. Across currently active mines in Arctic Canada, the average footprint of all infrastructure combined is approximately 18 km^2 per mine, although this value varies substantially across mines. By some definitions, the footprint also includes areas adjacent to infrastructure that has had direct physical changes to the habitat (Coulton et al. 2013). Through this definition, the footprint could include areas adjacent to roads where vegetation has been removed, or areas where natural water drainage has been altered (Coulton et al. 2013). Below we discuss the scale and characteristics of each component of the footprint of a typical Arctic mine.

2.111 Pits

All the mines in Arctic Canada are open-pit mines, where target minerals are accessed by digging down from ground level, rather than through shafts. Open-pits can vary widely in size, from 0.17 km^2 at the Meadowbank gold mine to as large as 0.56 km^2 at the Ekati diamond mine (Google Earth 2021). The depth of mine pits also varies. For example, in 2018 at the Meadowbank gold mine, the Portage pit was 154 m deep while the Vault pit was 175 m deep (Bilodeau et al. 2018). Each of the eight active mines in

Arctic Canada has a different number of pits, and the size and depth of the pit increases as mining activities progress.

The depth of the pit is achieved through a series of “benches” (vertical levels) that vary in height between mines (Sjöberg 1996, Yip and Pollock 2017). These benches prevent rocks from falling down the sides of the pit and allow for the development of a haul road that allows trucks to move up and down the depth of the pit, to remove waste rock or extracted minerals, along the benches in a series of concentric circles (Sjöberg 1996). The roads along the edge of the pits are typically two-to-three times the width of the largest haul truck that the mine uses for removal (JDS Energy & Mining Inc. 2018). These haul trucks can be large, with a capacity of 200 tonnes or more (JDS Energy & Mining Inc. 2018).

Figure 2.2. Image of the Ekati diamond mine in the Northwest Territories, 2014 (Dominion Diamond Mines 2014).

2.112 Buildings and other Physical Infrastructure

Physical infrastructure, such as buildings to house mine workers or ore processing facilities typically comprise a small proportion of the mine's footprint and vary as a function of the size of the mining operation. For example, Hope Bay mine in Nunavut can house up to 100 employees in a structure that covers approximately 0.04 km^2 (TMAC Resources Inc. 2018) while Diavik mine, in the Northwest Territories, can accommodate 700 employees in structures that are approximately 0.50 km^2 in area (Roscoe and Postle 2005). Other buildings commonly found at mine sites include maintenance shops for machinery, equipment storage sheds, and structures to house or process ore (JDS Energy & Mining Inc. 2018).

2.113 Roads, Railways, and Ports

Roads are an important component of the mining footprint. The length and distribution of roads vary widely across mines, based on the location of the minerals relative to the other infrastructure, and the proximity of the mine to other population centres and shipping options. For example, Meadowbank mine, in Nunavut, is connected to the hamlet of Baker Lake, Nunavut, by a 110 km road, with an additional 73 km of road connecting Meadowbank to Whale Tail/Amaruq (Bilodeau et al. 2018). These roads allow for goods to be transported by ship and then barge to Baker Lake, and by truck from Baker Lake. Meliadine, located near the hamlet of Rankin Inlet, Nunavut, has a 24 km all-weather access road that connects the main mine site to Rankin Inlet (Larouche et al. 2015). Mary River, located on northern Baffin Island, has a 100 km all-weather road between the mine and Milne Inlet so that ore can be transported from the location where it is mined to a port where it can be shipped by sea (Baffinland 2018). This road may eventually be replaced by a railway (Baffinland 2021), to increase the efficiency of the transport of ore from the mine to the port, which currently represents an operational bottleneck.

The ports at Milne Inlet and Deception Bay, for the Mary River Mine and the Raglan mine, respectively, allow the mines to transport ore by ship, which is more cost-effective than ground transportation. Facilities at these ports include infrastructure to handle, process and stockpile ore, catchment areas to manage runoff from stockpiles, and facilities and equipment to dock and load the large ships.

2.114 Waste Rock Piles

The minerals targeted by mines typically constitute a very small fraction of the material removed. As a result, mines often produce a large volume of unwanted mineral waste, or waste rock (defined as an undesirable rock that is closely associated with the mineral resource; Younger and Wolkersdorfer 2004). Waste rock may contain the desired minerals at too low a grade to be mined and processed or may be completely devoid of the minerals. Overburden, in contrast, is unconsolidated sediments or rock that is overtop of the mineral resource (Younger and Wolkersdorfer 2004). For the mineral resource to be extracted, the overburden must first be removed (Younger and Wolkersdorfer 2004). In most mining industries, the strip ratio (the ratio of waste rock to mineral ore) is normally much greater than one (Environmental Law Alliance Worldwide 2010). Although it varies widely across mines, the quantity of waste rock produced by mines can be substantial. For example, the Ekati diamond mine in Northwest Territories produced an estimated 22 million metric tons of waste rock in 2017, while the Meadowbank gold mine in Nunavut generated an estimated 11 million metric tons of waste rock in 2018. In contrast, the Mary River iron ore mine on Baffin Island produced only an estimated 630 metric tons of waste rock in 2018, because this operation targets an iron deposit of high purity, which is crushed and shipped with little processing (Baffinland 2018, McGregor et al. 2018).

These enormous volumes of waste rock are usually deposited on-site in piles or used to backfill open-pits (Environmental Law Alliance Worldwide 2010). Even when mining operations use the waste material to backfill old opencast mines, there is still typically a considerable amount of excess waste rock that remains (Harding and Boothroyd 2004). This is in large part because the excavated rock and soil take up 50% more volume above ground post-excavation than they did below ground (Harding and Boothroyd 2004). Consequently, waste rock can occupy a significant amount of land at a mine site. For example, at the Ekati diamond mine, a total of 4,281,000 m^2 of land is used for storing waste rock (Dominion Diamond Mines 2014). Although not studied directly, waste rock piles are assumed to offer little or no useful habitat for birds and therefore constitute an important direct source of habitat loss.

2.12 Water Management Structures and Activities

Arctic landscapes are often dotted with lakes, ponds, rivers and wetlands, and water management represents an important component of operating a mine in Canada’s North. Dams are often built to control the outflow of contaminated water from mine waste or to ensure the availability of fresh water needed for processing or other mining operations (Younger and Wolkersdorfer 2004, Budds and Hinojosa 2012). Depending on the quality of the waste water, mines may direct it into tailings ponds or consider diverting it into nearby waterbodies and wetlands (Younger and Wolkersdorfer 2004). The accessibility to fresh water is crucial for mining operations as it is often needed for mineral extraction and processing. For example, Meadowbank gold mine in Nunavut used an average of 82,344 m^3/month of water for the ore processing mill (Agnico Eagle Mines Limited - Meadowbank Division 2019). At the Ekati diamond mine, approximately 5 million m^3 of water was recycled and used for the processing plant in 2017 where machines crushed the ore into smaller pieces (Witherly et al. 2016, McGregor et al. 2018). In contrast, the Mary River mine which extracts high-grade ore, uses little water as there is no significant processing or concentration needed before the product is shipped off (Baffinland 2021). All water used in the mining process comes directly from nearby lakes and waterbodies, reducing available habitat.

It is also common for mines to remove surface water to access mineral deposits. To access the recently discovered gold deposit at Whale Tail Lake, a dike was constructed in 2018 to dewater the northern part of the lake (Bilodeau et al. 2018). The installation of the dike, and the shifting of the lake water from the northern portion of the lake over the dike, temporarily flooded the watershed (Bilodeau et al. 2018, Agnico Eagle Mines Limited - Meadowbank Division 2019). Before flooding, Whale Tail Lake had a surface water elevation of 152.50 masl (meters above sea level) in May of 2018. It was predicted that the surface water level would rise to 156.00 masl by July of 2020, resulting in 1.58 km^2 of land flooded (Agnico Eagle Mines Limited 2016). The flooding of lakes and wetlands demonstrates that the footprint of mines is not always static.

2.2 Indirect Effects of Mines on Habitat Quality

2.21 Road Dust

Road dust is an indirect by-product of road traffic, that can have substantial effects on the habitats adjacent to roads. There is no universal definition for the term “road dust”, but it is generally considered to be particles that are between 3 and 10 µm in size, dispersed from road surfaces to surrounding areas (Walker and Everett 1987). The chemical composition of the road dust depends on the source of the road materials and can differ from the surrounding geochemistry (Walker and Everett 1987). For gravel roads in Arctic ecosystems, it is generally accepted that the effects of dust are most pronounced within 25 m of the road edge (Auerbach et al. 1997, Myers-Smith et al. 2006).

Dust deposition also varies seasonally. One study found that the greatest amount of dust dispersion occurred during the late spring and summer months (mid-May to September; Creuzer et al. 2016). During the fall to spring months, there tends to be more precipitation and water on road surfaces, such as rain, ice, or snow which helps to reduce dust (Creuzer et al. 2016). A second study found the opposite pattern, where the winter months had approximately 10 times greater dust fall than the summer months, which the authors ascribed to erosion and drifting snowpack (Walker and Everett 1987). Winter dust accumulating on snow can have pronounced ecological effects that become apparent in early spring, where a reduced albedo can lead to a 10 to 14-day premature melting and surface exposure (Walker and Everett 1987).

Because dust is considered a major environmental issue at mine sites, resource companies use a variety of techniques and products to minimize the creation of dust. For example, to suppress road dust dispersal, mining companies use a wide variety of "dust suppressants", such as DL10, which is an asphalt product mixed with soap and water (Government of the Northwest Territories 2013), or calcium chloride, which draws moisture from the air and controls dust if frequently applied (Government of the Northwest Territories 2013). While the dust suppressants themselves could have environmental effects, they are effective at suppressing dust; the use of DL10 at the Ekati mine in the Northwest Territories helped reduce the daily road dust deposition within 5 meters of the road from 3.6 $g{\cdot}m^{-2}$ to 0.8 $g{\cdot}m^{-2}$ (Male and Nol 2005). Most studies agree that the most effective dust control methods are hygroscopic chemicals such as lignin sulfonate and calcium chloride, as they are effective at binding fine road aggregate particles together to reduce dust (Walker and Everett 1987).

The effects of road dust can be seen in the adjacent habitat. The distribution and abundance of road dust can impact surrounding wetlands, acidify soils over time, and inhibit vegetation growth (Knutsen 2014). Dust from unpaved roads can alter soil moisture (Spatt and Miller 1981, Auerbach et al. 1997), reduce vegetative species richness (Auerbach et al. 1997), and reduce ground cover (Walker and Everett 1987). The loss or reduction of suitable habitat adjacent to roads may have the most pronounced impacts on invertebrate species that rely on the vegetation and have limited ability to disperse to new areas.

2.22 Noise: Aircraft, Machines, and Transportation

Mining activities produce high sound pressure levels, and these artificial noises can adversely affect wildlife. The majority of noise at Arctic mines is from activities such as exploratory and production drilling, cutting, blasting, ventilation, crushing, handling of materials, conveying, transportation, and ore production (Donoghue 2004), sirens, reversing vehicles, horns, and explosions (Duarte et al. 2015), light truck and haul-truck traffic, heavy equipment operation, diesel-powered generators, and frequent aircraft over-flights (Smith et al. 2005).

2.23 Snow Melt

The presence of mines changes the accumulation and melting patterns of snow in the Arctic, through changes to the albedo of the snowpack from deposited dust, from activities that result in the moving of snow, and from changes in patterns of snow accumulation due to the presence of buildings or other obstructions that create snow drifts. At the community of Sagwon, Alaska, snow accumulation is seen on the lee of the road berm in winter (Auerbach et al. 1997). Snow accumulation patterns can also be altered with the construction of buildings or the installation of other barriers, such as fences surrounding landfill sites, that create drifts and shadows that prevent snow from gathering inside the landfill (Saalfeld et al. 2013a). In contrast, where road dust settles on areas adjacent to roads (typically within 100 m), this dust can decrease albedo and lead to early melt-out adjacent to the roads (Portier et al. 2010, Auerbach et al. 1997). The growth of vascular plants is linked to the timing of snowmelt (Tieszen 1974); this change in timing of snowmelt, therefore, has the potential to influence plant phenology, and influence all trophic levels above (Auerbach et al. 1997).

2.24 Altered Hydrology

The direct impacts of water management structures and activities are discussed above. However, hydrology can also be impacted indirectly by other infrastructure and mining activities. Changes in water tables and concomitant changes to wetland ecosystems as a result of shifting hydrology due to mining are difficult to predict (Creuzer et al. 2016). The construction of roads which includes the use of culverts, removal of vegetation, and the removal of snow from roads and runways in winter can all alter local hydrology (Gill et al. 2014). Many factors such as topography, underlying hydrology, soil types, and vegetation influence the susceptibility to changes in hydrology (Creuzer et al. 2016). In addition to changing water quantity, mining has been shown to alter measures of sulphates, total dissolved solids, electrical conductivity (EC), hardness, calcium, sodium, and magnesium levels in water (Creuzer et al. 2016). These changes in water quantity and quality, while difficult to predict, can greatly impact local fauna such as fish communities in nearby lakes.

2.25 Effect of Anthropogenic Waste on Generalist Predator Behaviour

In addition to inorganic waste, mines produce significant quantities of food and human waste that must be contained in landfill sites (Saalfeld et al. 2013a). In environments such as the Arctic where food is scarce and unpredictable, anthropogenic food waste is a strong attractant for some opportunistic species (Savory et al. 2014). Landfill sites that contain waste from mining operations, therefore, provide an alternative food source for many predator species (Saalfeld et al. 2013a). In Alaska, the Prudhoe Bay area has thousands of workers that support the extraction of oil, generating a large food demand and a subsequently large amount of food disposal (Savory et al. 2014). At Prudhoe Bay, mining organizations intended to cover organic material daily with gravel, but such actions were limited by the availability of gravel (Saalfeld et al. 2013a). Instead, waste was placed in a dedicated region of the landfill and managed with a “freezeback” method, where a gravel cover is deposited each summer to cover the previous year’s waste so that efficient cooling can occur back to permafrost temperatures (Saalfeld et al. 2013a). The storage conditions of the waste, and in particular food waste, can greatly affect how attractive and available it is to scavenging species.

2.26 Localized Pollution and Spills

Chronic pollution and spills are major environmental issues at mines and have the potential to impact wildlife. Some contaminants occur naturally in the environment but are released at unnatural levels through mining activities (Evans et al. 2005). Examples of these naturally occurring contaminants include metals like cadmium and mercury, which are released when ore is processed or the ground is disturbed (Evans et al. 2005). The removal of natural habitats by clearing or burial, and dust dispersal from dried tailings impoundments are other examples of unnatural pathways for the release of naturally occurring elements (Mallory et al. 2004).

Oil and fuel spills are also sources of pollution, especially of concern in opencast mining operations where more machinery is required to handle ore. In these mines, spills are more frequent and the effluent from equipment workshops may contain high amounts of grease and oil that are released when machines or vehicles are washed (Tiwary 2001).

Depending on the waste produced by the mine, different techniques are used to control chronic pollution and spills. Oil pollution is controlled by ensuring proper "bunding" (creation of a berm to contain liquids) of oil storage and workshop areas to prevent oil spillage, and by removing and treating contaminated soils (Tiwary 2001). Mines are obligated to manage and report any spills that occur (Baffinland 2021). At the Mary River mine in 2020, the largest spill that occurred was from sewage (15 m^3) with spills from oil and gasoline ranging from 0.00025 – 0.6 m^3 (Baffinland 2021). If contaminants from spills are not contained, then nearby habitats and wildlife can be impacted.

The combustion of fossil fuels to run the machinery also results in local pollution from poly-cyclic aromatic hydrocarbons (PAHs) and other byproducts of fuel-burning, including sulphur dioxide, heavy metals, and nitrogen dioxide (Pandey et al. 2014). These air pollutants deteriorate air quality and can affect fauna health around mining sites (Pandey et al. 2014).

A particularly potent threat to ecosystems from mine waste is acid mine drainage (AMD). Acid mine drainage is the process of exposing the sulphide in mine waste to air and water (i.e., oxidized) (Mine Environment Neutral Drainage (MEND) Program Report 1991). The most common sulphide mineral is pyrite, and when oxidized, it generates acidic waste (Rollo and Jamieson 2003). AMD discharge that flows into lakes, rivers, and marine waters has the potential to result in substantial impacts on the biota (Elberling et al. 2007).

Local water quality can also be degraded from silt and sediment. Water that is used in mining operations often contains high levels of total dissolved solids (TDS), total suspended solids (TSS), heavy metals, and hardness, which can contaminate surface and ground water (Tiwary 2001). There can also be sediment leakage when runoff from rain causes erosion of overburden piles, waste rock piles and ore stockpiles (Tiwary 2001). Through these pathways, mines can significantly alter the turbidity and water chemistry of nearby aquatic habitats.

2.27 Habitat Fragmentation

The impacts of habitat loss can be expanded through "habitat fragmentation"; the dividing of the landscape into more isolated and smaller sections of habitat (Franklin et al. 2002). When these habitat fragments are less valuable to wildlife, the impacts of habitat loss extend beyond the area lost directly (Franklin et al. 2002).

There are several forms of habitat loss from mining that can lead to habitat fragmentation (Sonter et al. 2018), and the responses, such as avoidance, can vary widely based on the season, species, the intensity of human disturbance, and habitat quality (Polfus et al. 2011). A study of Arctic caribou found that at a large spatial scale (100 km), roads, mines, and human settlements were completely avoided during the summer (Plante et al. 2018). Another study demonstrated strong effects of habitat fragmentation from mine sites on wolves and grizzly bears that resulted in strong avoidance behaviour throughout the year (Johnson et al. 2005a). The effects of habitat fragmentation from mining operations through roads and infrastructure seem to have a greater impact on large mammal species (Johnson et al. 2005a); smaller species such as birds may be less influenced by fragmentation in these open tundra environments.

In areas with extensive habitat loss, fragmentation can impose a significant additional source of impact. However, given the relatively small footprint of mining in the Canadian Arctic, the effects of fragmentation are expected to be localized.

2.3 Effects on Birds

The accumulation of both direct and indirect effects of mining can have consequences for breeding bird populations by altering habitat quantity and quality, within and outside of the mine footprint. The primary mechanisms through which these effects impact birds are the direct loss of habitat from the mining footprint, direct mortality of adult breeding birds or nests, and altered occupancy or reproductive success from indirect effects. These effects and mechanisms can also interact to yield cumulative effects that may be greater than the sum of the parts. I discuss each of these mechanisms of impact, and the literature documenting mining-related effects that contribute to them, below.

2.31 Direct Loss of Habitat

The Arctic spans approximately 7113 x 10^6 km^2 (Walker et al. 2005). Of this, Canada has the largest portion with 2553 x 10^6 km^2 (36%) (Walker et al. 2005). The average mine footprint totalled across all mines, consisting of the sum of the developed components of the mine including roads, pits, buildings, waterway ports, waste rock piles, and other infrastructure across the Canadian Arctic is approximately 145 km^2 as of 2018. Therefore, the mining footprint comprises <0.001% of the Canadian Arctic area. The average densities of shorebirds observed in plots surveyed using the PRISM protocol, for the broad regions that encompass the mine areas, appear in Table S2.1. As shown in previous studies (Morrison 1997, Bart and Johnston 2012, Brown et al. 2007), bird densities vary widely with habitat types. Assuming that these densities reflect the densities near mine sites, the potential number of birds lost through direct habitat loss from mine footprints ranges from 1,470 to 4,920 shorebirds (Table S2.2), depending on the habitat types lost to the mine footprint, and up to 15,305 additional non-shorebirds. The studies reviewed here suggest that indirect losses could extend to about 100 m around the perimeter of mines. This would increase the footprint by 256.41 km^2 and could lead to the loss of an additional 11,746 birds (if the indirect effects were considered as habitat loss, but see Chapter 3). The comparatively low numbers of shorebirds potentially lost reflects the low densities around mine sites; lower than the densities in some low-lying coastal areas of the Arctic that represent better shorebird habitat.

Table 2.1. Estimates of bird densities in various regions and habitat types surrounding the active mines in the Canadian Arctic. Region/Subregion refers to the PRISM area from within which plots were randomly selected and surveyed (Bart et al. 2007). These subregions encompass the mine sites but extend well beyond them. Wet habitat is described as wetlands and moist grasslands. Moist habitat is vegetated uplands, heaths, and drier grasslands. Upland habitat is sparsely vegetated uplands, barren areas, and bare gravel (Bart et al. 2007). The area of the mine footprints is also displayed. N/A indicates that no plots were surveyed in the habitat type, or that the habitat type was not present in the region.

Mine	Area (km^2)	Region/ Subregion	Bird Density in Wet Habitat (birds/km^2)	Bird Density in Moist Habitat (birds/km^2)	Bird Density in Upland Habitat (birds/km^2)	Bird Density in All Habitat Types (birds/km^2)
Ekati	39.33	6.3	38	N/A	8	8
Diavik	10.28	6.3	38	N/A	8	8
Gahcho Kué	13.23	6.3	38	N/A	8	8
Hope Bay	4.24	7.3	87	47	16	18
Mary River	31.94	2.3	3	6	13	11
Meadowbank	14.32	6.1	11	32	13	16
Meliadine	2.54	6.4	N/A	N/A	13	13
Raglan	29.20	1.1	64	26	6	20
Total	145.08					

Table 2.2. The potential number of shorebirds lost due to the mining footprint, based on the areas and densities reported in Table S2.1, assuming that the areas were entirely wet, moist or upland habitats, as well as the value estimated from the "all habitat" density estimates.

Mine	Total Potential Birds Lost From Mine Footprint in Wet Habitat (birds/km^2)	Total Potential Birds Lost From Mine Footprint in Moist Habitat (birds/km^2)	Total Density Lost From Mine Footprint in Upland Habitat (birds/km^2)	Total Density Lost From Mine Footprint in All Habitat Types (birds/km^2)
Ekati	1,507	N/A	329	331
Diavik	394	N/A	86	86
Gahcho Kué	507	N/A	110	21
Hope Bay	369	199	71	77
Mary River	99	220	445	362
Meadowbank	168	469	194	232
Meliadine	N/A	N/A	35	35
Raglan	1,876	769	197	609

2.32 Direct Mortality of Adult Breeding Birds or Nests

2.321 Localized Pollution and Spills

There are multiple types of pollution and contaminants that mining operations produce that can directly impact birds. Mines produce air emissions including polycyclic aromatic hydrocarbons (PAHs) from burning fuel, and release other chemical contaminants into the environment through their activities including polychlorinated dibenzo-p-dioxins and polychlorinated dibenzo-p-furans (PCDD/Fs) (Halsall 2004, Mallory et al. 2004). Exposure to high levels of these and other Persistent Organic Pollutants (POPs), or toxic elements such as mercury and cadmium can adversely affect birds' endocrine, immune, and nervous systems (Halsall 2004, Mallory et al. 2004).

While these chemicals have the potential to harm wildlife, the concentrations found within birds determine the level of impact. A study conducted on Common Eiders (*Somateria mollissima*) across the Canadian Arctic (not connected with mining, specifically) found that levels of POPs and trace elements in the liver tissue, breast muscle, and egg tissue were below the concentrations known to impact wildlife health (Mallory et al. 2004). Selenium, mercury, and cadmium are correlated with immune function, parasite burdens, and body mass, respectively, but the levels were below what was considered harmful for birds (Mallory et al. 2004). Though the contaminants emitted through mining activities are known to be harmful, focussed studies on the concentrations around mines and the potential impacts on wildlife are lacking.

Similarly, there are no studies that have determined the impact of tailings ponds or localized fuel or chemical spills from mining activities on breeding birds in the

Canadian Arctic. In more southern locations, tailing ponds in oil sands have been found to greatly impact migratory birds (Timoney and Lee 2009, Timoney and Ronconi 2010). If birds are similarly attracted to open tailings ponds in mines in the North, then it can be expected that similar negative effects occur in Arctic mining sites. Similarly, the chronic pollution and accidental spills described above could impact birds on a local scale, but studies of the magnitude of these impacts are lacking.

Pollution can have a direct effect on birds, but emissions can also have an indirect effect by reducing the availability of invertebrate food in a polluted environment (St. Louis et al. 1990, Eeva et al. 1997). In sub-Arctic Finland, elevated lead levels from air contamination have been observed to impede nestling growth through the alteration of insect abundance and nutrition that results in the loss of body mass (Eeva et al. 2003). Some birds, such as the Pied Flycatcher (*Ficedula hypoleuca*) near the copper smelter of Harjavalta, Finland, suffered primarily from direct acidic substances and toxic effects of heavy metal atmospheric emissions, especially lead, nickel, and copper (Saha and Padhy 2011). The Great Tit (*Parus major*), in the same location, suffered primarily from the reduction of suitable food abundance for nestlings and experienced a loss of plumage colour of chicks (Saha and Padhy 2011).

Mines report their air emissions annually. At Ekati diamond mine in Northwest Territories, annual reports state the volume of common air emissions released each year (primarily from fossil fuel burning for machines) (ERM 2015). In 2014 at Ekati mine, approximately 71,000,000 L of diesel fuel was used for mining operations, which resulted in close to 200,000 tonnes of CO_2 emissions, and methane gas emissions amounted to 180 tonnes of carbon dioxide equivalent (tCO_2e) (ERM 2015). The highest monthly average air emission of sulphur dioxide in 2014 was 0.8 parts per billion (ppb) in April and the lowest were at 0.0 ppb in July and August (ERM 2015). No current studies address the direct effects of emissions from mining in the Canadian Arctic on the birds.

2.322 Marine Oil Pollution

Spillage of heavy fuel oil pollutes seabird habitats and causes mortality, and it is often these mortalities that alert people that such a spill has occurred (Wiese and Robertson 2004). Shipping routes are used to carry provisions to mines, or ore from mines, and could lead to spills in marine environments. Seabirds are long-lived, and mortality sources that kill adults can greatly influence the population dynamics (Wiese and Robertson 2004). Marine birds are particularly vulnerable to oil spills since they tend to congregate in large flocks at sea (Dickson and Gilchrist 2002). Even a small spill can affect a large number of birds (Dickson and Gilchrist 2002).

Oil can result in bird mortality either through the matting of feathers or toxicological effects after ingestion (Dickson and Gilchrist 2002). If feathers become matted, birds can become hypothermic and drown, while cold air temperatures and water increase the hypothermic effects (Dickson and Gilchrist 2002). No current studies address the rate of oil spillage at Arctic mines and the impact of such spillage on birds.

2.323 Nest Loss from Habitat Clearing

Mining operations must clear vegetation from the land for a variety of reasons (e.g., roads, infrastructure, mining pits, ports), and this land clearing can destroy nests, leading to loss of eggs or nestlings (De Beers Canada Inc. 2013, Government of Canada

2019a). Prior to the construction of infrastructure, site preparation begins with the clearing of vegetation and removal of the uppermost soil level (Simmons et al. 2008). The loss of this habitat has a direct negative impact on breeding birds as they lose whatever nests were already established in that habitat, as well as losing the opportunities for future nesting. Flooding of habitats, as discussed above, can result in similar direct mortality of eggs or nestlings (*G. Holmes unpub*. 2021).

Direct mortality of birds or their nests is prohibited under the Migratory Birds Convention Act (Government of Canada 2021), and for this reason, resource companies must report and carefully manage these direct impacts. Companies undertake “pre-clearing surveys” to determine whether birds are nesting in areas slated for vegetation removal, attempt to carry out land clearing outside of birds’ breeding seasons, and report on the areas cleared and the potential nest mortalities (Baffinland 2021). For example, in 2020, Mary River postponed the construction of infrastructure after finding the nest of a Snow Bunting during pre-clearing surveys (Baffinland 2021).

2.324 Collisions and Death by Machinery

Birds frequently collide with human-made structures, and these collisions represent a significant source of mortality in some regions. Common sources of bird collision mortality include collisions with vehicles (Bishop and Brogan 2013), building windows (Machtans et al. 2013), power transmission lines (Rioux et al. 2013), and communication towers (Longcore et al. 2012). Rates of collisions vary widely across species and situations, and studies are primarily from southern Canada and USA. While there is no literature review on collisions of migratory birds at Canadian Arctic mines, I expect the patterns to be similar to those in other environments.

At Canadian mining sites, annual reports document bird mortalities from mining activities. For example, in 2020, the Mary River mine reported four mortalities (American Pipit (*Anthus rubescens*), Common Raven (*Corvus corax*), Snow Goose (*Chen caerulescens*), and Red-throated Loon (*Gavia stellata*)) and reported that two of these mortalities were from vehicle collisions and the remaining two were from accidental bycatch related to other wildlife monitoring programs (Baffinland 2021). In 2018, Meadowbank mine reported zero bird mortalities from mining-related activities (Agnico Eagle Mines Limited - Meadowbank Division 2019). Although most fatalities probably go undetected/unreported, the total level of mortality is nevertheless assumed to be low.

The major cause of bird mortality from human interactions in all of Canada comes from mobile individuals (i.e., individuals in flight compared to those sitting on a nest), 25% of which die from collisions (Calvert et al. 2013). In Canada, most collisions are with reflective panels or windows, followed by vehicles, and buildings (Longcore et al. 2012, Bishop and Brogan 2013, Machtans et al. 2013, Loss et al. 2015, Environment and Climate Change Canada 2017). In the Canadian Arctic, there are fewer vehicles, windows, and towers for birds to collide with, and therefore, the influence of collisions is likely low in comparison to more heavily developed southern regions.

Where human caused mortality is significant, it can result in a direct impact on bird populations, especially when added to natural mortality (Calvert et al. 2013). It can be inferred that since mining operations in the Arctic are similar to small towns in the south that the same collision risks apply. Windows, communication towers, and vehicles all exist in the Canadian Arctic; therefore, the risk of collision also exists although presumably at a lower rate due to the lower densities of these infrastructure elements on the landscape.

2.33 Evidence for Impacts on Altered Occupancy or Reproductive Output/Success

2.331 Habitat Quality Impacts on Occupancy

2.3311 Road Dust

While road construction results in direct losses of habitat (see above for *Mining Footprint*), additional alterations of regions adjacent to roads can effectively extend the footprint of loss if these alterations are severe. While many papers show reduced bird densities near roads outside of the Arctic (Van der Zande et al. 1980, Reijnen et al. 1995, Kuitunen et al. 1998, Canaday and Rivadeneyra 2001, Ingelfinger and Anderson 2004), there are few studies of the impacts of roads on occupancy or annual productivity of birds nesting in Arctic environments (Male and Nol 2005).

Road dust can indirectly affect the density or reproductive success of birds through reductions in habitat quality. However, few studies have been carried out in the Arctic to document the magnitude of the effects. One study showed that roads had no impact on the reproductive output or breeding density of Lapland Longspur (Male and Nol 2005), despite significant dust in the roadside habitats. Further studies are needed to confirm how other species breeding near Arctic mines are influenced by road proximity. Habitat generalists and a more widespread species like the Lapland Longspur may be less susceptible to anthropogenic disturbance.

Arctic breeding birds such as passerines and shorebirds rely on surface-active arthropods as a food source, and adults or developing chicks can have reduced body condition when invertebrate abundances are reduced (Tulp and Schekkerman 2008, Schekkerman et al. 1998). Thus, if surface-active arthropods are negatively impacted by road dust, birds nesting near roads would be expected to experience lower nestling growth rates and possibly lower nest success as parents need to leave the nest more frequently to find food for both themselves and their young (Smith et al. 2007, 2012).

Despite harsh conditions, there is a high diversity of insects in the Canadian Arctic (Danks 2004), and studies have demonstrated a wide variety of direct and indirect effects on invertebrates through changes arising from road dust (Ste-Marie et al. 2018). Examples of direct effects include smothering of larvae and adults, disruption of chemical cues used for mating and detection of host plants, and making flowers or leaves distasteful to their invertebrate hosts (Talley et al. 2006). Indirect effects arise because road dust covers the vegetation used by arthropods as food or habitat. This road dust can cause leaf shading, increased leaf temperatures, blocked stomata, increased water loss, inhibition of transpiration, and reduced vegetation and reproductive growth (Farmer 1993, Hirano et al. 1995).

In many cases, invertebrate species richness is reduced near roads as habitats adjacent to roads contain less organic material and have been compacted (Haskell 2000, Ste-Marie et al. 2018). For example, Collembola is less abundant near roads likely due to the increased soil pH and reduced snow albedo from road dust (Auerbach et al. 1997, Gill et al. 2014). The dust from roads makes lichen and moss growth difficult (Walker and Everett 1987), making invertebrate groups such as Collembola that depend on this vegetation type more sensitive to the changes in climate and moisture (Ste-Marie et al. 2018). These direct and indirect impacts can influence the abundance and diversity of invertebrates in habitats where road dust accumulates.

For some arthropod species, roads have a positive effect on abundance, for example for ground-dwelling habitat generalists that benefit from roads due to their colonization abilities in disturbed habitats (Koivula 2005, Knapp et al. 2013). The presence of roads may also benefit invertebrates that have low cold tolerance, as temperatures are higher within the first 10 m from roads (Ste-Marie et al. 2018). Studies have found that invertebrate orders Diptera and Hymenoptera are in greater abundance near roads than further away (Ste-Marie et al. 2018). Though the presence of road dust may reduce plant vegetation used by invertebrate species, some invertebrates have adapted to the habitat changes and have colonized disturbed habitats.

2.3312 Attraction to infrastructure

The highly impacted areas around mining infrastructure can alter the bird community at these small scales by attracting disturbance tolerant species, including some such as American Robins (*Turdus migratorius*), which occur at mines well beyond their normal range (Smith et al. 2005, Vanderhoff et al. 2020). Other species, especially raptors, are attracted to the artificial perches offered by infrastructure, or the artificial “cliff” faces present within mine pits (see below). Similarly, these disturbance tolerant species may be less affected by several of the impacts of mines, especially from factors that cause disturbance such as noise. High tolerance to disturbance has been shown in several Arctic species, including Long-tailed Ducks (*Clangula hyemalis*; Mallory 2016).

2.3313 Snow Melt

Many of the bird species breeding in the Canadian Arctic time their reproduction to coincide with the melting of the snow. The vast majority of birds in the Arctic are migratory, and these species move northwards to arrive on the breeding grounds as the snow begins to melt, establish territories and build nests as early as possible (Schekkerman et al. 2002, Meltofte et al. 2007a). Arctic birds rely on snow-free areas for egg laying, as most species are ground nesters (Martin and Wiebe 2004). The altered patterns of snow accumulation, because of snow drifts or snow shadows around infrastructure, or because of snow removal activities, can alter the timing of melt and the availability of breeding habitats. When snow melt is accelerated, it can lead to earlier nest initiation dates that in turn result in increased nest densities (Saalfeld et al. 2013a).

While many studies show the importance of the timing of snow melt to avian reproductive phenology, few have been conducted in or around mine sites. However, given that there is good evidence that in general, snow does melt earlier along roads and in the vicinity of mines (Walker and Everett 1987, Wiebe and Martin 2000, Morton 2002), it is assumed that avian phenology will also be earlier (Male and Nol 2005). These snowmelt conditions could play an important role in Arctic breeding bird phenology around mines. With earlier snowmelt near roads and mine sites, breeding birds may establish their territories in these early snow-free areas at higher densities than in areas farther away, where snow melt is not advanced.

2.3314 Altered Hydrology

Wetlands are a preferred habitat type for many Arctic birds, and changes in the quality and quantity of wetland habitat can therefore have a profound impact on the local abundance of birds. More than 70% of the 159 bird species occurring in Arctic Canada use wetlands (Smith et al. 2013). One of the primary sources of altered hydrology from mining activities that may have the greatest impact on breeding birds in the Arctic is lake dewatering/flooding. The Meadowbank mine in Nunavut drained the northern half of Whale Tail Lake, causing flooding of the southern portion that would last a year before receding (Agnico Eagle Mines Limited 2016, Bilodeau et al. 2018, Agnico Eagle Mines Limited - Meadowbank Division 2019). One study by G. Holmes (*unpubl*. 2021) estimated that 0.89 nests/ha of shorebirds and passerines would be flooded based on the mine's projected flood area. While the flood waters submerged the habitat for only one summer season (*S. Bonnett, pers. comm.*), there are potential lasting effects on the vegetation of the nesting habitat; vegetation that may be ill-adapted to being submerged. These longer-term effects on tundra vegetation from temporary flooding have yet to be studied in the Canadian Arctic.

2.3315 Habitat Fragmentation

Habitat fragmentation can extend the impacts of habitat loss by making the remaining fragments of otherwise suitable habitat unsuitable, by virtue of their isolation from other habitat fragments. Whether habitat fragmentation impacts Arctic breeding birds has not been studied to date. However, given that mines in the Canadian Arctic tend to be isolated developments surrounded by intact habitats, I expect the overall effects of habitat fragmentation to be small.

2.332 Changes in Generalist Predators' Behaviour and Impacts on Reproductive Success

While Arctic breeding birds can experience high levels of natural predation in sites not impacted by mines (Smith et al. 2007, 2010, 2012, Liebezeit et al. 2009), predation may be enhanced around mine sites due to two factors. First, predators may be attracted to mines because their waste systems (e.g., landfills) provide supplementary food (Liebezeit et al. 2009). This attraction can extend to the community of predators in which the mine is embedded, or, in rare cases, mines may attract predators from outside their historical range. Second, the mines may provide additional perches or breeding sites, particularly for avian predators, that then enhance local predation rates on other breeding birds (Liebezeit et al. 2009, Bernath-Plaisted and Koper 2016).

Few studies have examined predator attraction to mines in detail. However, studies from the Prudhoe Bay oil fields in coastal Alaska provide relevant examples from a northern location. The results from these studies have shown that some predatory species are associated with human development through subsidization of their energy needs, and through the use of human structures for denning and nesting (Liebezeit et al. 2009). The most common subsidized predator species in the Alaska Arctic Coastal Plain include Arctic Fox (*Vulpes lagopus*), Brown Bear (*Ursus arctos*), Red Fox (*Vulpes vulpes*), Common Raven (*Corvus corax*), and Glaucous Gull (*Larus hyperboreus*) (Liebezeit et al. 2009). In the eastern Arctic, nest predators like Glaucous Gull and Common Raven contribute relatively little to overall egg predation rates in locations where this has been documented (for example, contributing <13% of predation at Bylot Island, NU; Bêty et al. 2002). Thus, site-specific studies are required to understand the local impacts of increased potential nest predators on actual rates of nest predation.

Not all predators are attracted to mines. Some predators may avoid mine sites which could, in theory, relieve predation pressure on potential prey species that nest close to mines (Liebezeit et al. 2009) or allow mesopredators to be more active and hence, potentially altering the types of risks faced by prey (*sensu* Wang et al. 2015). The potential predators of birds and their nests that have been shown to avoid the Prudhoe Bay site include Parasitic Jaeger (*Stercorarius parasiticus*), Short-tailed Weasel (*Mustela erminea*), Arctic Ground Squirrel (*Spermophilus parryii*), Sabine's Gull (*Xema sabini*), Snowy Owl (*Nyctea scandiaca*), Arctic Tern (*Sterna paradisaea*), Peregrine Falcon (*Falco peregrinus*), and Long-tailed Jaeger (*Stercorarius longicaudus*) (Liebezeit et al. 2009). At Canadian coal mine sites in the boreal forest, avoidance behaviour from grey wolves (*Canis lupus*) has also been documented (Ehlers et al. 2014) although, in that study, wolves would occasionally use road corridors associated with mines, for short intervals especially in winter, when there are few to no nesting birds.

In some cases, the introduction of waste produced by mines allowed some traditionally non-Arctic species to expand their range (Savory et al. 2014). An example of this in Alaska is the Red Fox (*Vulpes vulpes*), which historically (e.g., pre-1988) was not abundant north of the Brooks Range, Alaska (Savory et al. 2014). Once the Prudhoe Bay industrial development occurred in the 1970s, Red Fox was observed foraging on human food (Savory et al. 2014). Prudhoe Bay Red Fox consumes anthropogenic waste year-round, and more so than Arctic Fox. The Red Fox was found to have a diet that consisted of lemmings and anthropogenic waste with little to no evidence of vole and/or egg consumption, in comparison to the Arctic Fox which had a moderate consumption of voles and/or eggs and consumed less anthropogenic waste (Savory et al. 2014). Though the Red Fox has expanded its home range northward, it is unknown whether anthropogenic waste is needed to reproduce and survive in this newly expanded range (Savory et al. 2014). Fox species are known to be the major predators on shorebird and passerine nests in the Arctic (Young et al. 2021).

Mines can influence both the abundance and the behaviour of predators, and the changes can have a significant influence on the reproductive success of tundra-breeding birds (Kristan and Boarman 2007). For instance, the ability of predatory birds to perch on human-made structures can lead to local increases in predation risk. Nest sites that are near the electrical distribution lines in Brooks, Alberta have been observed to have 15% higher predation, presumably because the power lines serve as perch sites for avian predators (Bernath-Plaisted and Koper 2016). In the Prudhoe Bay oil field, passerine nest survival is lower within 5 km of the infrastructure, similarly assumed to be due to the additional perching, nesting, and denning locations for nest predators (Liebezeit et al. 2009). Collectively, these changes in the abundance or behaviour of predators can lead to significant local impacts on reproductive success, which in turn could yield long-term declines in the local abundance of birds through reduced recruitment or reduced site fidelity following reproductive failure.

Over time, these interactions with predators and the resultant changes in return rates could contribute to changes in the composition of local bird communities. For example, in Barrow, Alaska, there are 37 species of regularly breeding shorebirds (Gill et al. 2008). Of these, 18 species nest in the area with the most intense oil development (Liebezeit and Zack 2009), and 11 were identified to occur within the fenced area surrounding the landfill site near Barrow. Following the construction of Prudhoe Bay's landfill fence, bird nest densities decreased for some species outside of the fence while densities within the fence remained the same, or in the case of Semipalmated Sandpiper, increased slightly (Saalfeld et al. 2013a). Since the Arctic Fox is a key population regulator of Arctic breeding birds (Liebezeit and Zack 2008), the reduction in the incidence of nest predation by fox has contributed to an increase in nest survival rates within this fenced area (Saalfeld et al. 2013a), and potentially contributed to the greater densities through enhanced site fidelity or recruitment.

2.333 Noise Effects on Reproductive Success

Noise pollution can also negatively influence breeding bird densities (Canaday and Rivadeneyra 2001), species diversity, population sizes, and breeding success (Rheindt 2003, Habib et al. 2007, Slabbekoorn and Ripmeester 2008, Saha and Padhy 2011). The high noise levels generated by mining activities can reduce habitat quality through noise pollution (Bayne et al. 2008), for example when signals of breeding birds are masked (Vincelette et al. 2020), reducing communication efficiency (Brumm 2004) and reproductive success (Halfwerk et al. 2011). Adult or nest survival can be reduced in noisy environments, due to the inability of birds to detect approaching predators (Habib et al. 2007).

For some Arctic breeding bird species, however, anthropogenic noise from sources such as vehicles has little impact. Male (2004) found that anthropogenic noise from mining had no impact on the nest success of Lapland Longspur birds within 300 m of major haul roads. There is little frequency overlap between the Lapland Longspur song (between 2 and 6 kHz) and truck-generated noises (<2 kHz), suggesting that the noise from trucks is primarily outside this species' song range (Male and Nol 2005). Also of consideration are cases where mine sites have few, episodic major noise disturbances like blasts (Smith et al. 2005); a situation that has received little study. The responses of species to the impacts of noise pollution in the Arctic are largely unknown but may vary substantially among noise sources, habitat types, and species.

2.4 Cumulative Effects: Final Thoughts

The concept of cumulative effects acknowledges a variety of interactions among stressors, including additive or synergistic effects. Each direct and indirect effect of mining on bird densities is itself a collection of several interacting environmental and anthropogenic factors. For example, road dust causes earlier snowmelt, which in turn leads to earlier insect emergence and increased insect abundance, all of which accumulate to impact habitat quality. While these interactions occur and could impact bird densities, applying the concept of cumulative effects in a quantitative way to understand these interactions remains challenging. For example, the interacting effects of road dust, altered timing of snowmelt, and insect abundance all extend the physical footprint of the mine and result in a reduction of habitat quality for breeding birds. However, if multiple areas have a reduction in habitat quality from mining effects, the cumulative effects can begin to expand even further, reducing habitat quality at a larger spatial scale. Habitats otherwise unimpacted by effects from mining activities could be rendered less suitable by the surrounding cumulative effects. For example, wolves and caribou have been shown to change migration patterns to avoid areas with a threshold level of disturbance (Johnson et al. 2005b, Plante et al. 2018), contributing to a tangible but difficult to measure cumulative effect.

In comparison to mammals, the cumulative effects and interactions among mining activities are more poorly known for birds. The impacts of various mining activities on breeding birds, their interactions, and the cumulative effects at various spatial scales, have received little study, especially in the Arctic. Tipping points or thresholds of impact could eventually be reached around mine sites, at local or regional scales, but it is difficult to determine when such a threshold might be reached for breeding bird species in the Canadian Arctic. Nevertheless, acknowledging and attempting to understand the cumulative effects of mining activities on breeding bird densities is important to adequately mitigate effects at appropriate spatial scales.

2.5 Future Considerations

Mining activities in the Canadian Arctic can influence the densities or survival of tundra-breeding birds through a variety of mechanisms. Moreover, many of the impacts of mining activities can interact with other anthropogenic or environmental factors. Regardless of how significant these mining activities may be near mine sites, given the scale of mining in Arctic Canada, the impacts are not expected to be a significant pressure on bird populations range-wide. This is because the breeding range of most Arctic bird species is very large in comparison to the small extent of the area covered by active mines in the Canadian Arctic.

Many knowledge gaps remain regarding the impact that Arctic mines have on northern environments and wildlife. Further research is needed to understand how direct and indirect effects influence the structure and dynamics of breeding bird populations. Analysis of existing bird data could help to clarify the extent of the direct and indirect effects of mining infrastructure, as well as how they interact to form cumulative effects. Without knowledge of the effects of mining on Arctic breeding birds, action cannot be taken to protect these species, and balance the economic benefits of resource development with the potential adverse consequences for the environment.

CHAPTER 3 – Densities of Birds are Enhanced Near Mines in the Canadian Arctic

Abstract

Few studies have investigated the impacts of mines on the distribution and densities of tundra-breeding birds. Here, I evaluate the impact that mines have on these distributions using count data collected during bird surveys that were performed at various distances from five mining sites distributed across the Canadian Arctic. Surveys occurred within 475 plots over 20 years in plots that ranged in size from 12 – 16 ha and were within 100 km of the nearest mine. I separated birds into those that breed in upland versus lowland habitats and attempted to control, in a statistical model, for covariates that might influence birds' densities including latitude, habitat type, and distance to the coast. After controlling for these covariates, I examined the influence of the distance to the nearest mine infrastructure on bird densities. A total of 25 bird species occurred on a minimum of 20% of the surveyed plots, of which 10 species occurred at each of the five major mining operations in the Canadian Arctic. I observed a statistical relationship with proximity to mines for 10 bird species, with higher densities near mines most common. One of the eight species (Long-tailed Jaeger) detected across multiple mines increased in abundance with increasing distance to the mine. For Horned Lark and all upland species that were combined to create an upland species group, there were inconsistent patterns among mines. Thus, for most common Arctic-breeding bird species mines impacted, either positively or negatively, the abundance, and hence

distribution as a function of distance from the mine. Further work should determine whether these effects in abundance translate into impacts on nest success.

3.0 Introduction

Human actions are the primary cause of habitat destruction and degradation that contribute to the loss of global biodiversity (Brooks et al. 2006, Diaz et al. 2019). Species-specific responses to human disturbance are important to understand so that conservation efforts can be designed and implemented where they are most needed (Maron et al. 2012). Worldwide, increases in mining activities for metals and minerals can alter bird breeding habitat in multiple ways, such as through habitat loss and fragmentation (Bridge 2004, Asner et al. 2013, Lechner et al. 2014, Sonter et al. 2018), introducing noise from trucks and machines (Donoghue 2004, Smith et al. 2005, Bayne et al. 2008, Duarte et al. 2015), and altering hydrology (Budds and Hinojosa 2012, Smith et al. 2013, Creuzer et al. 2016, Stewart 2016, see Chapter 2).

The impacts of mining on breeding birds have not been well studied, especially in Arctic ecosystems. An improved understanding of how mining in the Canadian Arctic impacts bird densities and distributions is important for the design of mitigation strategies and species conservation plans. One source of data on the distribution of Arctic-breeding birds is the Arctic Program for Regional and International Shorebird Monitoring (PRISM; Bart and Johnston 2012), a program designed to monitor the population status and trends of shorebirds and other broadly distributed Arctic birds. Between 1998–2019, Arctic PRISM surveys were conducted across the whole of the North American Arctic. For these surveys, the North American Arctic was divided into 20 regions, 13 of which are within Canada (Bart and Johnston 2012). Within these regions, surveyors visited randomly selected plots and recorded the abundance of breeding birds of all species in a single visit, including but not limited to shorebirds (Bart and Johnston 2012).

Shorebirds (*Charadrii*) are the dominant avifauna across the Arctic in terms of species richness (Järvinen and Väisänen 1978, Lindström and Agrell 1999). Of the 21 species of breeding shorebirds in the Canadian Arctic, approximately 17 species are experiencing population declines (Government of Canada 2017, Rosenberg et al. 2019); including species such as the Semipalmated Sandpiper (*Calidris pusilla*), Red Knot (*Calidris canutus*), Ruddy Turnstone (*Arenaria interpres*), and Dunlin (*Calidris alpina*). Several declining shorebird species (e.g., Red Knot) have been assessed by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) as meeting criteria for listing, or have been listed under the Federal Species at Risk Act (SARA; Government of Canada 2017). PRISM surveys, therefore, provide information for a group of species of substantial conservation concern.

While many habitats in the Arctic are free from human disturbance, mining is one source of disturbance that is increasing. As of 2017, there were 27 active agreements for mining operations in the Canadian Northwest Territories, Nunavut, and Arctic Quebec (Nunavik) (NWT & Nunavut Chamber of Mines 2016b, Natural Resources Canada 2018a). Of these 27 active mining agreements, eight are considered major mining operations (three in the Northwest Territories, four in Nunavut, and one in Nunavik), while the remaining are exploratory projects. The eight current major mining operations are Ekati, Diavik, and Gahcho Kué in the Northwest Territories, Hope Bay, Mary River, Meadowbank (including Amaruq/Whale Tail Project), and Meliadine in Nunavut, and Raglan in Quebec (Figure 3.1; NWT & Nunavut Chamber of Mines 2016).

The placement of mines, along with the nature of the surrounding habitat, can determine the amount of disturbance they inflict on wildlife. Mine locations are based on the predominant rock form that is associated with the target of mining interest; the eight active mines in Arctic Canada are located in areas of intrusive rock with scattered metamorphic and sedimentary rock (Natural Resources Canada 2018b). By contrast, birds and other wildlife in the Canadian Arctic tend to be concentrated in coastal lowlands underlain primarily by sedimentary bedrock (Cotter and Andres 2000, Natural Resources Canada 2018b). This segregation of the habitat types preferred by wildlife and targeted by mines could potentially limit the disruption to wildlife due to disturbance from mines.

There are various ways in which mining exploration and resource extraction lead to habitat loss, degradation, or fragmentation, and each technique used to extract minerals varies in its impact on the environment (Sonter et al. 2018). Almost all mines excavate areas, construct roads, and many drain lakes to access minerals underneath (Rollo and Jamieson 2003) or alter hydrology in other ways to accommodate infrastructure (Chapter 2). Mines create noise from various sources including vehicles and crushing machines and this noise can disturb birds or mask their mating calls (Donoghue 2004, Smith et al. 2005, Duarte et al. 2015). Mining camps create food and human waste, and the management of waste can attract predators, potentially increasing the rate of nest or adult mortality due to predation (Liebezeit and Zack 2009, Liebezeit et al. 2009, Saalfeld et al. 2013a, Savory et al. 2014). Nests may also be lost directly when vegetation is cleared for the expansion of mine infrastructure (Government of Canada 2019a). Effects may also be indirect. For example, road dust (Spatt and Miller 1981, Walker and Everett 1987, Auerbach et al. 1997, Male and Nol 2005, Naidoo and Naidoo 2005, Saalfeld et al. 2013a, Knutsen 2014), and altered snowmelt dynamics (Walker and Everett 1987, Auerbach et al. 1997, Saalfeld et al. 2013a) can promote earlier nesting, change the diversity and abundance of potential arthropod prey items for insectivorous tundra-birds (Haskell 2000, Ste-Marie et al. 2018), and thereby exert an indirect influence on nest survival (Chapter 2).

These disturbances, along with the physical footprint of the mine infrastructure, are not trivial in scale. Mary River, for example, is one of the largest mines in the Canadian Arctic with a footprint of approximately 31.94 km^2 which includes pits, ports, roads, tailings, waste rock piles, and other infrastructure (Baffinland 2018). The scale of mining operations also has important implications for the level of disturbance to birds. Smaller mines such as Hope Bay, have less infrastructure and accommodations (i.e., 100 employees; TMAC Resources Inc. 2018) compared with larger mine sites, such as Diavik, which has a larger footprint and more infrastructure to house a large number of employees (i.e., 700 employees in 2005; Roscoe and Postle 2005).

The habitat quality of land adjacent to the mine footprint can also be impacted through the mechanisms listed above, extending the area of influence. Various negative effects of mines on birds have been identified, such as reduced nest success close to human infrastructure from nest predation (Latour et al. 2005, Liebezeit et al. 2009, Knutsen 2014, Bernath-Plaisted and Koper 2016). However, many of these effects may also interact in additive or synergistic ways, leading to cumulative effects on the densities of birds at larger spatial scales; effects that have not yet been explored.

To date, studies examining the impacts of mines on Arctic-breeding birds have not focused on how the effects vary depending on the habitats within which mines are constructed. Some species of Arctic breeding birds prefer open tundra habitats that have short or nonexistent vegetation, often placing their nests on tops of ridges and mounds for the advantage of a wide, unobstructed view of potential predators (Johnson et al. 2009, Johnson and Walters 2011). Other species nest in wetland habitats, potentially because it becomes more difficult for predators such as Arctic Fox (*Vulpes lagopus*) to encounter and detect nests with inconvenient travel routes (Lecomte et al. 2008). At larger spatial scales, lowland habitats generally support higher densities of Arctic-breeding birds than do upland habitats (Liebezeit et al. 2011, Bart and Johnston 2012). The habitat surrounding Arctic mines could therefore have an important bearing on their potential to alter breeding bird densities or shift the distribution of species.

In many cases, these effects of mines could impact species of conservation concern, but regardless of the conservation status of populations, harming migratory birds and other wildlife is prohibited under various Federal regulations; appropriate enforcement of these regulations requires an understanding of the scale and nature of the impacts. In this chapter, I test the hypothesis that Arctic mines influence the densities of tundra breeding bird species at a local scale, and that this disturbance is greatest near the mines. Using data from PRISM surveys carried out at varying distances from mines across the Canadian Arctic, I tested the prediction that tundra-breeding bird density is depressed around mines. I predicted that the alterations to landscapes from mining activities would impact both upland and lowland species, but that the impact would be more detectable with lowland species since this habitat supports greater nesting densities than upland habitats (Liebezeit et al. 2011). I also tested the predictions that the effects of mining on breeding birds declines to a negligible level at a threshold distance away from the mine, and that the magnitude of impacts is species-specific.

3.1 Methods

3.11 Bird Surveys

Bird surveys were carried out in plots across the Canadian Arctic using the protocol developed by the Arctic Program for Regional and International Shorebird Monitoring (PRISM; Bart and Johnston 2012). The PRISM study area is the North American Arctic, as defined by Conservation of Arctic Flora and Fauna (CAFF; CAVM Team 2004), and this area was subdivided into 20 regions based on habitat and logistical considerations. The size of the PRISM regions was selected to be accessible by helicopter within a single season, and the boundaries were defined to follow geographical (i.e., islands) and habitat boundaries (i.e., a separation between barren, non-vegetated habitat, and suitable, wetland habitat), based on broad habitat classifications from the Circumpolar Arctic Vegetation Map (CAVM Team 2004).

Plot selection followed the Arctic PRISM methodology described elsewhere (Bart and Johnston 2012). Briefly, each region was partitioned into plots, excluding mountainous areas, glaciers, and deep water (i.e., unsuitable habitats). Areas were stratified by habitat type (wetlands, heavily vegetated uplands, lightly vegetated uplands) and plots were randomly selected from within these habitat strata. The methodology for selecting plots was different around mine sites. Typically, surveys were performed by Canadian Wildlife Service employees and volunteers, but in some years, mining companies conducted surveys that were within mining leased property. In these cases, mining companies often selected plots to survey inside their local study area (5 km radius from the main camp site). The exception to this rule was if the mining company was near other survey areas (i.e., for fisheries or aquatics monitoring) with similar terrain and vegetation as the mine site area, in which case surveys were performed in this area (Gebauer et al. 2008).

Surveys were completed in mid-to-late June, during the period of late-courtship to early incubation for shorebirds. At this time, species have settled into breeding territories and can be detected through territorial displays (see Bart and Johnson 2012). Surveys at mine sites occurred in a single year at each mine with data that spanned 17 years, and were carried out between 21 June to 5 July, 2001-2018. Survey plots were typically 300 m x 400 m (12 ha), but occasionally 400 m x 400 m (16 ha) in the early years of the survey. Surveys lasted roughly 90 minutes and were carried out by two trained observers spaced 25 m apart covering the plot completely with 50 m wide transects. The observers used GPS to navigate and ensure complete coverage. For each bird seen on a plot, the species, and highest evidence of breeding were recorded. Observations of a breeding pair were counted as two individuals and lone male, female, or unknown sex individuals were counted as single individuals. I did not distinguish between Canada and Cackling Geese and labelled all as Canada/Cackling Goose. Although not employed here, PRISM surveys also include a subsample of intensively surveyed plots used to correct for variation in the detectability of birds during these 90-minute rapid surveys (Bart and Johnston 2012). Here, I test my predictions by assuming that the detection probability was constant over time and with respect to distance from mines (Flemming et al. 2019).

When selecting plots to survey, a habitat category was first determined using remotely-sensed habitat data. Upon arrival at the plot, the two trained observers estimated the proportion of the plot covered by three general habitat types (lowland, upland, and permanent water), which, in some cases differed from the remotely-sensed classification. For the analyses described here, I used field-collected data when available and filled in the gaps using remotely sensed habitat classifications. Plots dominated by vegetated mesic and sparsely vegetated xeric habitats were classified as upland habitats, while plots dominated by heavily vegetated hydric to hygric habitats were considered lowland habitats (Flemming et al. 2019).

Since surveyed plots were scattered across the Canadian Arctic, many of these plots were thousands of kilometres away from the nearest active mine. To focus on the effects of mines, I excluded data from plots that were >100 km from the footprint of the active mines included in the analyses (see below). Previous studies found that mine-related activities can impact bird species up to 3 km away due to the influence of noise (Van der Zande et al. 1980, Reijnen et al. 1995, Canaday and Rivadeneyra 2001), while increases in the risk of predation on nesting passerines in the Prudhoe Bay oil field of

Alaska extended 5 km away from mining operations (Liebezeit et al. 2009). Therefore, I assumed that plots within 100 km from mine sites would capture all potential effects of mining while simultaneously preventing latitudinal effects that might impact the distribution of species (Flemming et al. 2019).

In the analyses, I looked at patterns within 100 km of the mines to determine a threshold distance for the effects of mining (see *Data Analyses*). To help interpret my results and test my hypothesis, bird species were examined separately before being placed into one of two categories; those that prefer to breed in either upland or lowland habitats (Table 3.1). There are nine bird species that are classified as being upland birds, while 16 additional species make up the lowland bird group after the exclusion of species that did not occur on ≥20% of surveyed plots at any given mine, totalling 25 birds with enough occurrence and density to be included in the analysis (Table 3.1). These 25 bird species include eight passerine, five shorebird species and 12 other species of waterfowl, landbirds, raptors, and gulls had sufficient observations (n >100 sightings and occurring in ≥20% of surveyed plots at any given mine; Table 3.1). Of these 25 species, only 10 occurred at all five mines across the Canadian Arctic. Some species prefer to nest on dry open tundra that can range from heavily vegetated to barren (Johnson et al. 2009, Johnson and Walters 2011); these species are considered upland species. An example of an upland species that prefer sparse vegetation is the Rock Ptarmigan (*Lagopus muta;* Wilson and Martin 2008, Montgomerie and Holder 2020). By contrast, lowland species prefer to nest in low, wet, vegetated habitats (Lecomte et al. 2008). An example of a lowland species is the Red-necked Phalarope (*Phalaropus* *lobatus;* Rodrigues 1994, Rubega et al. 2020). Habitat coverage within the plots was typically recorded in the field, but for 163 plots that were missing these data, I relied on the remotely sensed values from the Circa-2000 Northern Land Cover of Canada (Olthof et al. 2008). A list of all recorded species that occurred within 100 km of mines is included in Appendix Table S3.2 which includes 25 waterfowl, 23 shorebirds, 25 landbirds, 13 birds of prey, and 4 gulls. The percent coverage of lowland habitat in plots within 100 km of the nearest mine varied between 0 and 100 (Appendix Figure S3.1). Any mines not within the species' breeding range as determined by the Cornell Lab of Ornithology: Birds of the World database (The Cornell Lab of Ornithology 2021), were removed from the analyses.

3.12 Mine Locations

Five of the eight active mines or advanced exploration projects were selected for analysis: Mary River, Hope Bay, Meliadine, and Meadowbank from Nunavut, and Gahcho Kué from Northwest Territories, Canada (Figure 3.1 & 3.2, Table 3.2). The Raglan mine in northern Québec was not included in the analysis since there were only two PRISM plots surveyed within 100 km of the mine footprint. The Diavik and Ekati mines were not selected for analysis since they both lack PRISM surveys within 100 km of the mine footprint. Gahcho Kué mine in the Northwest Territories specializes in diamond production located in Kennady Lake, approximately 300 km east-northeast of Yellowknife (JDS Energy & Mining Inc. 2018). The Gahcho Kué mine is situated at the edge of the continuous permafrost area, where taiga meets tundra (JDS Energy & Mining Inc. 2018). This region consists of knolls, heath/tundra, surface depressions with lakes, and bedrock outcrops (JDS Energy & Mining Inc. 2018). The Hope Bay, Meadowbank, and Meliadine mines are located on the mainland of Nunavut: Hope Bay is about 685 km northeast of Yellowknife in Kitikmeot Region, Meadowbank is near Baker Lake, and Meliadine is approximately 25 km northwest of Rankin Inlet on the west coast of the Hudson Bay (Larouche et al. 2015, Bilodeau et al. 2018, TMAC Resources Inc. 2019). Hope Bay, Meadowbank and Meliadine are located in regions characterized by lowlands interspersed with gentle, rolling uplands with long eskers spread across the landscape, and cryosols as the dominant soils (Sullivan and Dagbert 2006, Larouche et al. 2015, Bilodeau et al. 2018). The landscape is scattered with innumerable wetlands, lakes, and ponds (Sullivan and Dagbert 2006, Larouche et al. 2015, Bilodeau et al. 2018). These three mines target the extraction of gold (Larouche et al. 2015, Bilodeau et al. 2018, TMAC Resources Inc. 2019). The final mine included in the sample is the Mary River, located on northern Baffin Island, and targeting iron ore (Baffinland 2018). Mary River consists of a topography that is largely glaciofluvial outwash with direct deposition of moraines, kames, and eskers (Baffinland 2018). The outwash valley has little local relief and is relatively flat except for esker deposits and waterbodies (Baffinland 2018).

The footprint of each mine is typically found in the annual reports of the mine, and for those that lacked an accessible footprint, I used Google Earth Pro (ver. 7.3.2.5776) to determine location and footprint layout. The boundaries of each mine used for the analyses represent the outermost edge of all infrastructure including pits, buildings, tailings ponds, waste rock piles, ports, and roads. Other advanced exploration projects in the Canadian Arctic were not included in the analysis because the footprint of the infrastructure could not be determined; it was assumed that these projects were smaller than the projects that were included (Figure 3.1, Appendix Table S3.1). The distance from each surveyed plot to the nearest mine was calculated as the shortest distance between the plot edges and mine footprint polygons using the *near* function in ArcMap Version 10.6.1 (ESRI 2019).

3.13 Data Analysis

Shorebird abundance is known to decrease with increased distance from the coast (Morrison 1997, Bart and Johnston 2012), due to the abundance of preferred habitats (mostly wetlands) near the coast (Brown et al. 2007). I therefore considered distance to the nearest coastline as a covariate in my models. For each PRISM plot, I measured the distance from the edge of the surveyed plot to the nearest coastline using the *st_nn* function in the *nngeo* package Version 0.3.0 in R (Dorman 2019). The coastline location was retrieved from the Global Administrative Areas database (Hijmans et al. 2010).

I used generalized additive models (GAMs) to test the relationship between covariates and bird abundance, due to expected non-linear relationships. Distance to coast, an offset of the log-transformed plot area (in km^2), latitude, and the proportion of lowland habitat per plot were included in all models as fixed effects. The response variable was the total count of birds. However, by including the log-transformed plot area as an offset, I accounted for variation in plot size and modelled bird density. Mines were specified as a random effect, and run using a penalized ridge function, which allows for the interpretation of their importance based on effective degrees of freedom (edf) and *p*-values. Since each species may have different habitat preferences, I expected species-specific responses to vary in relation to distance to mine. I ran separate models for each species (n = 25), each mine (n = 5), and species groups (Lowland and Upland Habitat; Table 3.3). Only species that demonstrated a significant relationship with mine proximity across all five mines are presented in the *Results* section of this paper. Further figures can be found in the *Appendix*. For individual mine models, the latitude covariate and the random effect of mine ID were removed, and the proportion of lowland habitat and distance to coast variables were modelled as linear covariates (i.e., the spline term was removed). I acknowledge that there may be spatial auto-correlation for the Meadowbank mine due to clustered plot sampling. Meliadine mine was included in the grouped mine analysis but was removed from individual mine analysis due to a low number of survey sites and sample size.

I visualized the effect of distance to mines on bird abundance with penalized regression splines. Other covariates (distance to coast, latitude, and lowland proportion) were held constant at the mean when predicting bird densities. Holding these variables constant allows for predicted bird densities to represent changes from mine distance as opposed to other variables.

To determine the final model per species at all mine situations (across all mines or per mine), I included all covariates in the starting model and examined the degrees of freedom for each smooth term coupled with the Restricted Maximum Likelihood (REML) via the *gam* function in the *mgcv* package Version 1.8-31 (Wood 2001, 2019). When determining the model of best fit, three deciding conditions had to be met to remove a term from the model: 1) the effective degrees of freedom (edf) for the term is approximately 1; 2) the plot confidence band for the term possesses a value of zero everywhere; and 3) the REML score is reduced (Wood 2001), has no change, or increases by a max value of 2. If all three deciding conditions were met, then the term was removed from the model. The best fit model then included the remaining variables that were not removed after performing this backward step-wise elimination process.

I expected a threshold distance beyond which the impact of mines on bird densities has little to no effect. This distance threshold is expected to be different for each species since species can respond to disturbance differently. To determine this threshold distance, I first determined if the data fit a Poisson or Negative Binomial distribution by using the *dispersiontest* function. Once the appropriate model distribution was determined, I used a segmented analysis with the *lavielle* function from the *adehabitatLT* package Version 0.3.24 (Calenge 2019). This function determines a break point in the splines beyond which mines had little or no effect on bird abundance (Calenge 2015). The data for each species were broken up into a maximum of 20 segments. By using the function *chooseseg*, I could see the number of segments (*K)* increase as the contrast function decreases (Calenge 2015). To determine the optimal number of segments, I examined the number of segments (*K)* in relation to the decrease in the contrast function *J(K)*(Calenge 2015). I chose the first *J(K)* value that fell below 0.75 as my maximum number of segments *(K)* to split the data (Calenge 2015). Using this (*K*) value, I then graphed the data using the *findpath* function and selected the segment that had the largest change in species abundance with distance from nearest mine, and determined the distance at which each species was no longer influenced by mine proximity (Calenge 2015). I used the *tibble* function to hold variables constant and used the *predict* function to predict the impact of mine distance on bird densities/km^2 based on the model best fit determined using *gam* (RDocumentation 2019, Muller and Wickham 2021).

Species that were detected at all five mines and occurred on ≥20% of plots at each mine were selected for analysis when looking at the overall impact of mine proximity on bird density. For individual mines, species selected for analysis were those that occurred on ≥20% of plots surveyed at that mine site. All statistical analyses were performed using R Version 3.3.2 (R Core Team 2018).

Table 3.1. Broad habitat preferences for birds sighted during Arctic PRISM plot surveys within 100 km of mines. Only species with >100 observations and occurring at ≥20% of plots are displayed; see Appendix Table S3.2 for a complete list of species observed.

Classification	Common Name	Scientific Name	References Supporting Classification
Lowland Habitat	Canada/Cackling Goose	*Branta canadensis/hutchinsii*	(Mowbray et al. 2020b)
	Glaucous Gull	*Larus hyperboreus*	(Weiser and Gilchrist 2020)
	Greater White-fronted Goose	*Anser albifrons*	(Mickelson 1975, Ely and Raveling 1984)
	Herring Gull	*Larus argentatus*	(Nisbet et al. 2020)
	King Eider	*Somateria spectabilis*	(Powell and Suydam 2020)
	Lapland Longspur	*Calcarius lapponicus*	(Sutton and Parmelee 1955, Hussell and Holroyd 1974, Montgomerie et al. 1983)
	Long-tailed Duck	*Clangula hyemalis*	(Robertson and Savard 2020)
	Long-tailed Jaeger	*Stercorarius longicaudus*	(Wiley and Lee 2020)
	Northern Pintail	*Anas acuta*	(Dwernychuk and Boag 1972, Duncan 1987)
	Pectoral Sandpiper	*Calidris melanotos*	(Farmer et al. 2013, Richards and Gaston 2018)

	Red Phalarope	*Phalaropus fulicarius*	(Tracy et al. 2020)
	Sandhill Crane	*Grus canadensis*	(Gerber et al. 2020)
	Savannah Sparrow	*Passerculus sandwichensis*	(Wiens 1969, Richards and Gaston 2018, Wheelwright and Rising 2020)
	Semipalmated Sandpiper	*Calidris pusilla*	(Holmes and Pitelka 1968, Richards and Gaston 2018)
	Snow Goose	*Chen caerulescens*	(Mowbray et al. 2020a)
	White-rumped Sandpiper	*Calidris fuscicollis*	(Parmelee 2020)
Upland Habitat	American Golden-Plover	*Pluvialis dominica*	(Johnson et al. 2020)
	American Pipit	*Anthus rubescens*	(Hendricks and Verbeek 2020)
	American Tree Sparrow	*Spizelloides arborea*	(Richards and Gaston 2018, Naugler et al. 2020)
	Common Raven	*Corvus corax*	(Boarman and Heinrich 2020)
	Common Redpoll	*Acanthis flammea*	(Knox and Lowther 2000)
	Horned Lark	*Eremophila alpestris*	(Drury 1961, Beason 1995)
	Rock Ptarmigan	*Lagopus muta*	(Montgomerie and Holder 2020)
	Snow Bunting	*Plectrophenax nivalis*	(Meltofte 1983, Montgomerie et al. 1983)
	White-crowned Sparrow	*Zonotrichia leucophrys*	(Richards and Gaston 2018)

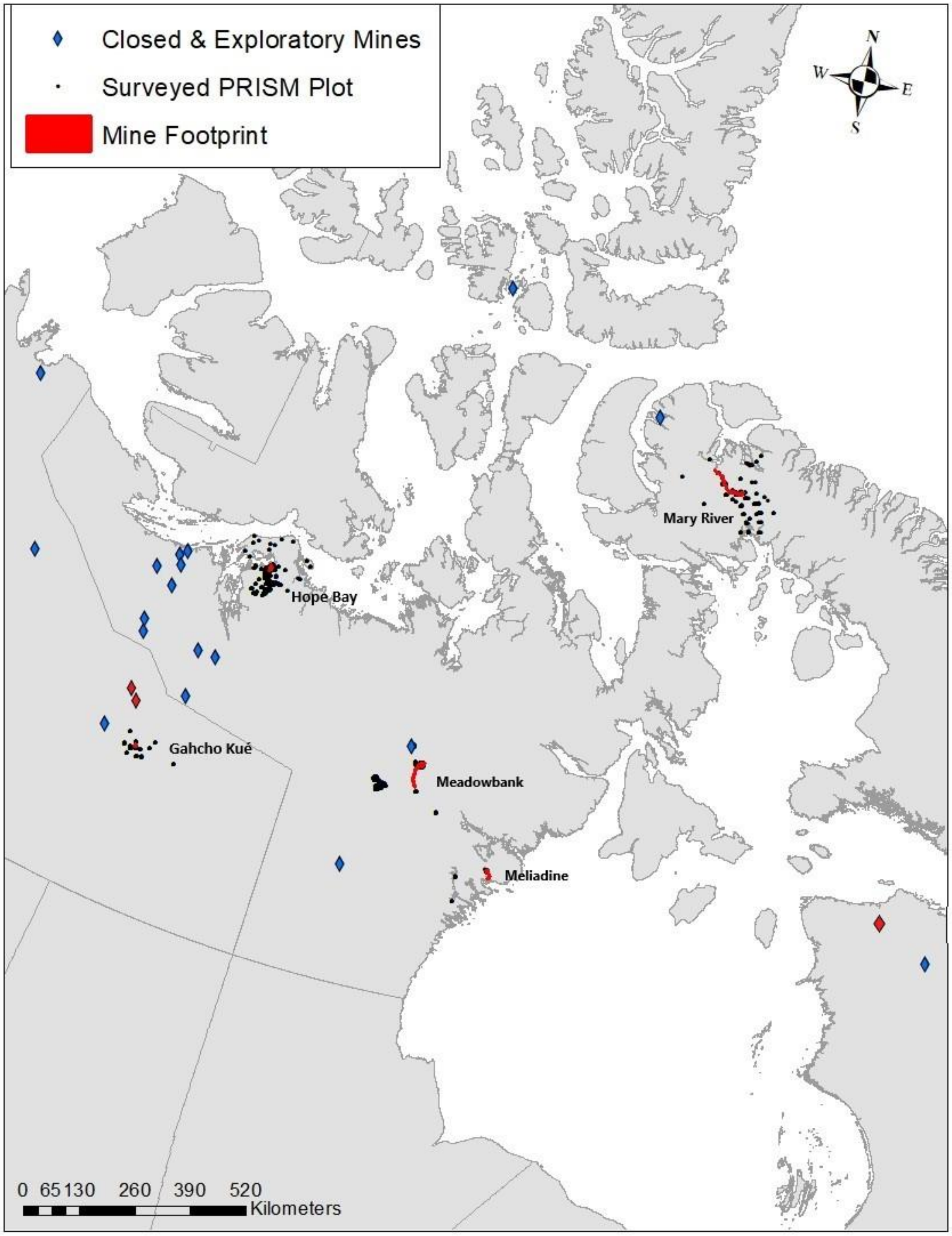

Figure 3.1. PRISM survey plots within 100km of mines (black dots), the footprint of mines and advanced exploration projects included in the analysis (red polygons), location of additional advanced exploration projects not included in the analysis (red diamonds), and additional mining/exploration projects not included in analyses (blue diamonds).

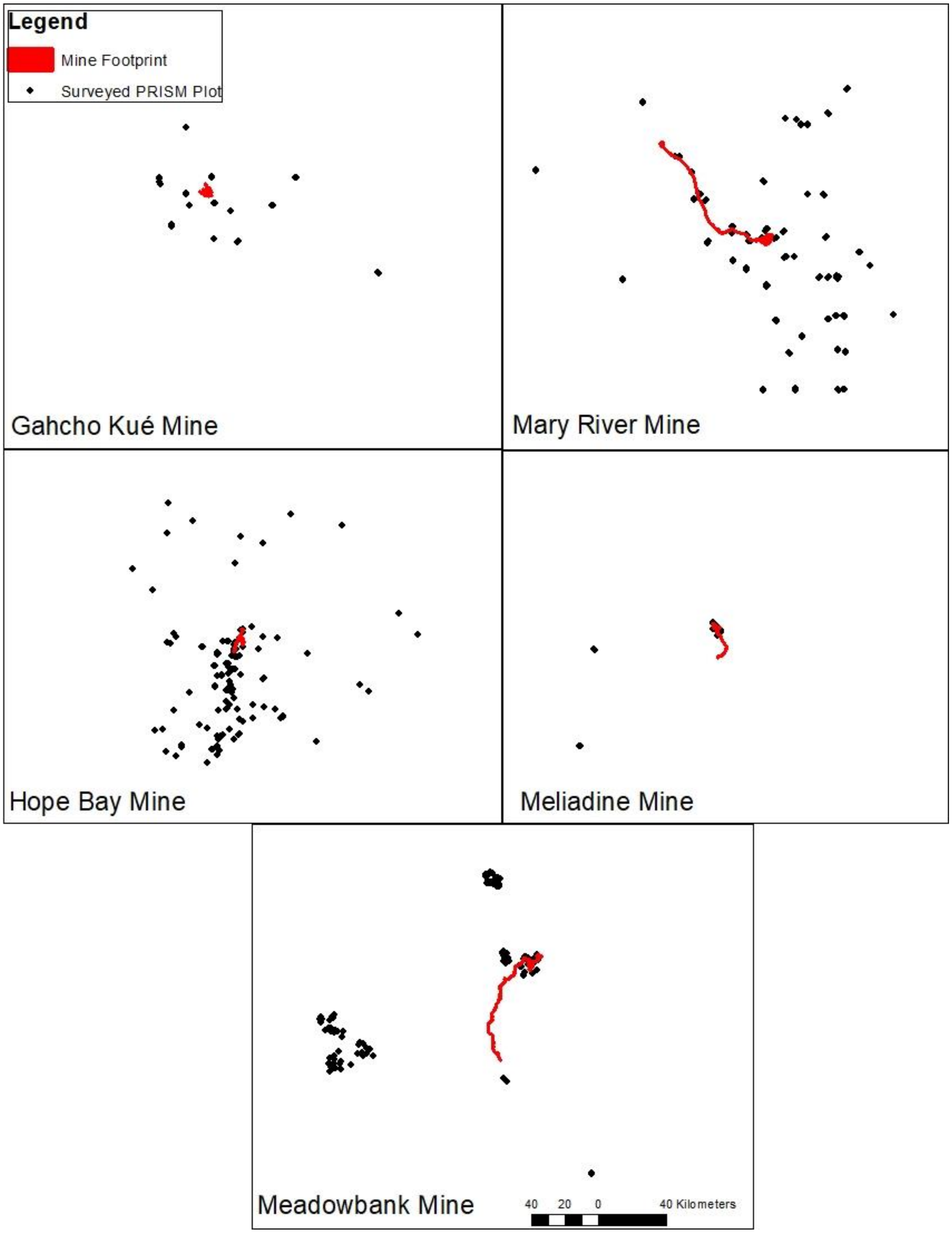

Figure 3.2. Close up maps of each mine that has PRISM survey plots within 100 km. Red polygons represent the mine footprint (including roads, ports, pits, infrastructure) and the black dots are individual survey plots. Ekati, Diavik, and Raglan mines are excluded from analysis, as they had no or few surveyed PRISM plots within 100 km.

Table 3.2. The northern Canadian mines included in analyses, their location, and the minerals mined at each.

Mine Name	Mine Location	Mineral Mined	References
Gahcho Kué	Kennady Lake, Northwest Territories	Diamond	(JDS Energy & Mining Inc. 2018)
Mary River	Northern Baffin Island, Nunavut	Iron	(Baffinland 2018)
Hope Bay	Kitikmeot Region, Nunavut	Gold	(TMAC Resources Inc. 2019)
Meadowbank	North of Baker Lake, Nunavut	Gold	(Bilodeau et al. 2018)
Meliadine	Near Rankin Inlet, Nunavut	Gold	(Larouche et al. 2015)

3.2 Results

3.21 Summary of bird occurrences

A total of 475 PRISM bird survey plots were completed within 100 km of the five selected mining projects (Figure 3.1). A total of 25 bird species had sufficient data for analysis (Table 3.1). There was a total count across all species of 12,349 individuals included in the analyses, with individual species densities found on a single plot ranging from 0 across multiple species to 1,667 birds/km² (SD ± 51.38) for Snow Goose. Lapland Longspur had the greatest mean density, with 65.18 individuals per km², and occurred in 64.6% of plots. The Snow Goose was the species with the second-highest density, with a mean of 36.09 individuals per km², and occurring in 68.6% of plots. The Canada/Cackling Goose had the third-highest densities, with a mean of 31.14 individuals per km², and occurring in 38.2% of plots, followed by Horned Lark, occurring in 68.6% of plots, with a mean density of 22.74 individuals per km². An additional 66 species were observed infrequently and were not included in analyses (Appendix Table S3.2).

3.22 Importance of covariates: latitude, lowland habitat, and distance to the coast

Models of density in relation to the distance from mine infrastructure, across all five mines, included latitude as a significant predictor variable for five of 10 species for which species-specific models were developed (Horned Lark, Lapland Longspur, Long-tailed Duck, Rock Ptarmigan, Savannah Sparrow), as well as both species groups (upland and lowland nesting species groups; Table 3.3). For plots below a latitude of 66.29^{o}N, the mean density (±SD) of all birds was 10.44 ± 19.33 individuals/km², while the mean density for plots north of this latitude was 6.23 ± 14.37 birds/km². Horned Lark and Rock Ptarmigan reached their peak density around 64ºN, Lapland Longspur and Long-tailed Jaeger reached their peak around 65ºN, Savannah Sparrow peaked twice, once at approximately 65ºN and again at approximately 67ºN (Appendix Figure S3.2). Though Pectoral Sandpiper counts did not include a significant effect of latitude, the peak bird density for this species was at approximately 66.5ºN (Appendix Figure S3.2).

The effects of distance to coast on bird densities were less pronounced than expected. Distance to the coast was a significant predictor of density for two of the 10 species detected at all five mines that were analyzed separately (upland species group and Rock Ptarmigan), with Rock Ptarmigan showing an increase in densities with increased distance from the coast and the upland species group showing similar trends but peaking at approximately 70 km from the coast before densities begin to decrease with increased distance from the coast (Table 3.3, Appendix Figure S3.3). Across all five mines, the relationship between distance to coast and bird densities varied widely across sites with an equal mix of positive and negative correlations (Tables 3.4 - 3.8). Counter to my prediction, the average density of all birds over 50 km from the nearest coastline was 10.78 ± 19.53 birds/km² while the average bird density for all species within the first 50 km was 6.11 ± 14. 15 birds/km².

To determine whether there were consistent habitat composition differences across distances from the mine, I plotted the proportion of lowland habitat in plots against distance (Figure S3.1). There was large variability and no significant trend, but on average, lowland habitat constituted approximately 25% of the plots (Figure S3.1). The proportion of lowland habitat in a plot was a significant predictor of density for two of 10 species that were analyzed independently (Lapland Longspur and Pectoral Sandpiper), with greater proportions of lowland habitat predicting greater bird densities (Table 3.3, Appendix Figure S3.4). For bird species found at all five mines, the relationship between lowland proportion and bird densities varied widely across sites with more positive correlations than negative across species (Tables 3.4 - 3.8). There was an average density of 8.48 ± 16.75 birds/km^2 in plots with up to 50% wet lowland habitats, which was similar to the density found in plots with greater than 50% (9.73 ± 20.23 birds/km^2).

3.23 Effects of distance to mine

After accounting for variation in latitude, distance to coast, and habitat type of the plots, I identified a significant relationship between species density and distance to mine across all mines for five lowland species (Canada/Cackling Goose, Long-tailed Duck, Long-tailed Jaeger, Pectoral Sandpiper, Savannah Sparrow) and one upland species (Rock Ptarmigan; Table 3.3). A significant relationship was also found for both the combined upland and lowland habitat species groups (Table 3.3). Of these eight significant species, seven had greater densities closer to mines, while one of the eight species had greater densities farther away. Only Horned Lark and the combined upland habitat species group had substantial variation among mines (Table 3.3). Thus, for these two groups, I also present individual mine results for each mine with sufficient data (Tables 3.4 and 3.5; additional results for other species and other mines can be found in

Appendix Table S3.3 - S3.6). For each mine, there were slightly more lowland species (64%) than upland species that were significantly impacted by mines (57.1%; Appendix Tables S3.3 - S3.6). The break point distance was around 10 km for most species detected at all five mines but varied for each species at each mine (Meadowbank and Gahcho Kué; Tables 3.4 and 3.5, Tables S3.3 – S3.6).

Table 3.3. Final GAM model selection results for the densities of birds near five mines across the Canadian Arctic. Approximate significance (*p*-value) and estimated degree of freedom (edf) are displayed for each covariate. The '-' symbol indicates variables that were removed from the model after performing a backwards stepwise selection process. I removed variables in the model selection process that had a linear term (edf = 1), where the confidence intervals overlap 0 along the observed range of values. An edf of 1 means that adding the term does not substantially improve the model fit unless paired with a significant p-value. Break point distance (km) represents the distance at which mines no longer influence bird densities (see text for methods).

	Canada/Cackling Goose		**Horned Lark**		**Lapland Longspur**		**Long-tailed Duck**	
Family	Negative Binomial		Negative Binomial		Negative Binomial		Negative Binomial	
Adjusted r^2	0.06		0.27		0.33		0.02	
Deviance explained (%)	5.6		34.1		32.8		3.7	
REML score	708.89		402.01		1324.70		290.34	
Break Point Distance (km)	8.37		-		-		9.85	
	edf	***p*-value**	**edf**	***p*-value**	**edf**	***p*-value**	**edf**	***p*-value**
Covariates								
Mine Distance	2.70	< 0.05	-	-	-	-	1.00	< 0.05
Coast Distance	-	-	3.45	0.11	-	-	-	-
Latitude	-	-	2.92	< 0.005	5.64	< 0.001	-	-
Lowland Proportion	-	-	2.45	0.22	1.00	< 0.001	-	-
Random Effect								
Mine	0.72	0.14	1.71	< 0.005	0.31	0.24	0.00	0.91

Table 3.3. Continued.

	Long-tailed Jaeger		**Pectoral Sandpiper**		**Rock Ptarmigan**		**Savannah Sparrow**	
Family	Negative Binomial		Negative Binomial		Negative Binomial		Negative Binomial	
Adjusted r^2	0.03		0.10		0.22		0.19	
Deviance explained (%)	15.0		25.7		37.3		25.9	
REML score	316.88		317.35		320.44		657.96	
Break Point Distance (km)	9.84		2.56		6.96		10.26	
	edf	***p*-value**	**edf**	***p*-value**	**edf**	***p*-value**	**edf**	***p*-value**
Covariates								
Mine Distance	2.75	< 0.05	3.90	< 0.005	3.35	< 0.001	2.68	< 0.05
Coast Distance	-	-	-	-	1.00	< 0.05	-	-
Latitude	3.48	< 0.05	2.20	0.54	2.68	< 0.001	7.83	< 0.001
Lowland Proportion	-	-	1.00	< 0.001	-	-	-	-
Random Effect								
Mine	0.00	0.33	0.00	0.99	0.00	0.47	0.00	0.45

Table 3.3. Continued.

	Upland Species Group		**Lowland Species Group**	
Family	Negative Binomial		Negative Binomial	
Adjusted r^2	0.37		0.42	
Deviance explained (%)	45.9		39.0	
REML score	570.84		1782.80	
Break Point Distance (km)	10.26		12.41	
	edf	***p*-value**	**edf**	***p*-value**
Covariates				
Mine Distance	2.73	< 0.001	3.35	< 0.001
Coast Distance	4.37	< 0.001	-	-
Latitude	1.00	< 0.001	5.97	< 0.001
Lowland Proportion	2.53	0.11	-	-
Random Effect				
Mine	1.79	< 0.001	0.01	0.29

Table 3.4. Final GAM model selection results for bird densities found in 27 plots at Gahcho Kué mine. Approximate significance (*p*-value) and estimated degree of freedom (edf) are displayed for each covariate. The '-' symbol indicates variables that were removed from the model after performing a backwards stepwise selection process. I removed variables in the model selection process that had a linear term (edf = 1), where the confidence intervals overlap 0 along the observed range of values. An edf of 1 means that adding the term does not substantially improve the model fit unless paired with a significant p-value. Break point distance (km) represents the distance at which mines no longer influence bird densities (see text for methods).

	Horned Lark		**Upland Species Group**	
Family	Poisson		Poisson	
Adjusted r^2	0.44		0.57	
Deviance explained (%)	47.2		56.7	
REML score	33.89		69.02	
Break Point Distance (km)	22.34		3.65	
Spline Covariate	**edf**	***p*-value**	**edf**	***p*-value**
Mine Distance	2.44	0.21	3.88	< 0.001
Covariate	**Est. ± Std. Error**	***p*-value**	**Est. ± Std. Error**	***p*-value**
Coast Distance	- 0.09 ± 0.04	< 0.05	-	-
Lowland Proportion	0.03 ± 0.01	< 0.005	0.01 ± 0.01	< 0.05

Table 3.5. Final GAM model selection results for bird densities found in 145 plots at Meadowbank mine. Approximate significance (*p*-value) and estimated degree of freedom (edf) are displayed for each covariate. The '-' symbol indicates variables that were removed from the model after performing a backwards stepwise selection process. I removed variables in the model selection process that had a linear term (edf = 1), where the confidence intervals overlap 0 along the observed range of values. An edf of 1 means that adding the term does not substantially improve the model fit unless paired with a significant p-value. Break point distance (km) represents the distance at which mines no longer influence bird densities (see text for methods).

	Horned Lark		**Upland Species Group**	
Family	Negative Binomial		Negative Binomial	
Adjusted r^2	0.13		0.22	
Deviance explained (%)	21.6		30.3	
REML score	348.77		482.16	
Break Point Distance (km)	9.85		9.85	
	edf	***p*-value**	**edf**	***p*-value**
Spline Covariate				
Mine Distance	3.41	< 0.001	3.84	< 0.001
	Est. ± Std. Error	***p*-value**	**Est. ± Std. Error**	***p*-value**
Covariate				
Coast Distance	0.04 ± 0.01	< 0.001	0.04 ± 0.01	< 0.001
Lowland Proportion	-	-	-	-

Of the eight species and species groups that were influenced by proximity to mines across all mines, seven species (Canada/Cackling Goose, Long-tailed Duck, Pectoral Sandpiper, Rock Ptarmigan, Savannah Sparrow, plus both species groups) initially decreased in density with increasing distance from nearest mine, though the changes are minimal and do not persist (Figure 3.3). The remaining species (Long-tailed Jaeger) initially increased in density with an increase in distance from the nearest mine up to 25 km before decreasing with distance from the nearest mine (Figure 3.3). The lowland habitat group exhibited a reduction in density with increased mine distance while the upland habitat groups exhibited little to no change (Figure 3.3).

Horned Lark densities were significantly related to distance to the mine at the Meadowbank mine only, with greater bird densities closer to and farther from the mine, but depressed densities at intermediate distances (Figure 3.4). At the Gahcho Kué mine, bird densities appeared to peak at approximately 20 km from the mine (Figure 3.4).

For the upland species group, two mines (Gahcho Kué and Meadowbank) had a significant impact on bird densities while the remaining two mines (Mary River and Hope Bay) did not have sufficient data collected at these mines for analysis. Gahcho Kué had greater densities of upland species approximately 20 km away from the mine and a secondary peak at 100 km away due to two plots that had large numbers of birds counted (Figure 3.5). Meadowbank had greater bird densities closest to and farthest away from the mine (Figure 3.5).

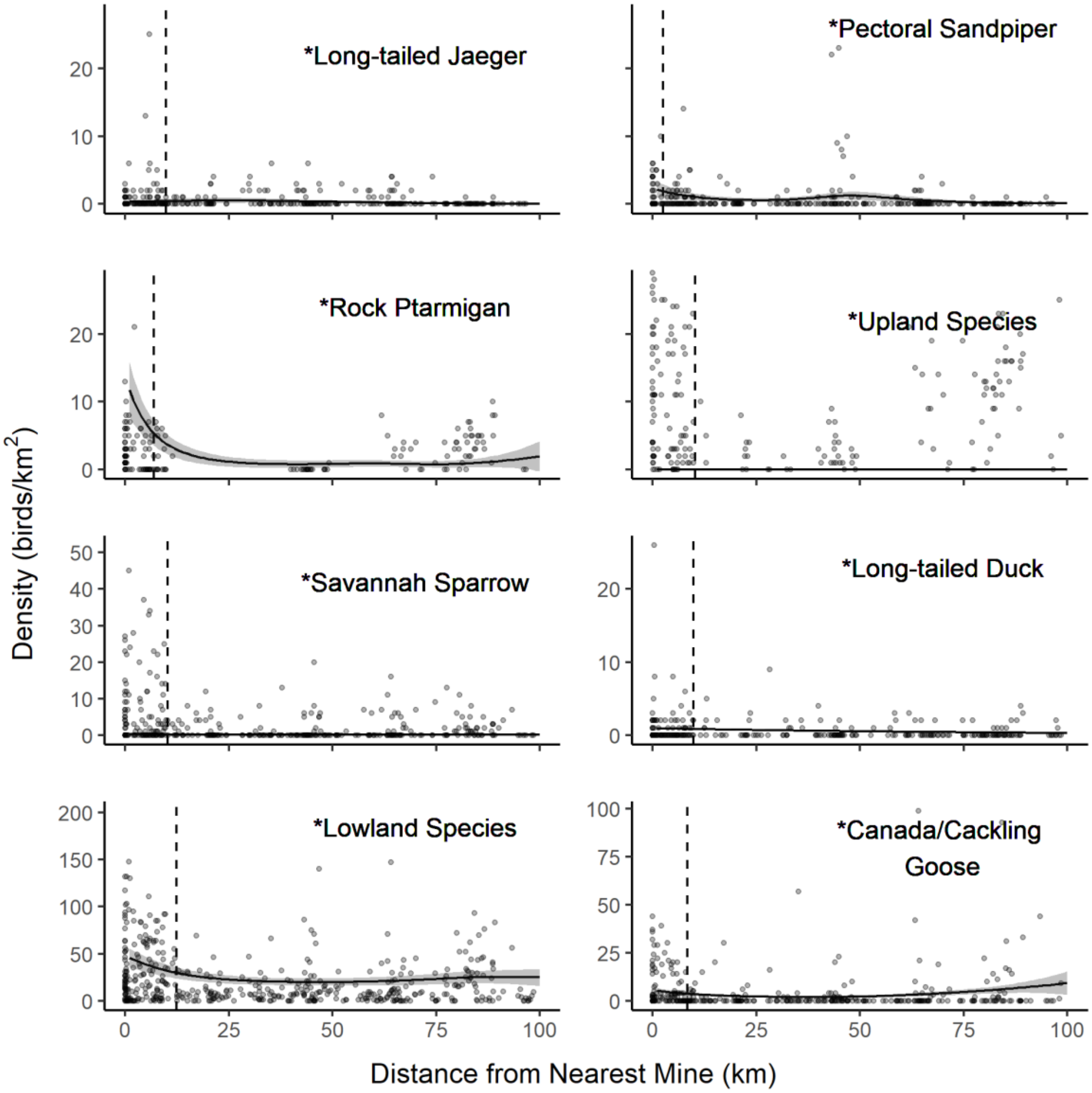

Figure 3.3. Changes in densities (birds per km^2) with increasing mine distance (km) across all five mines, for species where densities were significantly related to mine proximity. Black line indicates predicted fit, and the grey shading is the standard error. Dashed line indicates breakpoint for mine influence on bird species as indicated by the breakpoint analysis. Dots are observed bird counts.

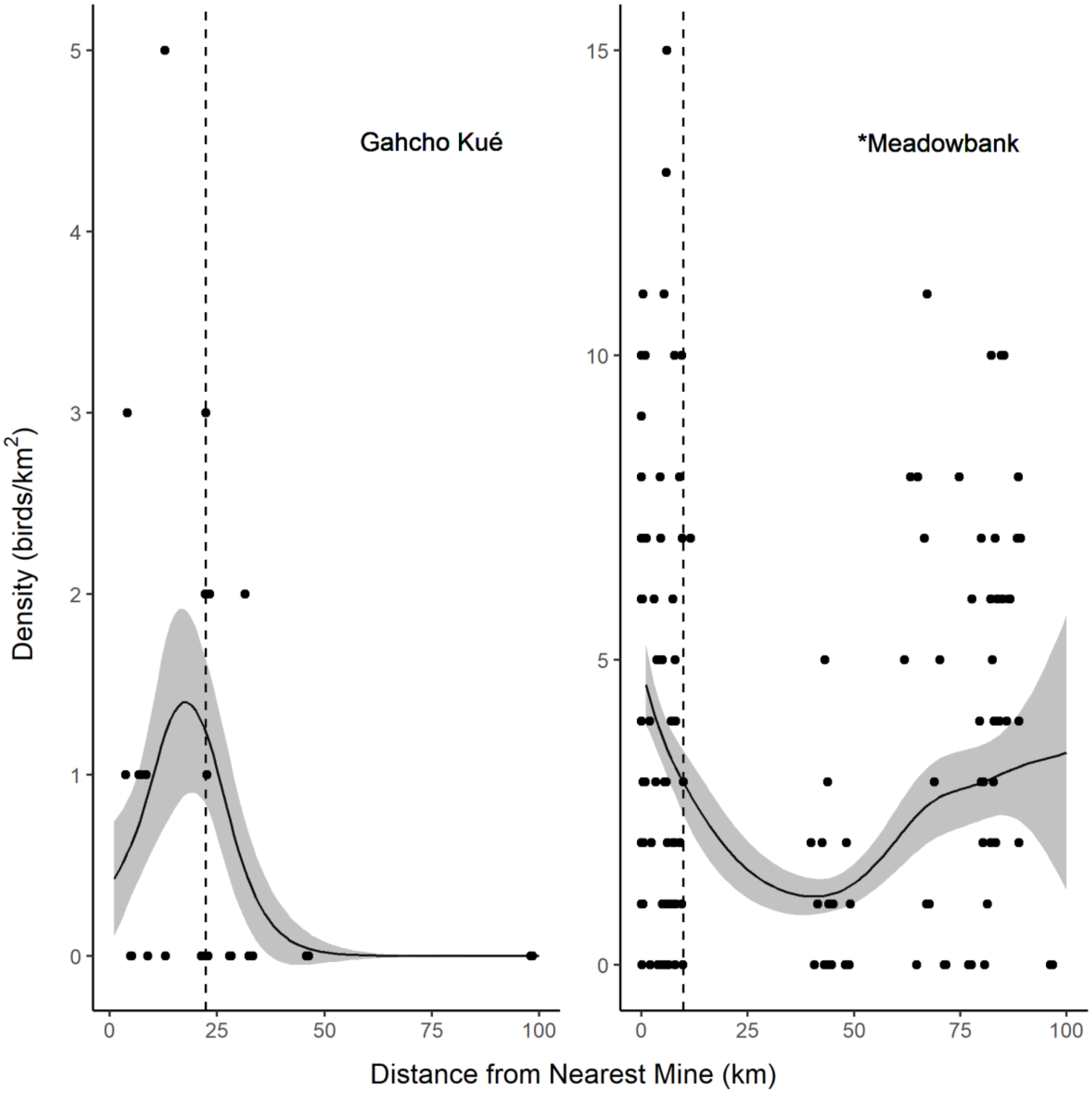

Figure 3.4. Changes in Horned Lark density (birds per km^2) with increasing distance to the nearest mine (km), for the two mines with sufficient data (Gahcho Kué and Meadowbank). Black line indicates predicted fit, and the grey shading is the standard error. Dashed line indicates breakpoint for mine influence on bird species as indicated by the breakpoint analysis. Mines with an '*' exhibited a significant relationship between density and distance to the mine ($p < 0.05$). Dots are observed bird counts.

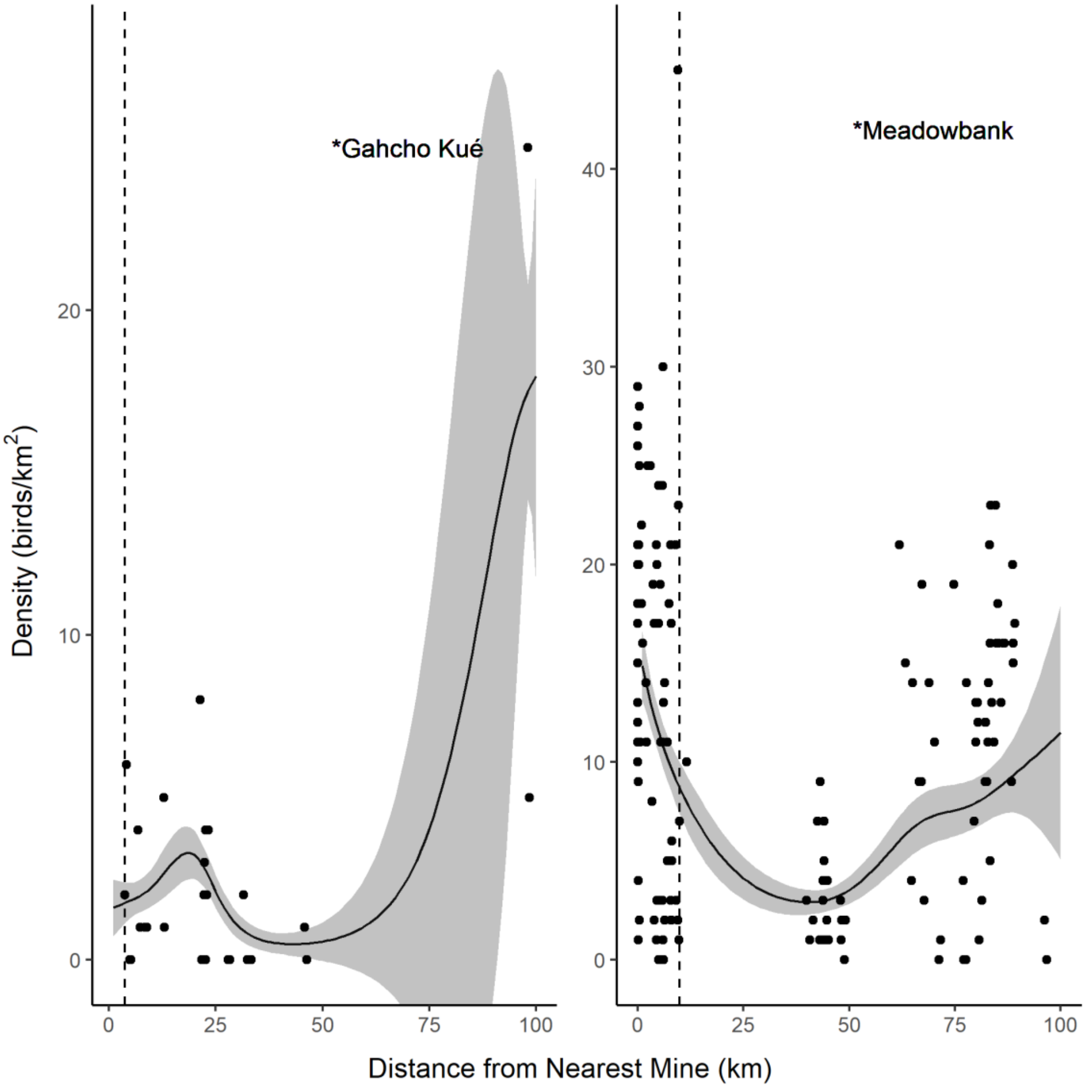

Figure 3.5. Changes in density for the Upland species group (birds per km^2), with increasing mine distance (km), for the two mines that had distance to mine as a significant covariate of density (Gahcho Kué and Meadowbank). Black line indicates predicted fit, and the grey shading is the standard error. Dashed line indicates breakpoint for mine influence on bird species as indicated by the breakpoint analysis. Mines with an '*' exhibited a significant relationship between density and distance to the mine ($p < 0.05$). Dots are observed bird counts.

3.3 Discussion

My thesis provides some of the first results to address how mines in the Canadian Arctic are affecting the densities of tundra-nesting bird species at a large spatial scale. Within 100 km of the nearest mine, one species was found at significantly reduced densities in plots nearer to mines than farther away, and this result was consistent across the five mines from which I had the most data. For the Long-tailed Jaeger, densities were at least two times higher at plots farther from mines than those at closer locations. For seven of the ten species that occurred at all five mines, species densities were significantly greater near mines than farther away. For the remaining two species on which I conducted detailed analyses (Lapland Longspur and Horned Lark), there was no significant effect of distance to the mine on their densities. I also found significant variation in densities of both the Horned Lark and the upland species group among the five mine sites. Finally, in this thesis, I demonstrate that neither habitat nor distance from the coast had strong effects on the densities of the Arctic breeding bird species that I studied. However, there were significant effects of latitude on densities for most species.

3.31 Species significantly affected by mine proximity

Most species were more abundant near mines, however, densities were significantly reduced near mines for the Long-tailed Jaeger. This pattern is unlikely to be explained by habitat. Long-tailed Jaeger nests are widely dispersed across varied habitats on the Arctic tundra (Wiley and Lee 2020). The species prefers to nest in marshy lowland habitats located near lakes (Maher 1970, Wiley and Lee 2020), but can also use barren upland sites with little vegetation and elevations that range from 50 – 250 m above sea level at some locations (Maher 1970, Wiley and Lee 2020).

Instead, the Long-tailed Jaeger may have reduced densities near mines because of sensitivity to human disturbance. Human disturbance has been found to negatively impact Long-tailed Jaeger nesting in Denali National Park, Alaska, where the species was observed to avoid areas with human disturbance and activity (Meeker 2019). The species is also well known to flush from their nests at long distances and respond to approaching humans through aggressive mobbing (Wiley and Lee 2020). This sensitivity to disturbance could make it difficult for long-tailed jaegers to successfully nest in the disturbed areas around mines.

The remaining significant effects of mines on densities were all positive; seven species or species groups showed greater densities near mines than farther away. These increased densities could arise because of how mining activities alter the habitat around the mining footprint. By draining lakes to access deposits or constructing roads that disrupt hydrology, mines could create additional wetland habitat. Lowland species that breed in wetlands consisting of marshy sedges and low hummocks, such as the Long-tailed Duck and Pectoral Sandpiper (Richards and Gaston 2018), may find more suitable habitat close to mines.

These moist habitats with low topographical relief are sensitive to small changes in water levels, whereas drier, higher elevation rolling terrain would require much larger changes in hydrology to be impacted. However, mines may also create suitable habitats for some upland species. For example, Rock Ptarmigan like to nest in dry, upland habitats and on rocky, well-drained tundra (Richards and Gaston 2018). Numerous ptarmigan have been observed on snow-free roads when migrating north for breeding (Walker and Everett 1987). The building of roads and vegetation clearing for mining activities could provide suitable sparsely vegetated breeding habitats for upland species like the Rock Ptarmigan.

Birds may also respond to areas that are snow-free early in the nesting season, because of dust from roads and other mine infrastructure and activities. Deposition of dust on snow, for example near roads, reduces the albedo and can lead to significantly earlier snowmelt in areas within 10's to 100's of metres of roads (Portier et al. 2010, Auerbach et al. 1997). These early snow-free areas could attract birds during the early portion of the season when territories are established. This is especially true for species with low site fidelity, such as the Pectoral Sandpiper (Liebezeit et al. 2014, Farmer et al. 2020). Areas adjacent to these snow-free areas could become attractive to later-breeding individuals through social attraction, extending the effect beyond the reach of the dust. This hypothesis requires further testing, but the time constraints faced by birds breeding in the Arctic are such that early snow-free areas have the potential to be a significant attractant.

3.32 Species not affected by mine proximity

For two of the ten bird species that occurred at all five mines (Horned Lark and Lapland Longspur), mine proximity was not a significant predictor of densities. Both the Horned Lark and Lapland Longspur defend small territories during the breeding season and exhibit some degree of nest site fidelity (Beason 2020, Hussell and Montgomerie

2020); this tendency to return to the same, small territories could explain the lack of effects of proximity to mines observed in our study. The Horned Lark's territories are multi-purpose, used for feeding, courtship, and nesting, and this species can occur at breeding densities of up to 30 pairs/km^2 (Richards and Gaston 2018, Beason 2020). The Lapland Longspur has territories that averaged 4.6 ha at Sarcpa Lake in Nunavut (Hussell and Montgomerie 2020). For both species, nest site fidelity is considered to be moderate or high (Beason 2020, Hussell and Montgomerie 2020). Horned Lark have limited Arctic data, but individuals have been known to return to the same territory, or nearby areas (Beason 2020). Similarly, Lapland Longspur has relatively high nest site fidelity, where 54.7% of birds at Sarcpa Lake, Nunavut, returned in subsequent years (Hussell and Montgomerie 2020). Horned larks prefer dry, sparsely vegetated habitats, but the nest habitat preferences of Lapland Longspur are broad. Individuals have been found nesting most often in hummocky, wet, tundra meadows, but have also been found on well-vegetated slopes with a drier substrate regardless of the proximity to mining roads (Male and Nol 2005, Hussell and Montgomerie 2020). Broad habitat preferences and a tendency to return to the same small territories could mean that these species are unlikely to be displaced by mine infrastructure and associated habitat changes.

3.33 Horned Lark and Upland Species Group variation across mines

Most of the eight species significantly impacted by mine proximity had increased densities near mines and no significant variation in this pattern across mines. Horned

Larks and the upland species group were two exceptions. The Horned Lark varied significantly in densities across two of the mines for which I had enough data to test for distance effects (Gahcho Kué and Meadowbank), although mine distance was not a significant predictor of changes in its density. When examined at the individual mines (Gahcho Kué and Meadowbank), Horned Lark densities at Gahcho Kué mine increased in density, though not significantly, farther from mines up to approximately 25 km before decreasing. At the Meadowbank mine, Horned Lark densities significantly decreased with increased distance from the mine up to 50 km away before densities increased. For the upland species group, both individual mines significantly impacted bird densities, with similar patterns as the Horned Lark. These mines occur in different geographic locations and habitat contexts. The Gahcho Kué mine is located in the Northwest Territories and has a topography that consists of occasional knolls, heath/tundra, bedrock outcrops, and numerous lakes, including Kennady Lake where kimberlite pipes are mined (JDS Energy & Mining Inc. 2018). Meadowbank mine is located in Nunavut and has a topography that is scattered with large boulder fields, eskers and is flat immediately near the mine site (Bilodeau et al. 2018). Upland species like the Horned Lark prefer to nest in upland habitats that are mostly free of vegetation, old beaches, hilltops, ridges, and gravel (Drury 1961), potentially making the Meadowbank mine site more of an attractive nesting site than the lakes near the Gahcho Kué mine. However, differences in patterns at individual mines, especially when non-significant, should be interpreted with caution.

3.34 Difference in species effect size

Most species impacted by mines had at least twice the density closer to mines (<10 km) than farther away (>25 km). For example, the Rock Ptarmigan had densities that were six times greater within 10 km of mines than at 25 km away from the mine (approximately 12 birds/km^2 versus approximately 2 birds/km^2). These densities near the mines may in fact be atypical; a study by Bart et al. (2011) found Rock Ptarmigan in the Yukon Territory had a density of 1.32 birds/km^2 in a dry habitat. For the Pectoral Sandpiper, I found that densities were two times greater near the mine than farther away, with an average density of around 2 birds/km^2 within the first 10 km of the nearest mine. While densities are higher near mines, they are still low in comparison to other parts of the species' range. For example, greater densities were observed in the Teshekpuk Lake Special Area of Alaska, where Andres et al. (2012a) recorded an average density of 15.11 birds/km^2. And although Pectoral Sandpipers are common in Alaska, they are rare to absent on Baffin Island, Prince Charles Island, and Air Force Island in Nunavut (Bart and Johnston 2012), so when interpreting patterns in density across large spatial scales, as is done in this study, it is important to consider species' ranges.

3.35 Other covariates

Aside from the main predictor variable (mine distance), I included latitude, distance to coast, and habitat as covariates in my models. Of the eight species that were significantly impacted by mine proximity at all five mines, models for five species also included a significant effect of latitude. Distance to coast and the proportion of lowland habitat were less commonly found to be significant predictors of density; distance to coast influenced densities for Rock Ptarmigan and the upland species group, while habitat type was an important predictor for Lapland Longspur and Pectoral Sandpiper.

The effect of latitude was included as a predictor because each species has its own unique breeding range that may encompass the geographic area of where the mine is located. For species influenced by latitude, there was no clear trend, with some species having greater densities at southern latitudes (Horned Lark, Lapland Longspur, Rock Ptarmigan), and others at northern latitudes (Long-tailed Jaeger); a result you might expect given different geographical ranges of the species that I studied. Some species, like the Savannah Sparrow, had multiple peak densities at various latitudes. The full suite of biogeographic factors governing species' ranges are beyond the scope of this study, however, species nesting at higher latitudes could benefit from reduced nest predation risk (McKinnon et al. 2010), greater insect abundance with longer daylight hours for feeding (Schekkerman et al. 2003), and a reduced risk of parasites (Laird 1961). But these benefits come at the cost of increased migration distance to reach higher latitude breeding areas.

The proportion of lowland habitat within a plot was an important predictor for both Pectoral Sandpiper and Lapland Longspur, with both species showing greater densities in wetland habitats than uplands. Similarly, Brown et al. (2007) found that the Pectoral Sandpiper had significantly greater densities in habitats that were moist and wet than riparian and upland areas. Lapland Longspur also occurred at greater nesting densities in habitat that was wet compared to dry uplands (Liebezeit et al. 2011). Nesting in wet and lowland habitats may be beneficial for ground-nesting species such as these, as they may use the wetland habitat as a possible deterrent to predators, like the Arctic fox that must take complex travel routes to reach nests while avoiding water in these wet habitats (Lecomte et al. 2008). Additionally, wetlands may provide more abundant arthropods for prey for both adults and chicks, as many of the preferred prey items have an aquatic larval stage.

The distance to the coast was the third predictor variable that was included in my models but not a significant predictor for most of the eight species impacted by mines (except Rock Ptarmigan and upland habitat species group). While this result is counter to “conventional wisdom”, it is consistent with several other reports based on large-scale surveys. For example, on Prince Charles Island, Nunavut, Morrison (1997) found that American Golden-Plover (*Pluvialis dominica*) preferred nesting habitats farther inland, in drier upland habitat, and showed no significant relationship between abundance and distance to the coast. Similarly, a study in the Alaskan Arctic Coastal Plain determined that the type of habitat near coastlines and elevation had greater impacts on breeding bird densities, than the distance to coastline per se (Saalfeld et al. 2013b). By controlling for latitude, habitat, and coast distance, the true effects of mine proximity on bird species densities could be seen.

3.36 Adequacy of PRISM surveys

PRISM surveys have been ongoing for approximately 25 years (1994 – 2019) to estimate Arctic breeding bird densities, and surveys have been carried out across the entire Canadian Arctic. Because of this large study area, the density of plots in any one area is low, and surveys are carried out across a number of years. Despite that mining companies participated in the surveys to increase sample size near mines, the samples are still modest and we extended the area under consideration out to 100 km to capture a larger sample of plots.

At each mine location, plots were surveyed only once, but surveys may have been performed over several years. Because bird populations may have been changing (Andres et al. 2012b) during the period over which surveys were carried out, interannual variation and population trends may become a source of variation between mine sites.

The modest sample of plots within 100 km of mines also limits power to determine spatial patterns and threshold points where mines stop impacting bird densities. I decided, based on the frequency of PRISM surveys, to use a distance of 100 km from the mine to assess effects, but the scale may have been too coarse to accurately assess the true effects on bird density. Had the sample size been greater within 25 km of mines, for example, this may have offered a better scale of spatial resolution to understand the effects. Several studies (Van der Zande et al. 1980, Reijnen et al. 1995, Canaday and Rivadeneyra 2001, Liebezeit et al. 2009) have found impacts such as noise or increased predation can occur up to 5 km away from the mine footprint. However, in these data, there were insufficient PRISM surveys to use a finer grain of analysis.

3.4 Conclusion

Mining activity is increasing in the Canadian Arctic, and these activities can alter the quality and quantity of habitat through the removal of vegetation, changes in landscape attributes, and alteration of natural patterns of water drainage (Coulton et al. 2013). The results shown here indicated that the effects of mine infrastructure on the densities of individual bird species varied, but that increases in density nearer to mines were more common than decreases. For both upland and lowland species, the greatest changes in species densities occurred within 25 km of mines. The responses that I documented for upland and lowland species groups were primarily driven by the most abundant species.

Although I hypothesized that densities of birds near mines would be reduced, owing to disturbance from noise, dust, subsidized predators, altered hydrology, and various other factors suggested elsewhere in the literature, I found the opposite pattern. A greater number of individuals closer to mines implies that these factors are not universally negative or positive in their influence and do not consistently affect species with a wide range of life histories, from waterfowl to passerines. Many species were excluded from the study because they were not sufficiently abundant near mines for analysis, and their rarity or absence may be a form of mine avoidance not previously identified. Current monitoring of bird populations around mining operations, like PRISM and other wildlife monitoring protocols, should continue so that future avian management decisions can be made in relation to future mining changes. This monitoring, if it includes more detailed observations of nest success could then establish whether the attraction of birds to mines could potentially result in ecological traps (Male 2004).

CHAPTER 4: General Discussion

Mining activities in the Arctic can influence tundra-breeding birds through a wide variety of mechanisms, both direct and indirect. Since the Canadian Arctic is so large (2553 x 10^8 ha)(Walker et al. 2005) and the amount of infrastructure due to mining so small (on the order of 14,508 ha, or < 0.001% of the Canadian Arctic), the effects of habitat fragmentation and loss may not be as important to tundra-breeding birds as I expected at the start of this project. The effects of mining can extend well beyond the physical footprint of the mine, through variables such as noise and road dust (Male and Nol 2005), greatly extending the zone of influence. However, even still, the area represents a small fraction of the Arctic, and abundant undisturbed habitat appears to remain available to birds.

Moreover, some of the presumed adverse effects have been shown to have variable impacts on birds. For example, noise at the Ekati Diamond Mine has little effect on breeding Lapland Longspurs (*Calcarius lapponicus*) while other mining impacts, such as road dust, have pronounced impacts on roadside vegetation and habitat suitability for breeding shorebirds (Male and Nol 2005). As reviewed in Chapter 2, proximity to mining infrastructure can have a negative impact on the nest success of tundra-breeding birds, through subsidization of predator populations (Liebezeit et al. 2009). In contrast, in this study, I found little evidence for reduced densities of breeding birds near mines (Chapter 3), a compelling overall measure of the impact of mine-related disturbance on birds. However, mines may differ widely in their potential impacts, and species differed in their responses. To understand the true extent of mining activities' impacts on tundra-breeding birds, additional targeted research would be beneficial.

Regardless of the magnitude of impacts of mines on birds, regulations prohibit the destruction of nests, and the harming of adult birds. Research such as this, to understand the impacts, can allow for more effective management by focusing energy on the most pressing environmental concerns. An understanding of the extent and mechanisms of impacts can also help to guide the reclamation activities that take place once mines inevitably reach the end of their profitability, and close.

Restoration of the land to its natural state is difficult (Shigley et al. 2016), and studies of current responses to varying levels of habitat disturbance could help to inform land reclamation efforts. At the Diavik mine, for example, reclamation plans take into account the restoration of the original shoreline of the Lac De Gras area where an open-pit currently exists (Shigley et al. 2016). All facilities and buildings will be removed and dismantled and kimberlite waste will be placed in a containment area (Shigley et al. 2016). The waste piles from mining operations will be shaped to match the surrounding landscape, ensuring the slope of any hills is stable, so as not to endanger wildlife or people (Shigley et al. 2016). The overall reclamation results must have a neutral effect in that the terrain is neither harder nor easier for escaping caribou to pass through while being hunted, and that revegetation of the area neither attracts nor deters migrating animals (Shigley et al. 2016), which would extend to avian species. Though mines may have difficulty restoring wetlands to a fully functional ecosystem, my results suggest some flexibility in birds' use of degraded habitats near mines, suggesting that they may also be tolerant of restored habitats.

4.0 Mine Proximity

For species groups, and most individual bird species, I demonstrated that proximity to mines did not have a predominantly negative influence on density. Most species or groups were more abundant near mines. Additionally, the effects on lowland species as a group seemed to be greater than for upland species. Each species and grouping varied in the severity of the effects of mining, but most shared a similar pattern of an initial decline in density before rebounding to some level.

Earlier snowmelt near mines is a leading hypothesis to explain this unexpected pattern of higher bird densities near mines. Studies have found that mines have earlier snowmelt, from road dust and altered accumulation of snow, and this earlier snowmelt could attract birds during the early season when territories are established. The earlier timing of snowmelt, along with other abiotic factors, also lead to an altered arthropod abundance and diversity near mines, and this too could lead to elevated bird densities near infrastructure (Auerbach et al. 1997, Haskell 2000, Ste-Marie et al. 2018). Mines also alter hydrology, draining and flooding areas as needed (Gill et al. 2014), potentially providing suitable habitat for various species of tundra-breeding birds.

An important caveat to the findings discussed in this thesis is that an increase in breeding bird densities does not necessarily mean that habitats are suitable (Van Horne 1983). Birds could use cues, such as snowmelt, to settle in areas near mines and then suffer increased predation from elevated predator populations. This phenomenon, where birds use misleading cues and demonstrate a preference for habitats that lead to reduced fitness, is known as an ecological trap (Male 2004) and is most common in disturbed environments or situations where natural predator-prey relationships are altered. Follow-up studies should prioritize examining the impacts of proximity to mines on reproductive success.

4.1 Conclusions

Arctic ecosystems are sensitive to change and are experiencing rapid human-induced ecological change from increased global temperatures, altering vegetation cover, plant biomass, the length of the growing season, snow depth and timing of snowmelt, and innumerable other factors (Williams et al. 2000, Stow et al. 2004). Resource development, including mining, can add an additional layer of changes experienced by Arctic environments. Many Arctic breeding bird populations are declining, and shorebirds, in particular. Shorebirds are the most species-rich avifauna in many tundra habitats (Lindström and Agrell 1999) and several studies have found Arctic-breeding shorebird populations to be in a state of decline (Bart et al. 2007, Andres et al. 2012b, North American Bird Conservation Initiative Canada 2019, Smith et al. 2020). These declining trends underscore the need to fill in knowledge gaps regarding population responses to all forms of human-induced environmental changes, including through resource development.

Mining in the Arctic is becoming more common as the demand for resources increases, providing an opportunity to test how northern mining activities and shorebird taxa may respond in the future if resource development continues to expand in the Arctic. I found that the effects of mining activities on the densities of breeding birds were mixed. Proximity to mines seemed to have pronounced negative effects for only a limited number of tundra-breeding species, and far more species had elevated abundance near mines. However, each species varied in their response, and the mechanisms underlying the positive and negative responses could be clarified through additional research.

The Arctic is often represented as a safe haven for breeding birds, but anthropogenic climate change and expanding resource development have led to widespread increases in human disturbance in otherwise remote environments. Breeding bird populations in the Arctic would therefore benefit from additional research and continued monitoring, to determine what breeding ground influences may be contributing to the observed declines in their populations.

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Appendix

Table S3.1. Complete list of all mines and advanced exploration projects above treeline in Northwest Territories and Nunavut, Canada as of December 2019 (n = 27; from Natural Resources Canada 2018a).

Project Name	Location (Territory)	Commodities
Aber	Northwest Territories	Diamonds
Amaruq	Nunavut	Gold
Anialik (CO81)	Nunavut	Diamonds, Copper, Zinc
Anialik (CO31)	Nunavut	Zinc, Copper
Anialik (CO30)	Nunavut	Zinc, Copper
Angilak	Nunavut	Uranium
Back River	Nunavut	Gold
Coronation Gulf Area (Hammer Project)	Nunavut	Diamonds
Darnley Bay Project	Northwest Territories	Nickel, Copper, Platinum Group Metals (PGM), Diamonds
Diavik Mine	Northwest Territories	Diamonds
Ekati Mine	Northwest Territories	Diamonds
Eldorado South	Northwest Territories	Uranium
Gahcho Kué Mine	Northwest Territories	Diamonds
Hackett River	Nunavut	Gold, Silver

Hope Bay Mine	Nunavut	Gold
Jericho	Nunavut	Diamonds
Lupin Mine	Nunavut	Gold
Marry River Mine	Nunavut	Iron
Meadowbank Mine	Nunavut	Gold
Meliadine Mine	Nunavut	Gold
Nanisivik	Nunavut	Zinc, Lead, Silver
Nunavik	Quebec	Nickel
North Thelon (parcel BL-21)	Nunavut	Uranium
Raglan	Quebec	Nickel
Silvertip	Nunavut	Silver, Zinc
Snap Lake Mine	Northwest Territories	Diamonds
Ulu	Nunavut	Gold

Table S3.2. Total number of individuals seen for all bird species observed (n = 90) within 100 km of mines in the Canadian Arctic, during Arctic PRISM surveys, sorted by the number of individuals observed.

Common Name	**Scientific Name**	**Total Seen**
Lapland Longspur	*Calcarius lapponicus*	4193
Savannah Sparrow	*Passerculus sandwichensis*	1124
Snow Goose	*Chen caerulescens*	837
Canada/Cackling Goose	*Branta canadensis/hutchinsii*	747
Horned Lark	*Eremophila alpestris*	665
Greater White-fronted Goose	*Anser albifrons*	546
Red Phalarope	*Phalaropus fulicarius*	491
Rock Ptarmigan	*Lagopus muta*	461
Semipalmated Sandpiper	*Calidris pusilla*	436
Common Redpoll	*Acanthis flammea*	360
King Eider	*Somateria spectabilis*	353
Glaucous Gull	*Larus hyperboreus*	315
Northern Pintail	*Anas acuta*	289
Pectoral Sandpiper	*Calidris melanotos*	287
Long-tailed Jaeger	*Stercorarius longicaudus*	266
Sandhill Crane	*Grus canadensis*	247
Red-necked Phalarope	*Phalaropus lobatus*	238

Long-tailed Duck	*Clangula hyemalis*	236
White-rumped Sandpiper	*Calidris fuscicollis*	223
Sabine's Gull	*Xema sabini*	187
Ruddy Turnstone	*Arenaria interpres*	170
Arctic Tern	*Sterna paradisaea*	163
Ross's Goose	*Chen rossii*	159
American Pipit	*Anthus rubescens*	156
White-crowned Sparrow	*Zonotrichia leucophrys*	156
American Golden-Plover	*Pluvialis dominica*	147
Dunlin	*Calidris alpina*	128
American Tree Sparrow	*Spizelloides arborea*	112
Pacific Loon	*Gavia pacifica*	106
Common Raven	*Corvus corax*	106
Parasitic Jaeger	*Stercorarius parasiticus*	98
Red-throated Loon	*Gavia stellata*	94
Willow Ptarmigan	*Lagopus lagopus*	91
Whimbrel	*Numenius phaeopus*	89
Brant	*Branta bernicla*	89
Wilson's Snipe	*Gallinago delicata*	78
Snow Bunting	*Plectrophenax nivalis*	68
Herring Gull	*Larus argentatus*	66
Least Sandpiper	*Calidris minutilla*	64

Sanderling	*Calidris alba*	63
Stilt Sandpiper	*Calidris himantopus*	61
Pomarine Jaeger	*Stercorarius pomarinus*	59
Black-bellied Plover	*Pluvialis squatarola*	55
Buff-breasted Sandpiper	*Tryngites subruficollis*	53
Rough-legged Hawk	*Buteo lagopus*	50
Yellow Warbler	*Setophaga petechia*	47
Semipalmated Plover	*Charadrius semipalmatus*	46
Northern Shoveler	*Anas clypeata*	46
American Green-winged Teal	*Anas crecca*	46
Greater Scaup	*Aythya marila*	45
Baird's Sandpiper	*Calidris bairdii*	42
White-winged Scoter	*Melanitta fusca*	41
Purple Sandpiper	*Calidris maritima*	34
Hoary Redpoll	*Acanthis hornemanni*	34
Tundra Swan	*Cygnus columbianus*	34
Snowy Owl	*Bubo scandiacus*	30
Red Knot	*Calidris canutus*	27
Smith's Longspur	*Calcarius pictus*	26
Hudsonian Godwit	*Limosa haemastica*	22
Thayer's Gull	*Larus thayeri*	21

Peregrine Falcon	*Falco peregrinus*	21
Short-eared Owl	*Asio flammeus*	17
Lesser Scaup	*Aythya affinis*	16
Northern Harrier	*Circus cyaneus*	15
Fox Sparrow	*Passerella iliaca*	15
Common Loon	*Gavia immer*	13
American Wigeon	*Anas americana*	12
Red-breasted Merganser	*Mergus serrator*	10
Northern Waterthrush	*Parkesia noveboracensis*	9
Long-billed Dowitcher	*Limnodromus scolopaceus*	9
Common Eider	*Somateria mollissima*	9
Mallard	*Anas platyrhynchos*	8
Gadwall	*Anas strepera*	8
Cliff Swallow	*Petrochelidon pyrrhonota*	8
Bald Eagle	*Haliaeetus leucocephalus*	6
Yellow-billed Loon	*Gavia adamsii*	5
Lincoln’s Sparrow	*Melospiza lincolnii*	4
Gyrfalcon	*Falco rusticolus*	4
Common Merganser	*Mergus merganser*	4
Merlin	*Falco columbarius*	3
Lesser Yellowlegs	*Tringa flavipes*	3
American Robin	*Turdus migratorius*	3

Mew Gull	*Larus canus*	2
Greater Yellowlegs	*Tringa melanoleuca*	2
Golden Eagle	*Aquila chrysaetos*	2
Black Scoter	*Melanitta nigra*	2
Wilson's Warbler	*Cardellina pusilla*	1
Say's Phoebe	*Sayornis saya*	1
Gray-cheeked Thrush	*Catharus minimus*	1
Cassin's Sparrow	*Peucaea cassinii*	1

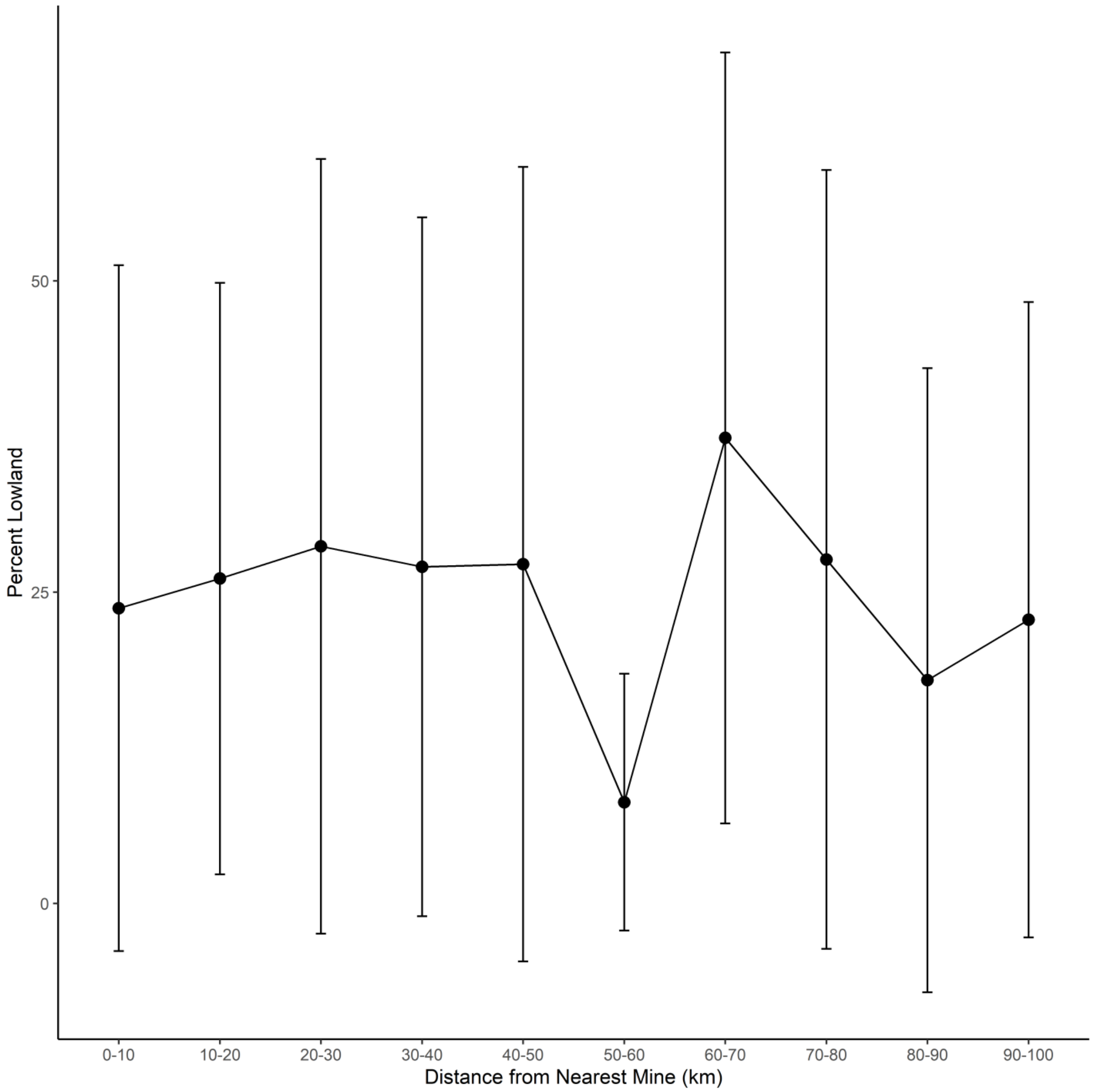

Figure S3.1. Average percentage of lowland habitat within plots (±SD), versus distance from the nearest mine, for plots within 100km from mines, grouped into bins of 10km. Variability among plots was high, and there was no clear trend in habitat characteristics with respect to distance from mines.

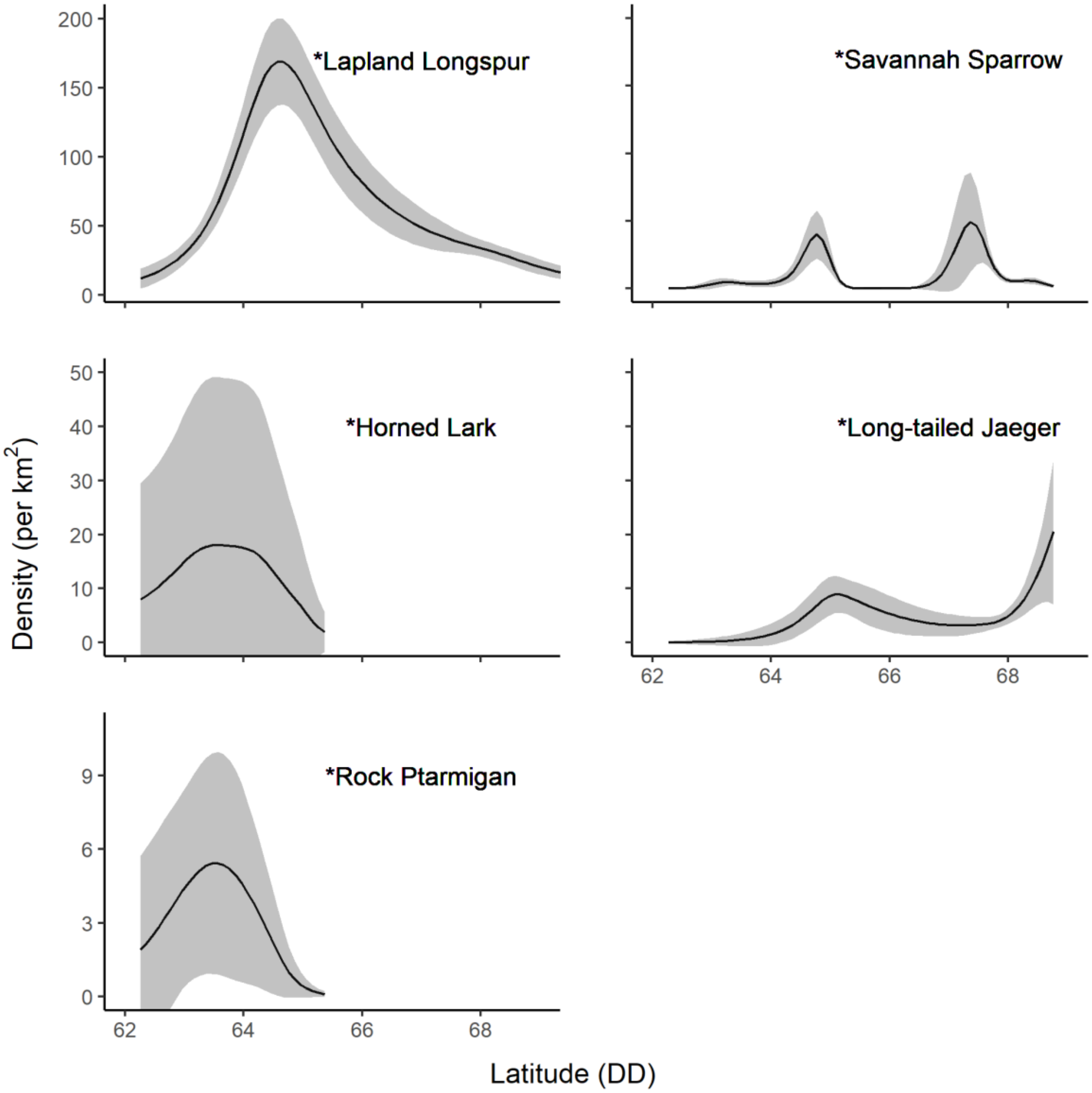

Figure S3.2. Changes in species densities (birds per km^2) with increasing latitude (decimal degrees). Species included are ones identified from the top model across all mines that included latitude as a final model variable. Black line indicates predicted fit, and the grey shading is the standard error. The '*' indicates species that were significantly influenced by latitude in the top model.

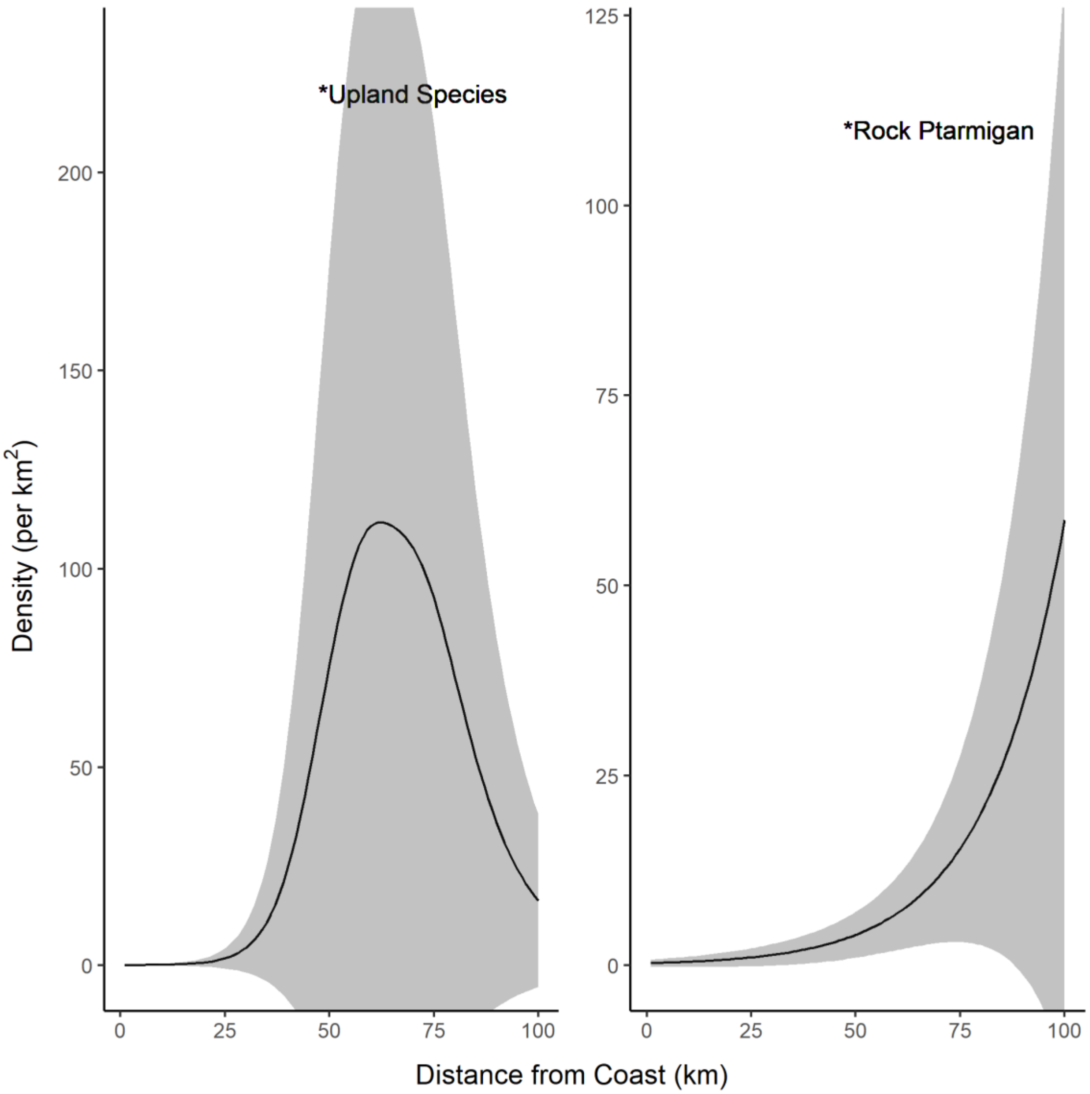

Figure S3.3. Changes in species densities (birds per km^2) for the only two species that were impacted by distance to coast (km) when assessed across all five mines. Black line indicates predicted fit and the grey shading is the standard error. The '*' indicates species that were significantly influenced by coast distance in the top model.

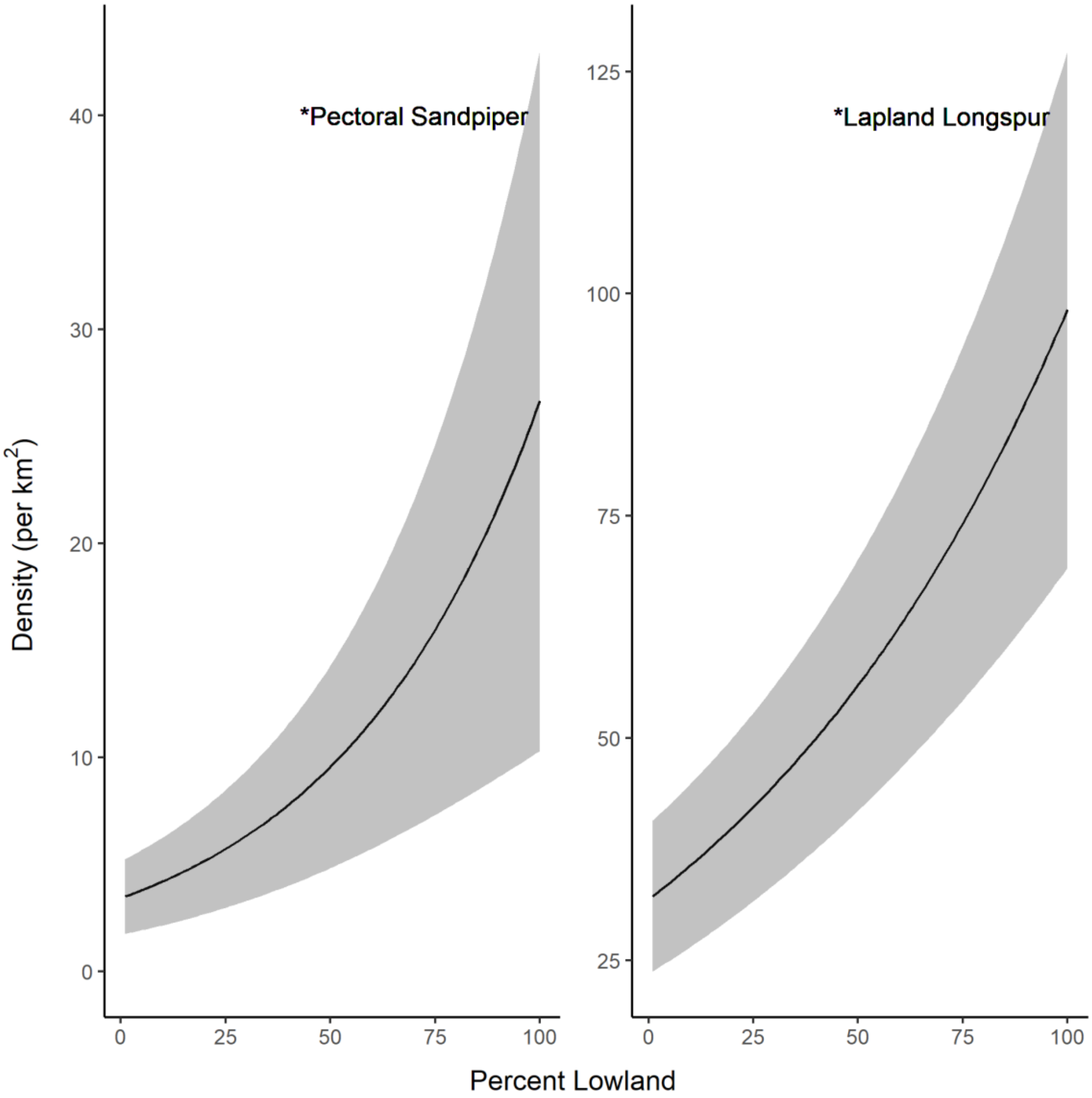

Figure S3.4. Changes in species densities (birds per km^2) across multiple mines with increasing percent lowland coverage within plots. Species represent those that had lowland proportion as part of the top model. The black line indicates predicted fit and the grey shading is the standard error. The '*' indicates species that were significantly influenced by lowland proportion.

Table S3.3. Final GAM model selection results for bird densities found in 27 plots at Gahcho Kué mine. Approximate significance (*p*-value) and estimated degree of freedom (edf) are displayed for each covariate. The '-' symbol indicates variables that were removed from the model after performing a backwards stepwise selection process. I removed variables in the model selection process that had a linear term (edf = 1), where the confidence intervals overlap 0 along the observed range of values. An edf of 1 means that adding the term does not substantially improve the model fit unless paired with a significant p-value. Break point distance (km) represents the distance at which mines no longer influence bird densities (see text for methods).

	American Golden-Plover		**Canada/Cackling Goose**		**Horned Lark**		**Lapland Longspur**	
Family	Poisson		Negative Binomial		Poisson		Poisson	
Adjusted r^2	0.00		0.00		0.44		0.50	
Deviance explained (%)	0.0		0.0		47.2		69.3	
REML score	25.23		49.58		33.89		103.03	
Break Point Distance (km)	-		-		22.34		12.88	
Spline Covariate	**edf**	***p*-value**	**edf**	***p*-value**	**edf**	***p*-value**	**edf**	***p*-value**
Mine Distance	-	-	-	-	2.44	0.21	8.35	< 0.001
Covariate	**Est. ± Std. Error**	***p*-value**	**Est. ± Std. Error**	***p*-value**	**Est. ± Std. Error**	***p*-value**	**Est. ± Std. Error**	***p*-value**
Coast Distance	-	-	-	-	- 0.09 ± 0.04	< 0.05	-	-
Lowland Proportion	-	-	-	-	0.03 ± 0.01	< 0.005	0.02 ± 0.00	< 0.001

Table S3.3. Continued.

	Long-tailed Duck		**Savannah Sparrow**		**Snow Bunting**		**Upland Species**	
Family	Poisson		Poisson		Poisson		Poisson	
Adjusted r^2	0.25		0.76		0.98		0.57	
Deviance explained (%)	45.8		71.9		93.7		56.7	
REML score	32.46		35.66		36.10		69.02	
Break Point Distance (km)	27.88		4.88		3.65		3.65	
	edf	***p*-value**	**edf**	***p*-value**	**edf**	***p*-value**	**edf**	***p*-value**
Spline Covariate								
Mine Distance	4.55	< 0.005	5.35	< 0.001	6.67	< 0.001	3.88	< 0.001
	Est. ± Std. Error	***p*-value**	**Est. ± Std. Error**	***p*-value**	**Est. ± Std. Error**	***p*-value**	**Est. ± Std. Error**	***p*-value**
Covariate								
Coast Distance	-	-	-	-	-	-	-	-
Lowland Proportion	-	-	-	-	- 0.08 ± 0.03	< 0.05	0.01 ± 0.01	< 0.05

Table S3.3. Continued.

	Lowland Species	
Family	Negative Binomial	
Adjusted r^2	0.08	
Deviance explained (%)	14.6	
REML score	92.47	
Break Point Distance (km)	-	
Spline Covariate	**edf**	***p*-value**
Mine Distance	-	-
Covariate	**Est. ± Std. Error**	***p*-value**
Coast Distance	-	-
Lowland Proportion	0.02 ± 0.01	< 0.05

Table S3.4. Final GAM model selection results for bird densities found in 145 plots at Meadowbank mine. Approximate significance (*p*-value) and estimated degree of freedom (edf) are displayed for each covariate. The '-' symbol indicates variables that were removed from the model after performing a backwards stepwise selection process. I removed variables in the model selection process that had a linear term (edf = 1), where the confidence intervals overlap 0 along the observed range of values. An edf of 1 means that adding the term does not substantially improve the model fit unless paired with a significant p-value. Break point distance (km) represents the distance at which mines no longer influence bird densities (see text for methods).

	American Golden-Plover		**American Pipit**		**American Tree Sparrow**		**Canada/Cackling Goose**	
Family	Poisson		Poisson		Negative Binomial		Negative Binomial	
Adjusted r^2	0.15		0.05		0.16		0.09	
Deviance explained (%)	25.0		10.4		53.2		4.6	
REML score	160.19		182.49		115.70		389.56	
Break Point Distance (km)	49.13		9.85		9.79		9.85	
Spline Covariate	**edf**	***p*-value**	**edf**	***p*-value**	**edf**	***p*-value**	**edf**	***p*-value**
Mine Distance	4.11	< 0.001	3.06	< 0.05	2.28	0.75	2.39	0.16
Covariate	**Est. ± Std. Error**	***p*-value**	**Est. ± Std. Error**	***p*-value**	**Est. ± Std. Error**	***p*-value**	**Est. ± Std. Error**	***p*-value**
Coast Distance	-	-	0.03 ± 0.01	< 0.05	-	-	-	-
Lowland Proportion	- 0.03 ± 0.01	< 0.005	-	-	- 0.04 ± 0.02	< 0.05	-	-

Table S3.4. Continued.

	Common Raven		**Common Redpoll**		**Greater White-fronted Goose**		**Herring Gull**	
Family	Poisson		Negative Binomial		Negative Binomial		Poisson	
Adjusted r^2	0.14		0.15		0.16		0.08	
Deviance explained (%)	21.5		33.2		27.6		13.0	
REML score	121.95		265.26		219.53		139.54	
Break Point Distance (km)	9.85		2.09		39.93		-	
	edf	***p*-value**	**edf**	***p*-value**	**edf**	***p*-value**	**edf**	***p*-value**
Spline Covariate								
Mine Distance	2.37	< 0.001	4.82	< 0.001	1.00	< 0.001	-	-
	Est. ± Std. Error	***p*-value**	**Est. ± Std. Error**	***p*-value**	**Est. ± Std. Error**	***p*-value**	**Est. ± Std. Error**	***p*-value**
Covariate								
Coast Distance	-	-	0.04 ± 0.01	< 0.05	-	-	0.06 ± 0.01	< 0.001
Lowland Proportion	-	-	-	-	-	-	-	-

Table S3.4. Continued.

	Horned Lark		**Lapland Longspur**		**Long-tailed Duck**		**Long-tailed Jaeger**	
Family	Negative Binomial		Negative Binomial		Negative Binomial		Negative Binomial	
Adjusted r^2	0.13		0.14		0.01		0.05	
Deviance explained (%)	21.6		20.0		0.00		27.3	
REML score	348.77		575.50		161.05		138.92	
Break Point Distance (km)	9.85		9.85		-		9.79	
	edf	***p*-value**	**edf**	***p*-value**	**edf**	***p*-value**	**edf**	***p*-value**
Spline Covariate								
Mine Distance	3.41	< 0.001	3.16	< 0.001	-	-	2.12	< 0.005
	Est. ± Std. Error	***p*-value**	**Est. ± Std. Error**	***p*-value**	**Est. ± Std. Error**	***p*-value**	**Est. ± Std. Error**	***p*-value**
Covariate								
Coast Distance	0.04 ± 0.01	< 0.001	0.02 ± 0.01	< 0.001	-	-	-	-
Lowland Proportion	-	-	-	-	-	-	- 0.03 ± 0.01	< 0.05

Table S3.4. Continued.

	Northern Pintail		**Pectoral Sandpiper**		**Rock Ptarmigan**		**Sandhill Crane**	
Family	Negative Binomial		Negative Binomial		Negative Binomial		Negative Binomial	
Adjusted r^2	0.20		0.09		0.19		0.07	
Deviance explained (%)	47.9		23.6		36.4		10.8	
REML score	165.08		137.82		298.58		199.07	
Break Point Distance (km)	9.79		39.93		9.85		9.85	
Spline Covariate	**edf**	***p*-value**	**edf**	***p*-value**	**edf**	***p*-value**	**edf**	***p*-value**
Mine Distance	3.09	< 0.001	1.72	< 0.001	5.48	< 0.001	2.63	< 0.01
Covariate	**Est. ± Std. Error**	***p*-value**	**Est. ± Std. Error**	***p*-value**	**Est. ± Std. Error**	***p*-value**	**Est. ± Std. Error**	***p*-value**
Coast Distance	-	-	-	-	0.03 ± 0.01	< 0.05	-	-
Lowland Proportion	- 0.04 ± 0.01	< 0.01	-	-	-	-	-	-

Table S3.4. Continued.

	Savannah Sparrow		**Semipalmated Sandpiper**		**White-crowned Sparrow**		**Upland Species**	
Family	Negative Binomial		Negative Binomial		Negative Binomial		Negative Binomial	
Adjusted r^2	0.16		0.02		0.12		0.22	
Deviance explained (%)	38.3		3.03		35.3		30.3	
REML score	341.19		264.90		117.22		482.16	
Break Point Distance (km)	9.85		-		9.85		9.85	
	edf	***p*-value**	**edf**	***p*-value**	**edf**	***p*-value**	**edf**	***p*-value**
Spline Covariate								
Mine Distance	5.12	< 0.001	-	-	1.00	< 0.001	3.84	< 0.001
	Est. ± Std. Error	***p*-value**	**Est. ± Std. Error**	***p*-value**	**Est. ± Std. Error**	***p*-value**	**Est. ± Std. Error**	***p*-value**
Covariate								
Coast Distance	0.87 ± 0.03	< 0.05	0.02 ± 0.01	< 0.05	0.25 ± 0.09	< 0.005	0.04 ± 0.01	< 0.001
Lowland Proportion	-	-	-	-	- 0.03 ± 0.02	< 0.05	-	-

Table S3.4. Continued.

	Lowland Species	
Family	Negative Binomial	
Adjusted r^2	0.37	
Deviance explained (%)	43.4	
REML score	640.18	
Break Point Distance (km)	9.85	
	edf	***p*-value**
Spline Covariate		
Mine Distance	3.77	< 0.001
	Est. ± Std. Error	***p*-value**
Covariate		
Coast Distance	0.03 ± 0.00	< 0.001
Lowland Proportion	-	-

Table S3.5. Final GAM model selection results for bird densities found in 108 plots at Mary River mine. Approximate significance (*p*-value) and estimated degree of freedom (edf) are displayed for each covariate. The '-' symbol indicates variables that were removed from the model after performing a backwards stepwise selection process. I removed variables in the model selection process that had a linear term (edf = 1), where the confidence intervals overlap 0 along the observed range of values. An edf of 1 means that adding the term does not substantially improve the model fit unless paired with a significant p-value. Break point distance (km) represents the distance at which mines no longer influence bird densities (see text for methods).

	Lapland Longspur		**Long-tailed Duck**		**White-rumped Sandpiper**		**Lowland Species**	
Family	Negative Binomial		Negative Binomial		Negative Binomial		Negative Binomial	
Adjusted r^2	- 0.05		0.01		0.02		0.00	
Deviance explained (%)	7.7		7.4		12.2		0.00	
REML score	119.38		100.83		124.88		223.27	
Break Point Distance (km)	-		23.55		-		-	
Spline Covariate	**edf**	***p*-value**	**edf**	***p*-value**	**edf**	***p*-value**	**edf**	***p*-value**
Mine Distance	-	-	1.00	< 0.05	-	-	-	-
Covariate	**Est. ± Std. Error**	***p*-value**	**Est. ± Std. Error**	***p*-value**	**Est. ± Std. Error**	***p*-value**	**Est. ± Std. Error**	***p*-value**
Coast Distance	-	-	-	-	-	-	-	-
Lowland Proportion	0.03 ± 0.01	< 0.05	-	-	- 0.05 ± 0.02	< 0.005	-	-

Table S3.6. Final GAM model selection results for bird densities found in 179 plots at Hope Bay mine. Approximate significance (*p*-value) and estimated degree of freedom (edf) are displayed for each covariate. The '-' symbol indicates variables that were removed from the model after performing a backwards stepwise selection process. I removed variables in the model selection process that had a linear term (edf = 1), where the confidence intervals overlap 0 along the observed range of values. An edf of 1 means that adding the term does not substantially improve the model fit unless paired with a significant p-value. Break point distance (km) represents the distance at which mines no longer influence bird densities (see text for methods).

	Canada/Cackling Goose		**Glaucous Gull**		**King Eider**		**Lapland Longspur**	
Family	Negative Binomial		Negative Binomial		Negative Binomial		Negative Binomial	
Adjusted r^2	0.02		0.00		0.01		0.07	
Deviance explained (%)	8.8		0.00		6.82		6.2	
REML score	204.73		187.81		172.04		469.52	
Break Point Distance (km)	-		-		41.28		-	
	edf	***p*-value**	**edf**	***p*-value**	**edf**	***p*-value**	**edf**	***p*-value**
Spline Covariate								
Mine Distance	-	-	-	-	1.00	< 0.01	-	-
	Est. ± Std. Error	***p*-value**	**Est. ± Std. Error**	***p*-value**	**Est. ± Std. Error**	***p*-value**	**Est. ± Std. Error**	***p*-value**
Covariate								
Coast Distance	- 0.16 ± 0.05	< 0.001	-	-	-	-	-	-
Lowland Proportion	-	-	-	-	-	-	0.01 ± 0.00	< 0.005

Table S3.6. Continued.

	Long-tailed Jaeger		**Pectoral Sandpiper**		**Red Phalarope**		**Savannah Sparrow**	
Family	Poisson		Negative Binomial		Negative Binomial		Negative Binomial	
Adjusted r^2	0.00		0.11		0.08		0.04	
Deviance explained (%)	8.1		25.1		48.5		8.8	
REML score	210.26		173.32		216.90		268.34	
Break Point Distance (km)	18.00		0.45		2.56		44.87	
	edf	***p*-value**	**edf**	***p*-value**	**edf**	***p*-value**	**edf**	***p*-value**
Spline Covariate								
Mine Distance	4.31	< 0.005	3.13	0.17	4.44	< 0.001	2.71	0.06
	Est. ± Std. Error	***p*-value**	**Est. ± Std. Error**	***p*-value**	**Est. ± Std. Error**	***p*-value**	**Est. ± Std. Error**	***p*-value**
Covariate								
Coast Distance	- 0.04 ± 0.02	< 0.05	-	-	0.25 ± 0.07	< 0.001	0.11 ± 0.04	< 0.005
Lowland Proportion	-	-	0.03 ± 0.01	< 0.001	0.02 ± 0.01	< 0.01	-	-

Table S3.6. Continued.

	Snow Goose		**White-rumped Sandpiper**		**Lowland Species**	
Family	Negative Binomial		Negative Binomial		Negative Binomial	
Adjusted r^2	0.05		0.03		0.07	
Deviance explained (%)	8.8		14.7		10.9	
REML score	258.09		202.16		719.47	
Break Point Distance (km)	39.99		10.45		12.57	
Spline Covariate	**edf**	***p*-value**	**edf**	***p*-value**	**edf**	***p*-value**
Mine Distance	1.00	< 0.005	3.47	< 0.05	2.47	< 0.005
Covariate	**Est. ± Std. Error**	***p*-value**	**Est. ± Std. Error**	***p*-value**	**Est. ± Std. Error**	***p*-value**
Coast Distance	-	-	0.12 ± 0.05	< 0.05	-	-
Lowland Proportion	-	-	-	-	0.01 ± 0.00	< 0.005

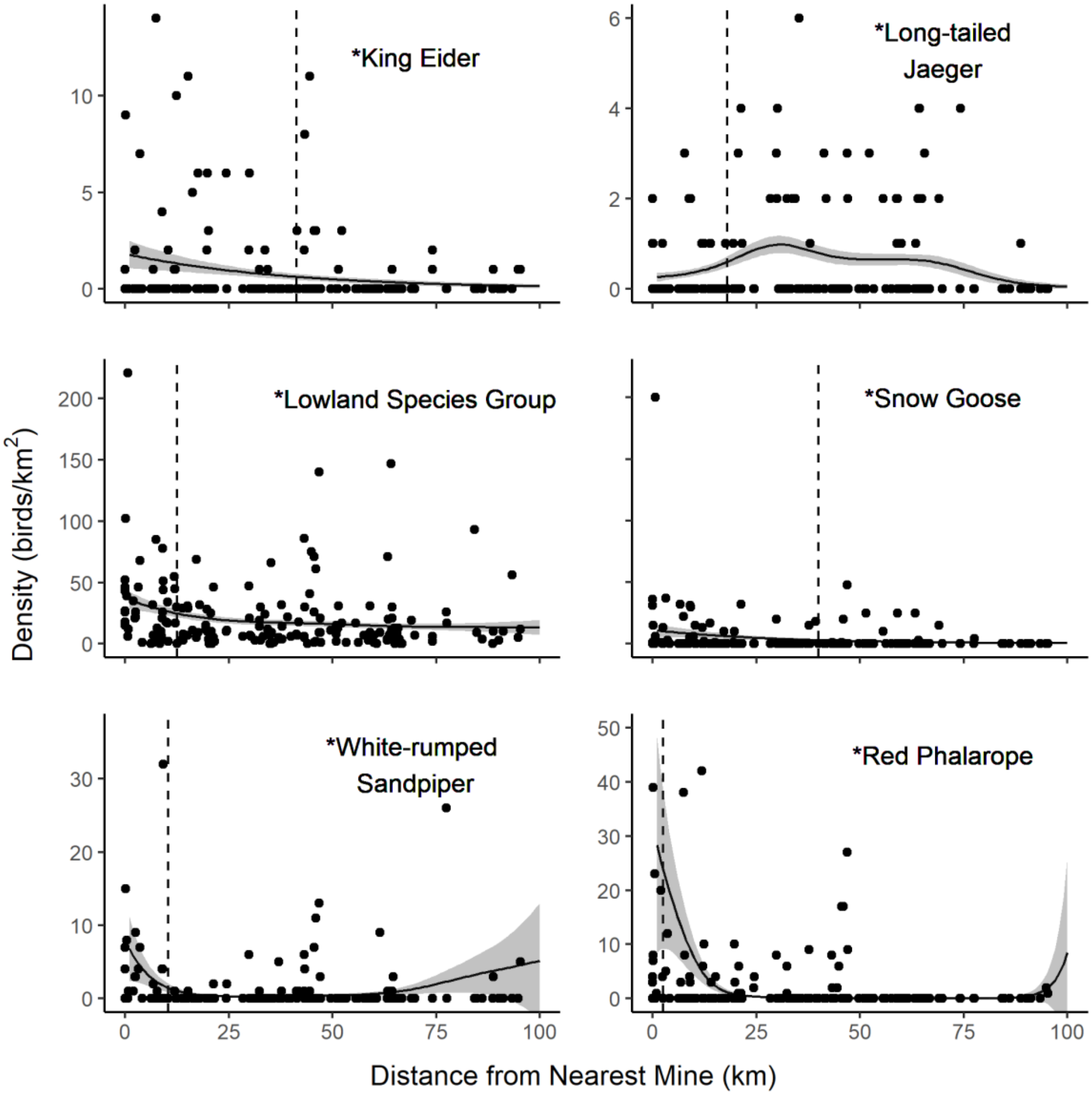

Figure S3.5. Changes in species' densities (birds per km^2) with increasing mine distance (km) from Hope Bay mine. Black line indicates predicted fit, and the grey shading is the standard error. Species that were significantly impacted by mine proximity are shown. Dashed line indicates breakpoint for mine influence on bird species as indicated by the breakpoint analysis. Species with an '*' exhibited a significant relationship between density and distance to the nearest mine ($p < 0.05$). Dots are raw bird counts.

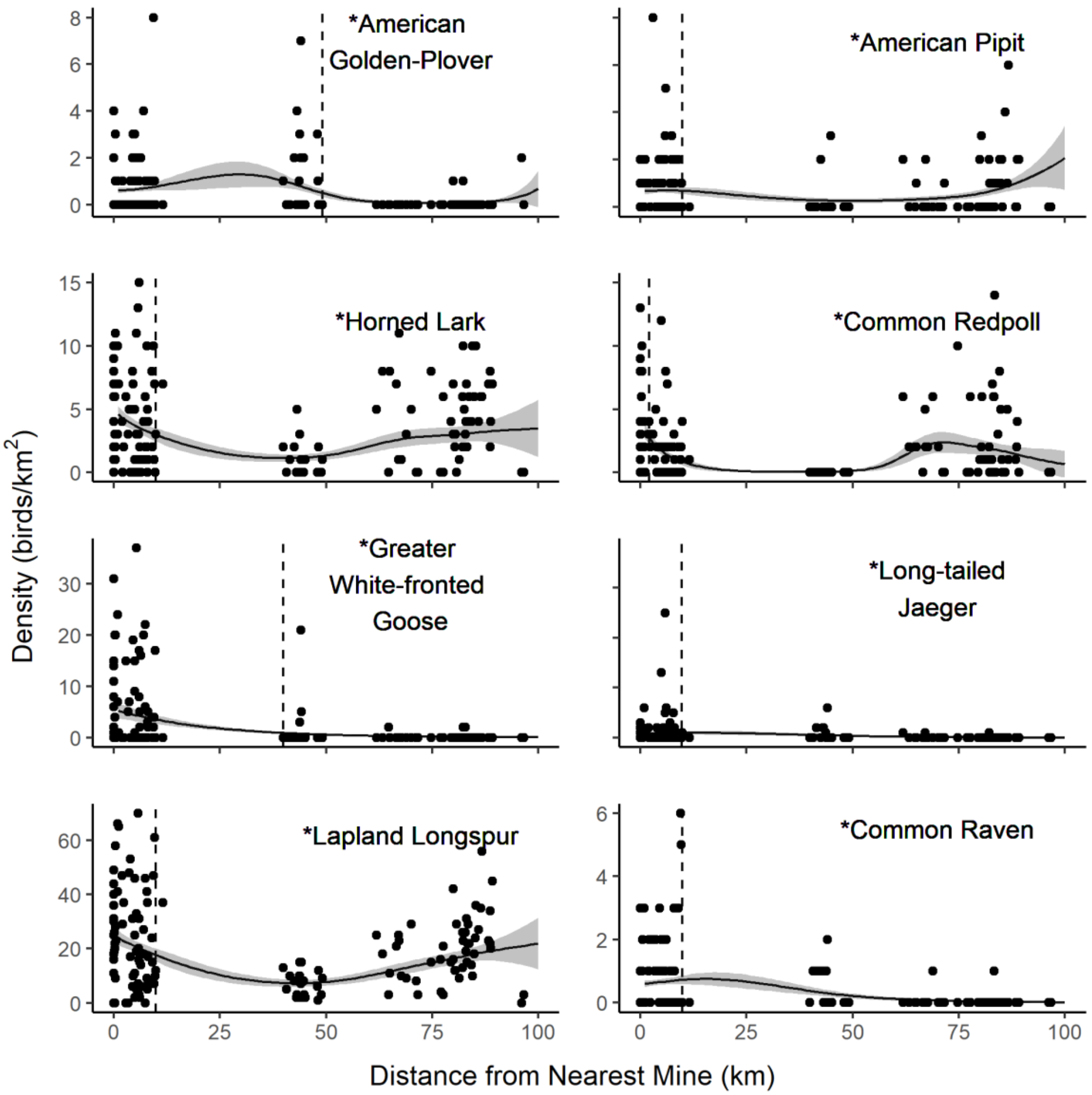

Figure S3.6. Changes in species densities (birds per km^2) with increasing mine distance (km) from Meadowbank mine. Black line indicates predicted fit, and the grey shading is the standard error. Species that were significantly impacted by mine proximity are shown. Dashed line indicates breakpoint for mine influence on bird species as indicated by the breakpoint analysis. Species with an '*' indicate species that are significantly influenced by mine ($p < 0.05$). Dots are raw bird counts.

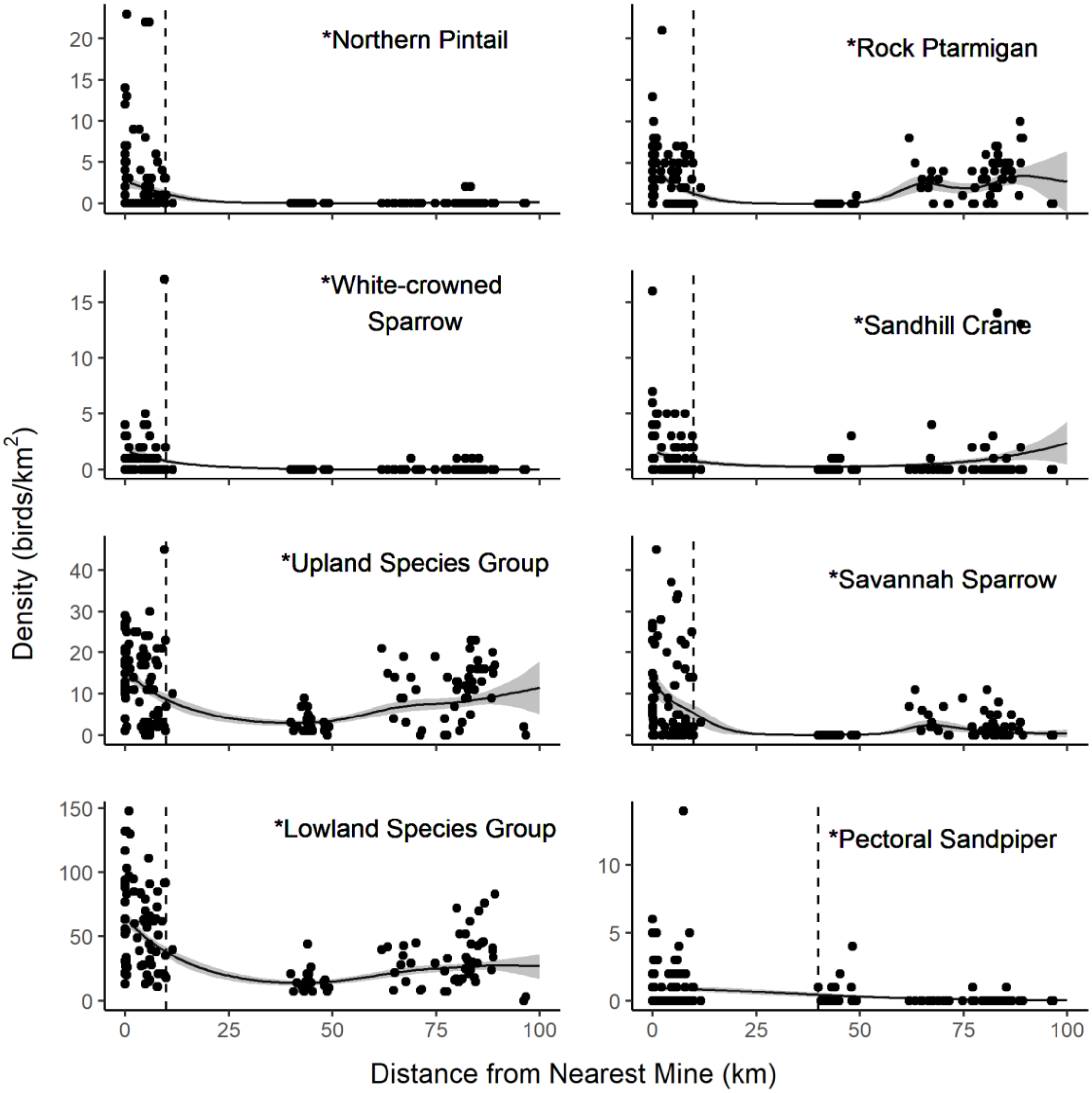

Figure S3.6. Continued.

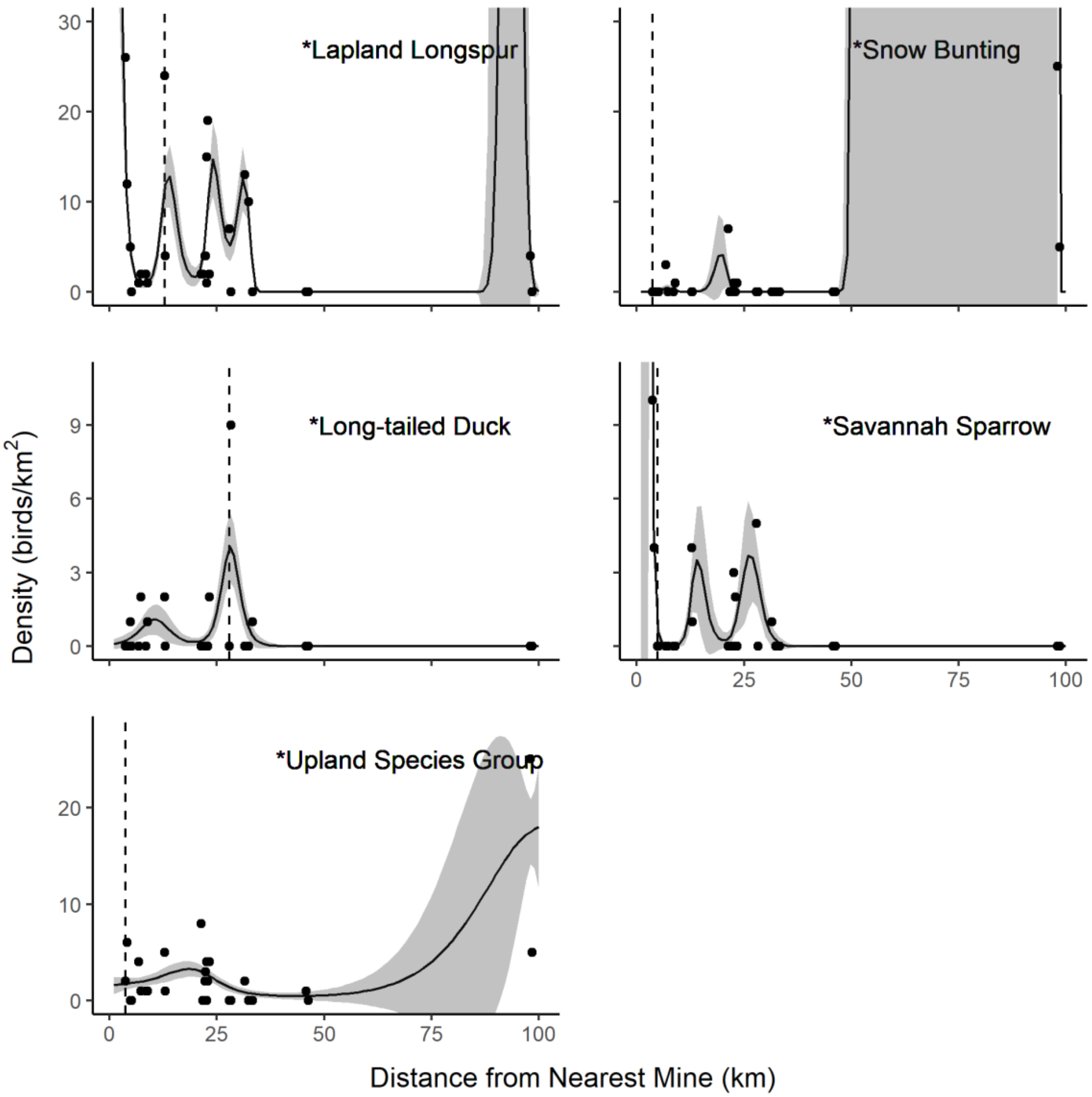

Figure S3.7. Changes in species densities (birds per km^2) with increasing mine distance (km) from Gahcho Kué mine. Black line indicates predicted fit, and the grey shading is the standard error. Species that were significantly impacted by mine proximity are shown. Dashed line indicates breakpoint for mine influence on bird species as indicated by the breakpoint analysis. Species with an '*' indicate species that are significantly influenced by mine ($p < 0.05$). Dots are raw bird counts.

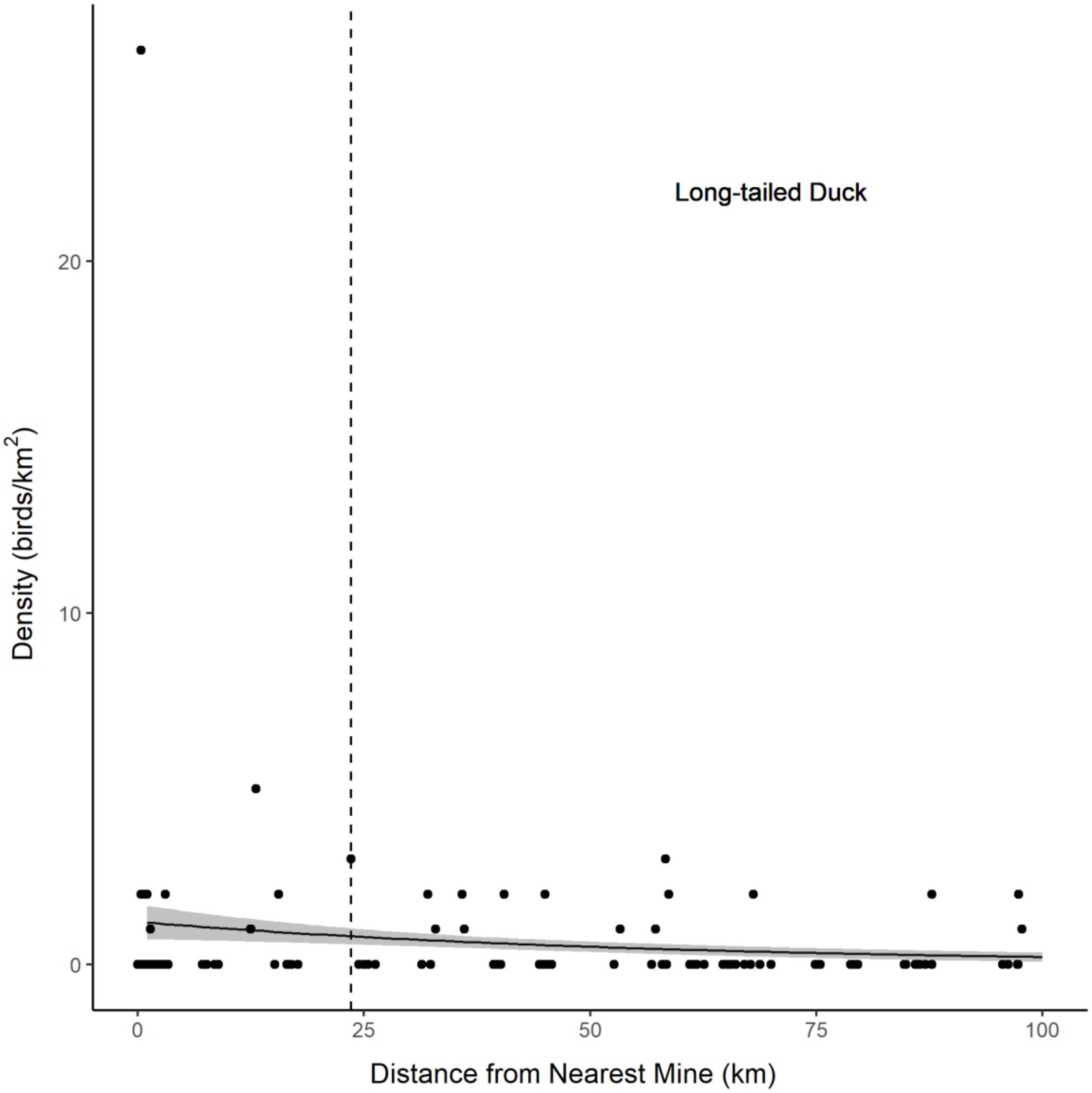

Figure S3.8. Changes in species densities (birds per km^2) with increasing mine distance (km) from Mary River mine. Black line indicates predicted fit, and the grey shading is the standard error. Species that were significantly impacted by mine proximity are shown. Dashed line indicates breakpoint for mine influence on bird species as indicated by the breakpoint analysis. Species with an '*' indicate species that are significantly influenced by mine ($p < 0.05$). Dots are raw bird counts.