

**EXAMINING IMPACTS OF CLIMATE CHANGE AND HABITAT
LOSS ON THE DISTRIBUTION OF LONG-BILLED CURLEWS, A
SPECIES AT RISK IN CANADA**

by

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B.Sc., University of Alberta, 2020

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE IN ENVIRONMENTAL SCIENCE

Thompson Rivers University

Kamloops, British Columbia

August 2024

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ABSTRACT

Climate change and habitat loss are severely impacting wildlife species at a global scale, shifting their distributions and driving population declines. Grassland birds are experiencing the steepest decline of any bird group due to ongoing degradation and loss of grassland habitats. These losses are largely driven by agricultural and urban expansion to feed and house a growing human population. The Long-billed Curlew (*Numenius americanus*) is an at-risk grassland species that breeds in grassland and agricultural habitats throughout western North America. I investigated recent changes in the distribution of Long-billed Curlews within British Columbia and across their widespread North American breeding range. Additionally, I worked to identify the potential drivers behind observed distribution shifts.

British Columbia contains the northern periphery of the Long-billed Curlew's breeding range and as such, this region makes an excellent case study to understand how habitat loss and climate change are impacting leading-edge grassland bird populations. Using targeted survey data from British Columbia spanning two decades (2000-2002 and 2022-2023), I asked how changes in land-use and climate have affected Long-billed Curlew distribution and range limits in the province. Furthermore, I developed occupancy models to understand how environmental variables such as habitat type predict Long-billed Curlew occupancy and detection within the province. Taking a range-wide approach, I then used community science data (eBird) to investigate recent (2010-2022) changes to Long-billed Curlew distributions across North America as a whole and within each of the Bird Conservation Regions (groupings of similar bird communities and habitats) within which it occurs.

Long-billed Curlews showed an apparent ~177 km northern range expansion in British Columbia between the early 2000s and 2023. Additionally, we uncovered a 228 km northern shift of their population centroid across North America between 2010 and 2022. These findings are consistent with the unprecedented loss and degradation of grassland habitats in southern British Columbia, along with agricultural expansion and a warming climate in northern British Columbia. Eastern and western population centroid shifts were detected in several Bird Conservation Regions, which may be related to local patterns of grassland loss and/or population declines. In British Columbia, curlews were detected at

higher frequencies in agricultural lands when compared to grassland and wetland habitats, likely due to the increased availability of agricultural lands in their newly expanded range. Consistent with the above, curlew occupancy was positively associated with agricultural habitats and northern latitudes, and negatively associated with grassland habitats.

My results indicate that climate and habitat changes may interact to drive changes in population distributions. On a range-wide scale, it appears that climate change is causing a northward expansion of Long-billed Curlew distribution, but on a local scale, habitat losses and gains may play a stronger role in driving regional distributional changes. My research demonstrates the importance of examining both the regional and range-wide changes to informing effective management of Long-billed Curlews. Future management should focus on restoring grassland habitats through prescribed burns, as well as identifying important grassland regions for Long-billed Curlews and implementing protections for these key areas.

Keywords: agriculture, occupancy, climate change, habitat loss, Long-billed Curlew, distribution, *Numenius americanus*, conservation, grassland birds

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ACKNOWLEDGEMENTS

I acknowledge with deep respect and gratitude that this research was conducted on the traditional, ancestral, and unceded territories of the Indigenous Peoples of British Columbia including the Okanagan, Ktunaxa, Nlaka'pamux, Dakelh, Secwepemc, and many other nations who have stewarded the land for countless generations. I am grateful to have the opportunity to learn from and collaborate with Indigenous communities and I recognize the privilege and responsibility that comes with conducting research on Indigenous lands.

I would first and foremost like to thank Matt Reudink and Ann McKellar for their continuous support, guidance, and expertise throughout this journey. Your words of encouragement, patience, and kindness did not go unnoticed, and I consider myself incredibly lucky to have had you both as my supervisors. Thank you for believing in my abilities and pushing me to succeed. To Matt, thank you for fostering an inclusive and fun work environment where I was challenged to push the boundaries of my knowledge. I would also like to extend my gratitude to Scott Flemming for providing me with incredible opportunities throughout my thesis and guiding me as I navigated my career options. Your support and mentorship has been invaluable and I cannot thank you enough.

To all that helped me navigate my statistical analyses and GIS work, thank you, I would not have been able to complete my thesis without you. Specifically, I would like to thank Matt Coghill and Steffi LaZerte. To Matt Coghill, I am so grateful for all the hours you dedicated of your own time to help me with the many GIS issues that I encountered. I never thought I would say this but with your help, I have come to truly enjoy spatial work. To Steffi LaZerte, I am so appreciative of all the work you put into my Chapter 3 analysis, this chapter only came together so nicely because of your hard work.

Thank you to the BEAC lab, especially Sydney and Jacqueline, you all made my MSc journey so fun. Shae, I am forever grateful for getting to tackle this journey with you. You are an incredible friend, and I truly would not have been able to do this without you. Thank you for being my biggest supporter, the best birding (and banding!) partner, and always

giving me encouragement or a kick when I needed it. Thank you to my field technician, Aranza Molina, for dealing with incredibly early mornings, long days, and the embarrassingly bright orange rental car.

To my partner Lane and family, I am so appreciative for your ongoing support throughout. Lane, I would not have been able to achieve my goals or complete this journey without your words of encouragement and patience, thank you.

I extend my gratitude to Birds Canada, especially David Bradley and Remi Torrenta, Environment and Climate Change Canada, and Shaun Freeman with Skeetchestn Natural Resources Corporation for generously providing the essential data to make my thesis possible. Your contributions and dedication to conservation are admirable and I am thankful for the collaborative nature of this project.

Lastly, thank you to my funders. Scott Flemming and Tanya Luszcz both provided funding through Environment and Climate Change Canada that made my fieldwork possible. My research was additionally funded by a British Columbia Graduate Scholarship, the Thompson Rivers University Natural Science Fellowship Award, the Thompson Rivers University Sustainability Grant, an American Ornithological Society Travel Award, and a Western Hemisphere Shorebird Group Travel Award. All field data was collected under Thompson Rivers University Animal Use Protocol #103408.



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CHAPTER 1: INTRODUCTION

OVERVIEW OF THREATS TO BIRD POPULATIONS

Habitat loss, degradation, and fragmentation driven by exponential increases in human populations and consumption present critical and ongoing threats to animal populations (Kennedy et al., 2019; Simkin et al., 2021; Hogue and Breon, 2022). From agricultural and urban expansion to feed and house growing human populations (Tilman et al., 2001; Kennedy et al., 2019; Simkin et al., 2021) to resource extraction such as logging and the oil and gas industry (Laurance, 2010; Scanes, 2018), these losses of natural habitat have immensely impacted species worldwide (Rosenberg et al., 2019; Jaureguiberry et al., 2022). As a result, bird populations have faced population declines, local extinction events, and changes in their distributions (e.g. Mortelliti et al., 2010; Rosenberg et al., 2019). It is estimated that we have lost nearly 3 billion birds since 1970, marking a 29% decline in bird abundance (Rosenberg et al., 2019). Additionally, around 57% of North American (Rosenberg et al., 2019) and 37% of Canadian (Environment and Climate Change Canada, 2019) bird populations are exhibiting population declines.

Nearly 40% of the earth's terrestrial surface has been converted to agricultural lands (BirdLife International, 2022) and as such, agriculture has been identified as the primary extinction threat to grassland birds globally (Green et al., 2005). Grasslands throughout North America have lost over 60% of their historical land cover (Comer et al., 2018), impacting the many bird species that rely on grassland habitats (Green et al., 2005; Stanton et al., 2018; Rosenberg et al., 2019). Much of this loss has been attributed to agricultural and urban expansions, invasive species, and woody encroachment from fire suppression practices (Vickery et al., 2000; Stanton et al., 2018). To no surprise, grassland birds are facing unprecedented declines. It is estimated that around 74% of grassland birds in North America (Rosenberg et al., 2019) and 57% in Canada (Environment and Climate Change Canada, 2019) are declining, with the most likely driver of this decline being habitat loss. These losses in Canada equate to a net loss of nearly 300 million grassland birds since the 1970s (Environment and Climate Change Canada, 2019).

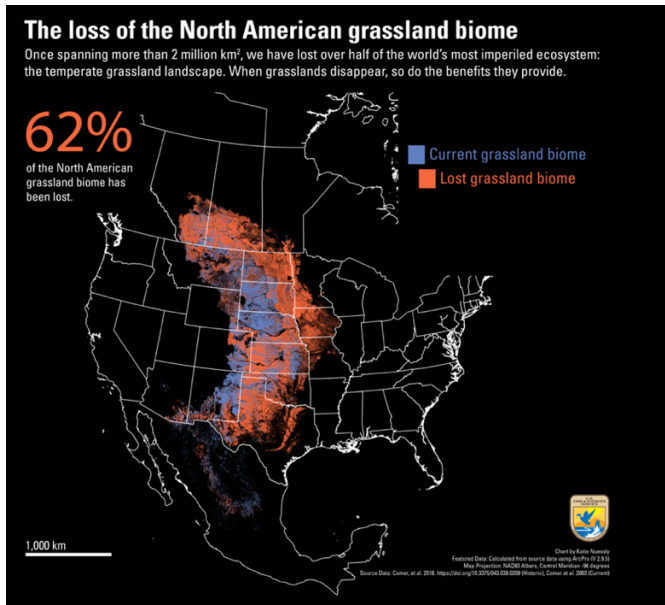


Figure 1.1. Grassland loss in North America (Image credit: Katie Nuessly, U.S. Fish and Wildlife Service).

Some grassland birds will nest in agricultural fields; however, agricultural lands can act as population sinks, marked by reductions in breeding success (Stanton et al., 2018) driven by pesticide use (Boatman et al., 2004; Stanton et al., 2018), high predation rates (Stanton et al., 2018), or direct mortality from farming equipment and livestock (Vickery et al., 2000; Perlut et al., 2008; Shustack et al., 2010). Pesticide use has direct and indirect impacts on birds including mortality from exposure and reduced food availability (Boatman et al., 2004; Stanton et al., 2018). Habitat fragmentation caused by agricultural conversion reduces cover, exacerbating the impacts of climate change (Jarzyna et al., 2016), and increases predation rates due to the installation of fencing and power poles, as well as clearings such as roads (Environment Canada, 2012). These human-made structures provide perches for raptors and corridors for mammalian predators (Environment Canada, 2012).

In addition to habitat loss, animal populations are facing a newer threat – climate change (Cristine and Kerr, 2011). Globally, temperatures have increased by 1°C because of human activities (IPCC, 2022). Climate change causes a wide range of problems for wildlife including habitat loss and degradation (Mantyka-Pringle et al., 2012), changes to plant and insect phenology (Schwartz et al., 2006), distribution shifts (Parmesan and Yohe, 2003; Hitch and Leberg, 2007; La Sorte and Jetz, 2010; Nixon et al., 2016; Rushing et al., 2020), and

ultimately results in losses of biodiversity (Urban, 2015). Many wildlife populations, including birds, have been responding to increasing temperatures by moving to higher elevations or latitudes (Parmesan and Yohe, 2003; Hitch and Leberg, 2007; La Sorte and Jetz, 2010; Nixon et al., 2016; Rushing et al., 2020), escaping the warming environment for more climatically suitable habitats (Skagen and Adam, 2012; Jarzyna et al., 2016; Nixon et al., 2016).

LONG-BILLED CURLEWS – ECOLOGY, STATUS, AND POPULATION ESTIMATES

Long-billed Curlews (*Numenius americanus*) are a buff-colored shorebird species that stands out due to their large size and distinctive long and downturned bill (COSEWIC, 2002; Fellows and Jones, 2009). Females are larger than males and have a considerably longer bill (COSEWIC, 2002; Fellows and Jones, 2009). Curlews were aptly named after the male's courtship call which sounds like "curlew curlew" while in flight (COSEWIC, 2002). Curlews nest in large and flat regions of short-grass or mid-grass prairies (COSEWIC, 2002). They have a wintering range along the west coast of the United States, into Mexico, and along the southwestern coast of Florida (Dugger and Dugger, 2020; COSEWIC, 2002). Their breeding range extends from western Canada into the mid-western and western United States (COSEWIC, 2002). Curlews historically had a range that extended much further east; however, they have been extirpated from much of this region, including Manitoba, Michigan, Minnesota, Wisconsin, Illinois, and Iowa as a result of habitat loss and overexploitation (COSEWIC, 2002; Fellows and Jones, 2009). In Canada, curlews are federally listed as a species of "Special Concern" on Schedule 1 of the Species at Risk Act (Fellows and Jones, 2009; Environment Canada, 2012) and as a species of concern in multiple U.S. states (Fellows and Jones, 2009). Additionally, curlews were recently upgraded from "Special Concern" to "Threatened" by the Committee on the Status of Endangered Wildlife in Canada due to intensifying population declines (COSEWIC, 2024). Overall, the North American Breeding Bird Survey (BBS) showed a significant negative trend (1980-2000) across the continent, leading to their initial listing in year 2005 (COSEWIC, 2002; Fellows and Jones, 2009). More recently, in Canada, BBS data show a significant negative short-term trend (-

4.4%/year [-7.27, -1.62], 2011-2021) and a non-significant negative long-term trend (-0.982%/year [-1.97, 0.0573], 1970-2021) (Smith and Edwards, 2020).



Figure 1.2. Left: Long-billed Curlew (Image credit: Kelsey Freitag). Right: Long-billed Curlew distribution map (Image credit: Dugger and Dugger, 2020). Orange represents the breeding range and blue represents the non-breeding range.

Breeding Bird Survey (BBS) data have been used to model curlew population trends; however, the results are likely inaccurate due to low precision (Fellows and Jones, 2009; Environment Canada, 2012). This is likely attributed to the time of year surveys are conducted and a lack of survey routes in suitable curlew habitats (Fellows and Jones, 2009). Surveys are often completed in June when curlews are nesting, which results in low detectability of the species due to their discrete nature during this period (Fellows and Jones, 2009). Researchers have attempted to estimate the breeding abundance of curlews, but these population estimates are highly varied and likely inaccurate as well (Environment Canada, 2012). The North American breeding population estimate ranges between 120,000 and 550,000 with 90% confidence intervals (Environment Canada, 2012). In Canada, estimates have ranged from 5,000 to 50,000 (Environment Canada, 2012). The high variability in these estimates demonstrates how difficult it is to get true estimates which ultimately impact the ability to effectively manage the species (Environment Canada, 2012).

To fill the knowledge gap of Long-billed Curlew distribution and abundance in British Columbia, Birds Canada in partnership with Environment and Climate Change

Canada conducted province-wide targeted curlew surveys in the early 2000s (Birds Canada, 2022). These targeted surveys provided in-depth information on curlew occupancy that cannot be obtained from the BBS data. These surveys provided ample survey routes through suitable habitats within the curlew's British Columbia breeding range. Furthermore, these surveys were conducted earlier than the BBS surveys, being completed between mid April and early May, encompassing curlew arrival on the breeding grounds. During this time, curlews are performing courtship displays and are vocal, increasing their detectability.

OVERVIEW OF THREATS TO LONG-BILLED CURLEW POPULATIONS

Some of the threats identified to curlew populations include habitat loss, predation, energy development, trampling by livestock, and pesticide use (COSEWIC, 2002; Fellows and Jones, 2009; Environment Canada, 2012). As a result of these threats, curlews are facing regional population declines and potential shifts in their distributions.

Habitat loss for curlews is primarily resulting from agricultural and urban expansion, invasive species, and woody encroachment due to fire suppression (COSEWIC, 2002; Fellows and Jones, 2009; Environment Canada, 2012). Alberta and Saskatchewan have suffered large losses of native grassland habitats within the curlew's breeding range, with an estimated loss of 57% and 79% of native habitat, respectively (Environment Canada, 2012). While total estimates of grassland loss in British Columbia are unknown, grasslands now represent just 1% of land cover within the province (Iverson, 2004; Environment Canada, 2012). While much of these losses of grasslands are due to agricultural expansion, such as vineyard and orchard development (COSEWIC, 2002; Lea 2008; Fellows and Jones, 2009), urban expansion has been attributed to the greatest loss of grassland habitats in the southern region of British Columbia (Cannings, 1999; COSEWIC, 2002; Lea 2008). Additionally, fire suppression practices have allowed shrubs and forests to encroach into the grasslands both reducing the quality of the habitat and causing direct losses (Cannings, 1999; Fellows and Jones, 2009; Environment Canada, 2012). In British Columbia, encroachment has created shrub-steppe habitats, which are subsequently avoided by curlews (Cannings, 1999; Fellows and Jones, 2009; Environment Canada, 2012). Lastly, invasive plant species such as Leafy Spurge (*Euphorbia esula*) and Knapweeds (*Centaurea sp*) overlap with the curlew's

distribution and have the potential to reduce the quality of habitat for curlews (COSEWIC, 2002; Environment Canada, 2012).

Energy development is a growing threat to curlew populations, especially in the prairie provinces (Fellows and Jones, 2009; Environment Canada, 2012). Oil and gas wells fragment the landscape and the number of well sites is rapidly increasing (Fellows and Jones, 2009; Environment Canada, 2012). Curlews show a preference for large and unfragmented regions of grassland habitats (Cannings, 1999; Environment Canada, 2012), and thus these wells decrease habitat quality and availability for curlews. Renewable energy such as wind energy is also on the rise which will ultimately fragment grassland habitats and increase human disturbances to curlews in these regions (Fellows and Jones, 2009; Environment Canada, 2012).

These threats highlight the severity of land-use changes on curlew populations. Land-use changes are often synonymous with habitat loss, but these changes can also interact with other threats, increasing their severity. As discussed above, energy demand can cause habitat loss, degradation, and fragmentation in the grasslands (Fellows and Jones, 2009; Environment Canada, 2012). However, these developments can also increase the risk of vehicle collisions due to the influx of traffic, introduce invasive species to the area, heighten human disturbances, and cause mortality from rotor blade strikes (Fellows and Jones, 2009; Environment Canada, 2012).

Additionally, land-use changes can interact with predation pressures, increasing predation rates as a result of lost and fragmented habitats (Fellows and Jones, 2009; Environment Canada, 2012). Land-use changes can introduce perches (e.g. power lines and fence posts) for avian predators and corridors (e.g. roads and pathways) for mammalian predators (Environment Canada, 2012). Frequent predators of curlews include coyotes, various hawk species, Great Horned Owls (*Bubo virginianus*), and corvids such as Black-billed Magpies (*Pica hudsonia*) and Common Ravens (*Corvus corax*) (Fellows and Jones, 2009; Environment Canada, 2012). Regardless of these threats, curlew populations are critically understudied across their range.

COMMUNITY SCIENCE DATA

Many bird species have widespread distributions, complicating researchers' ability to monitor populations by traditional local survey methods. As such, there is high value in community science data which can provide large-scale and long-term data (Sullivan et al., 2009; Sullivan et al., 2014). Community science is defined as public participation in scientific data collection or research (Vohland et al., 2021). Employing community science allows researchers to collect data over a large spatial region and increase the quantity of data collected (McCaffrey, 2005; Sullivan et al., 2009). For my thesis, I used two forms of community science – volunteer surveys and eBird data. For Chapter 2, Birds Canada and I engaged the public to assist with Long-billed Curlew surveys across the province. This allowed us to collect large-scale data on the presence and habitat use of Long-billed Curlews. This data collection would not have been possible in the absence of volunteer surveyors. For Chapter 3, I used eBird data which provides annual long-term data that can help answer questions about a species' distribution and abundance over large spatial scales (Sullivan et al., 2009; Sullivan et al., 2014). These data allowed us to effectively examine changes in curlew distribution across their entire North American range between 2010 and 2022. Although there are many benefits to community science data, there are also challenges. Surveys are often located near urban centers or easy to access areas and thus lack remote data (McCaffrey, 2005; Sullivan et al., 2009; Johnston et al., 2019; Johnston et al., 2021). Additionally, observer skill and effort such as time spent, distance traveled, and number of observers can vary greatly which can introduce biases in the data (McCaffrey, 2005; Sullivan et al., 2009). There are, however, standard data management and analysis practices that can help alleviate some of these biases.

THESIS OBJECTIVES

The objective of my thesis is to examine changes to the distribution of Long-billed Curlews in British Columbia and throughout their North American breeding range. In British Columbia, my goal is to highlight important habitat regions and fill a two-decade knowledge gap on the distribution of curlews in the province. To accomplish this, I will examine habitat use, changes in land cover, and changes in distribution, as well as develop occupancy models to identify the best predictors of curlew occupancy and detection probability. In North

America, my goal is to provide information on the overall trend of curlew distribution at a range-wide scale, but also at the eco-region level. To accomplish this, I will examine changes over a 12-year period to the curlew's breeding range boundaries and centroid position in North America, as well as their centroid position in eight Bird Conservation Regions (groupings of similar bird communities and habitats across North America) within which the species occurs.

This thesis is divided into this introductory chapter, two research chapters, and a conclusion chapter. Chapter 2 focuses on the drivers of Long-billed Curlew distribution and occupancy in British Columbia. This chapter utilizes historical and contemporary targeted curlew survey data, as well as land use data across the province. Chapter 3 focuses on exploring distribution trends across the curlew's North American breeding range. This chapter utilizes community science data obtained through eBird. The conclusion chapter, Chapter 4, focuses on management recommendations, suggests directions for future studies, and reflects on the impacts of anthropogenic stressors on at-risk species.

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CHAPTER 2: NORTHERN BREEDING RANGE EXPANSION OF LONG-BILLED CURLEWS IN RESPONSE TO CLIMATE CHANGE AND HABITAT LOSS IN BRITISH COLUMBIA

ABSTRACT

Climate change and habitat loss can have severe consequences for ecological communities, impacting the distribution and abundance of populations. Grassland species have been severely affected by these environmental pressures due to unprecedented loss and fragmentation of natural grassland habitats. Grassland birds are experiencing the most drastic declines of any bird group. The Long-billed Curlew (*Numenius americanus*) is an at-risk grassland bird with a breeding range spanning western North America. Using British Columbia as a case study, we examined how climate pressures and habitat loss may be impacting Long-billed Curlew distributions at the northern periphery of their North American breeding range. As this is a small periphery population, understanding how they respond to these stressors is critical for the future management of many northern-edge populations. We (i) examined Long-billed Curlew distribution using historical and contemporary survey data, (ii) evaluated changes in agricultural, grassland, and urban land cover between these survey periods, (iii) compared Long-billed Curlew habitat use between these survey periods, and (iv), developed occupancy models to evaluate the covariates that best predicted Long-billed Curlew occupancy and detection probability based on contemporary survey data. Our results indicate the northern edge of the Long-billed Curlew's breeding range has apparently shifted ~177 km north, and that curlews were detected more frequently in agricultural lands compared to grassland and wetland habitats. Furthermore, curlew occupancy was positively associated with agricultural habitats and higher latitudes, and negatively associated with grassland habitats. While grassland habitat has been lost in southern British Columbia, northern agricultural areas which were previously uninhabitable, have now become accessible with rapidly warming temperatures, likely driving the northern range expansion. Our results demonstrate how climate change and habitat loss can interact and facilitate changes to population distributions in unexpected ways, highlighting the need for both broad- and fine-scale studies on drivers of range shifts.

INTRODUCTION

Anthropogenic stressors such as habitat loss and climate change can greatly affect the abundance and distribution of ecological communities (Mantyka-Pringle et al., 2012; Jaureguiberry et al., 2022). The impact of human expansion and development on the world's land surfaces is profound, leaving just 5% of Earth's surface (excluding Antarctica) unmodified (Kennedy et al., 2019). Agriculture, one of the primary land uses by humans (Matson et al., 1997), has led to substantial losses of natural habitats, and it is one of the greatest contributors to biodiversity declines globally (Tilman et al., 2001; Maxwell et al., 2016). In Canada alone, nearly 90% of habitat loss is attributed to agriculture, which covers nearly 62 million hectares, or 6.2% of total land cover (Cristine and Kerr, 2011; Statistics Canada, 2021). Habitat loss can be exacerbated by human-induced climate change, a growing threat to biodiversity (Cristine and Kerr, 2011). Global mean temperatures have risen approximately 1°C from human activities (IPCC, 2022) and this change is impacting the distribution of species. For example, species often shift towards higher latitudes or elevations in the face of increasing temperatures (Parmesan and Yohe, 2003; Mac Nally et al., 2009; Chen et al., 2011; Mantyka-Pringle et al., 2012; Mantyka-Pringle et al., 2015). If species are unable to respond to a warming climate by shifting their distributions, they may face population declines or extinction (Urban, 2015). These human-induced changes in habitat and climate have affected all major taxa, and grassland birds appear to be especially vulnerable (Jetz et al., 2007; Dolman and Sutherland, 2008; Mac Nally et al., 2009).

On a global scale, agriculture poses the greatest extinction threat to grassland birds (Green et al., 2005). Roughly 74% of grassland bird species are in decline in North America (Rosenberg et al., 2019), with a growing body of evidence linking these declines to the loss and degradation of native grassland habitats through agricultural conversion and intensification (Askins et al., 2007; Jarzyna et al., 2016; Quinn et al., 2017; Stanton et al., 2018). Agricultural intensification is associated with increased mowing, replacing mixed crops with mono-cultured crops, increased pesticide use and irrigation, and decreased landscape heterogeneity (Matson et al., 1997; Tilman et al., 2001; Askins et al., 2007; Stanton et al., 2018). Grassland birds that nest in agricultural fields and pastures may experience decreased reproductive success and reduced survival from practices associated

with agricultural intensification (Stanton et al., 2018). This includes nest destruction, often by machinery or livestock (Vickery et al., 2000; Perlut et al., 2008; Shustack et al., 2010; Mandema et al., 2013; Beja et al., 2014), increased predation rates resulting from fragmentation (Stanton et al., 2018), and reduced food availability due to pesticide, insecticide, or herbicide use (Boatman et al., 2004; Stanton et al., 2018). High levels of pesticide use in North America have been linked to declines in grassland birds and millions of bird mortalities either through acute impacts of direct toxicity, or indirect impacts from reduced food availability (Boatman et al., 2004; Stanton et al., 2018).

Climate change is also threatening bird communities and altering their distribution (Parmesan and Yohe, 2003; e.g. Hitch and Leberg, 2007; Nixon et al., 2016; Rushing et al., 2020). Increasing temperatures are leading to distributional shifts towards higher elevations and latitudes (Parmesan and Yohe, 2003; Hitch and Leberg, 2007; La Sorte and Jetz, 2010; Nixon et al., 2016; Rushing et al., 2020). In particular, grassland birds may be less resilient to climate change than birds in other habitats due to the diminished buffering capacity of grassland habitats; for example, in the northeastern U.S., grassland birds were more sensitive to increasing temperatures than were forest birds, and this was exacerbated in areas with low grassland cover or that were highly fragmented (Jarzyna et al., 2016).

Long-billed Curlews (*Numenius americanus*) are the largest shorebird in North America and they use grassland and agricultural habitats for nesting (Cannings, 1999; COSEWIC, 2002; Fellows and Jones, 2009). In the winter, curlews inhabit coastal areas such as mudflats and wet inland habitats along the western United States coast and south into Mexico (Stenzel et al., 1976; Stanley and Skagen, 2007; Jones et al., 2008; Dugger and Dugger, 2020). The Breeding Bird Survey (BBS) indicates a non-significant negative long-term trend (1970 - 2021) estimate (-0.98% per year, 95% CI: -1.97 to 0.057) and a significant negative short-term trend (2011 - 2021) estimate (-4.4% per year, 95% CI: -7.27 to -1.62) for curlews in Canada (Smith et al., 2023). Curlews are listed as a species of concern throughout their range in Canada and the United States (Jones et al., 2008). In Canada, they are listed federally as a species of Special Concern under the Species at Risk Act and are Blue-Listed in the provinces of British Columbia and Alberta, meaning they are vulnerable (Cannings, 1999; Jones et al., 2008; Fellows and Jones, 2009). In the United States, curlews are not

designated under the U.S. Endangered Species Act, but they are listed in multiple states under various designations (Jones et al., 2008; Fellows and Jones, 2009). In Mexico, there are no official conservation designations for curlews, however, they are protected under the Migratory Birds Convention Act (Fellows and Jones, 2009). Like other grassland birds, curlews face a wide variety of threats to both their breeding and overwintering range, including habitat degradation and loss from agricultural conversion, urban encroachment, and climate change (Stanley and Skagen, 2007; Jones et al., 2008; Fellows and Jones, 2009; Saalfeld et al., 2010).

Population estimates of curlews in North America are highly variable but suggest total numbers range from 120,000 to 550,000, with approximately 43,000 individuals breeding in Canada (Environment Canada, 2012). In 2005, it was estimated that there were up to 7,436 curlews in British Columbia (Jones et al., 2008; Environment Canada, 2012), making up approximately 2% of the North American population. Curlews reach their northern geographical limit in British Columbia, making this a peripheral, leading-edge population. British Columbia has experienced a 1.9 °C increase in average temperature since the 1950s, and this pattern of warming is stronger in the northern compared to the southern region of the province (Gifford et al., 2022). Furthermore, southern British Columbia has suffered massive losses of native grassland due to urban encroachment and agricultural expansion (COSEWIC, 2002; Lea, 2008). It is estimated that grasslands now represent only 1% of the total land cover in the province (Iverson, 2004). Because of ongoing habitat loss, rising annual temperatures, and the small population of curlews in this leading-edge population, British Columbia makes an excellent case study to understand how anthropogenic stressors are impacting range dynamics and habitat use of curlews. Leading-edge populations may respond to climate change differently from the rest of the population (Cristine and Kerr, 2011). Populations at the leading edge may be able to establish their populations in areas that have been made suitable by a warming climate, providing flexibility in a species' ability to survive environmental change (Fraser, 1999). Therefore, protecting peripheral populations may be critical for the future survival of species (Fraser, 1999), and understanding the impacts of land conversion and climate change on curlews could help guide effective management of the species both in British Columbia and beyond.

Here, we analyzed Long-billed Curlew distribution in relation to changes in land cover over a two-decade period in British Columbia. Specifically, our goals were to (1) compare the species distribution based on historical and contemporary survey data; (2) evaluate changes in land cover between the two survey periods; (3) compare curlew habitat use (i.e., proportion of detections at each land cover type) between the two time periods; and (4) develop occupancy models to evaluate covariates that best predict curlew occupancy and detection probability based on contemporary survey data. Reports from Canning (1999) indicate that curlews have shown adaptability when faced with grassland loss by moving to agricultural fields such as hayfields and pasturelands (hereafter ‘agricultural lands’) for nesting and foraging. As such, we predicted that curlews would be detected at higher frequencies in agricultural habitats and lower frequencies in grassland habitats due to the widespread loss and degradation of grassland habitats across British Columbia. Furthermore, we predicted that there would be a loss of grassland cover in British Columbia over a two-decade period from ongoing agricultural and urban development.

METHODS

eBird Comparison Data

Long-billed Curlew data from 2000 to 2022 were acquired from the community science database, eBird (eBird, 2021). These data include checklists with the species observed, the location, the date and time, and the effort. We filtered the data to include data from British Columbia. We did not further filter our data following eBird best practices (Strimas-Mackey et al., 2023) as these data were used for comparison and to justify the historic survey locations and were not used for any modeling or analysis. In addition, filtering the data would have eliminated observations prior to 2010, which were our primary interest.

Historical Population Surveys

We obtained historical curlew survey data from the British Columbia Ministry of Environment (British Columbia Ministry of Environment, 2006). Multiple years of surveys were conducted in the East Kootenays and Cariboo-Chilcotin regions of British Columbia from 1999 to 2004, and in the Okanagan-Similkameen and Thompson-Nicola regions from 2000 to 2001 (Figure 2.1). Historical survey data were used to understand patterns of habitat

use and range dynamics but were not used for occupancy modeling; thus, we restricted our analysis to a single survey year. This was done to avoid repeating survey locations which would lead to double-counting habitat types during analysis. For the Cariboo-Chilcotin region, we used the 2002 survey data, and for the Okanagan-Similkameen, Thompson-Nicola, and East Kootenay regions, we used the 2000 survey data. While our contemporary surveys included data from the Prince George-Nechako region (see below), there were no surveys conducted in this region during the historical survey period as it was considered beyond the extent of the curlew breeding range.

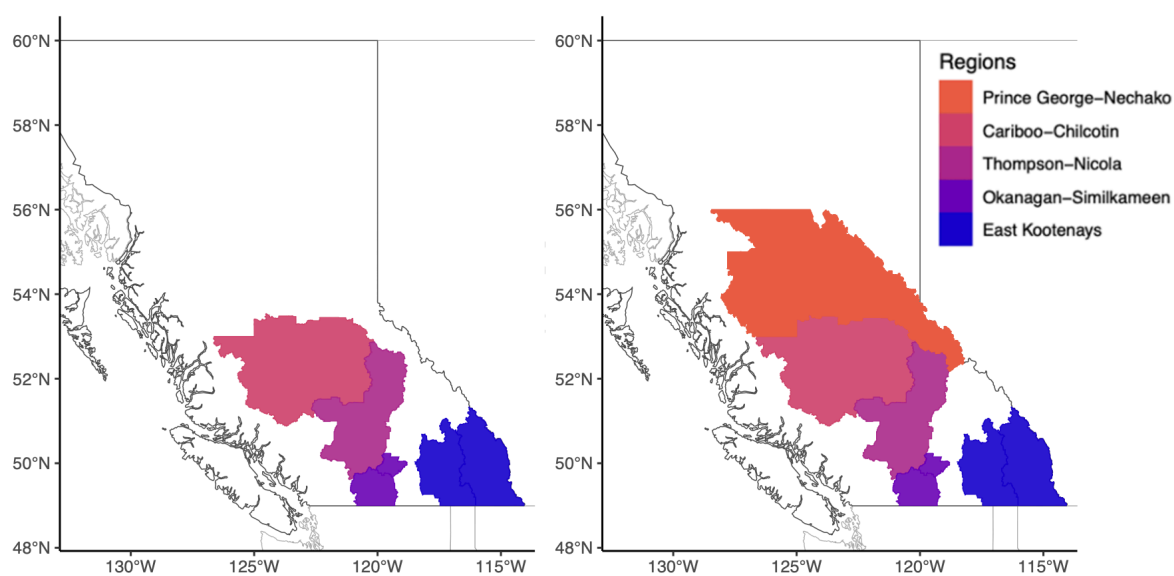


Figure 2.1. Left: map of historic survey regions (2000 and 2002) in British Columbia. Right: map of contemporary survey regions (2022) in British Columbia.

Records from eBird support a lack of Long-billed Curlews in the Prince George-Nechako region in the early 2000s, suggesting that it is unlikely that curlews were established in this northern region at the time these surveys were conducted (Figure 2.2). Additionally, the number of checklists submitted in the Thompson-Nicola and Prince George-Nechako region were similar, indicating it was unlikely to be a difference in effort responsible for the lack of detections in the northern region (Figure 2.2).

Historical surveys from 2000 to 2002 followed methods outlined by Saunders (2001). 32km long sample units were established in regions with variable levels of suitable habitat. Stops were performed every 800m along a survey route and surveys were conducted for five

minutes at each stop. Data collected in the East Kootenay and Cariboo-Chilcotin regions included how many curlews were seen or heard, the date each survey was conducted, and the geographic coordinates for each curlew detection. The data collected in the Okanagan-Similkameen and Thompson-Nicola regions included the above as well as the vegetation type and height at the survey location and whether it was a visual or aural detection. There was no information regarding what specific routes were surveyed, which locations were surveyed but had no detections, or any site-level data such as wind, temperature, precipitation, or the time of day surveys were conducted.

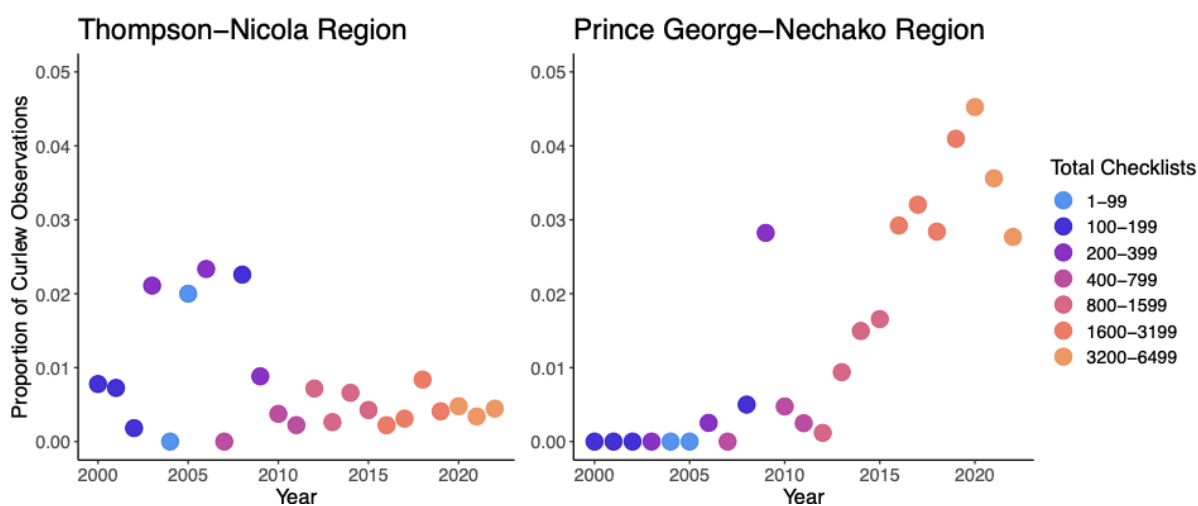


Figure 2.2. eBird observations of Long-billed Curlews in the Thompson-Nicola region (left) and the Prince George-Nechako region (right) of British Columbia.

Contemporary Population Surveys

Contemporary curlew surveys were conducted across British Columbia in 2022 and 2023. In 2022, surveys were organized by Birds Canada in partnership with Environment and Climate Change Canada and were conducted by volunteers (Birds Canada, 2022). Seasonal timing of surveys was divided into different survey windows that were specific to each region to account for differing arrival times of curlews on their breeding territories. In the southern regions (Okanagan-Similkameen and East Kootenays), surveys were conducted between April 23 and May 1, and in the northern regions (Thompson-Nicola, Cariboo-Chilcotin, and Prince George-Nechako), surveys were conducted between April 30 and May 8. Curlews start arriving during the first week of April in British Columbia and most individuals have arrived by late April (Dugger and Dugger et al., 2023). We chose these dates to ensure

curlews had established breeding territories and to avoid counting migrating birds. We selected transect routes by first identifying regions with suitable curlew habitats (i.e., grassland, agriculture, or pasture) and ensuring they were accessible by public road. All transect routes were approximately 40km long, with stops at point count locations every 800m. During point counts, observers recorded all curlews seen or heard within a 400m radius over a period of five minutes. We did not record curlews observed in flight unless they took off from or landed in the survey area. To capture peak curlew vocalization and activity we started surveys at sunrise and finished before noon. During point counts, observers recorded all curlews on a minute-by-minute basis (0-1 min, 1-2 min, etc.). If no individuals were recorded, we classified the survey as a zero detection. Volunteers also recorded the dominant habitat type observed within the 400m survey radius (agriculture, pasture, grassland, urban, other), as well as time of day, wind, precipitation, and temperature. Wind was recorded on the Beaufort scale from 0-6 where 0 is calm (>2km/h), 1 is light air (2-5km/h), 2 is a light breeze (6-12 km/h), 3 is a gentle breeze (13-19 km/h), 4 is a moderate breeze (20-29km/h), 5 is a fresh breeze (30-39 km/h), and 6 is a strong breeze (40-50 km/h). Precipitation was recorded on a scale from 0 to 6, where 0 was no precipitation, followed by rain (1), snow (2), rain and snow (3), hail (4), trace (5), and thunderstorm (6). Stops were only conducted if the habitat was considered suitable (i.e., grassland, agriculture, or pasture) and were only conducted in ideal weather, i.e., minimal precipitation (none or trace) and low wind speeds (Beaufort 3 or less).

Additional survey data were obtained from Skeetchestn Natural Resources Corporation. Skeetchestn conducted curlew surveys in the interior region of British Columbia following the above survey protocols in 2022 and 2023. These data included detection and non-detection data, location data, and the time of day the surveys were conducted.

In 2023, we conducted additional supplementary surveys in northern British Columbia, within the Prince George-Nechako region (Figure 2.1). This is an area with no native grasslands, but a high density of cropland, pastureland, and unmanaged grassy fields. We selected point count locations beforehand by reviewing satellite imagery to find locations that had a majority of suitable habitat (at least 50% cover of grassland, agriculture, or pasture) within a 400m radius. We confirmed the suitability of each location when we arrived

on site before conducting each point count survey. To encompass the arrival of curlews on their breeding grounds but prevent hatch-year birds from being included in the data, fieldwork was conducted from May 5 to May 31. In British Columbia, nesting is typically initiated in mid-late May, with late nesting starting in early June (Dugger and Dugger, 2020). Chicks often hatch in mid-late June (Dugger and Dugger, 2020). We conducted point count surveys following the same methodology as 2022 (above). Surveys were performed by K.F. and volunteer surveyors. Volunteer surveyors conducted a minimum of two surveys of their assigned point count locations to provide repeat data for calculating detection probabilities. Repeat surveys were conducted a minimum of one week apart.

Table 2.1 Summary of Long-billed Curlew survey locations in British Columbia.

Year	Location	Survey Source
2000 & 2002	Okanagan-Similkameen, East Kootenays, Thompson-Nicola, and Cariboo-Chilcotin	British Columbia Ministry of Environment
2022	Okanagan-Similkameen, East Kootenays, Thompson-Nicola, Cariboo-Chilcotin, and Prince George-Nechako	Birds Canada and Environment and Climate Change Canada
2023	Prince George-Nechako	K.F. and volunteer surveyors

Land Cover Changes over Time

To evaluate changes in land cover within the curlew breeding range in British Columbia between historical and contemporary curlew survey periods, we obtained land cover data from Agriculture and Agri-food Canada's (AAFC) Land Use Time Series datasets for 2000 and 2020 (AAFC, 2021). These two datasets have a 30m resolution and include the land cover categories forest, agricultural land, grassland, wetland, urban land, and water. We split both datasets into half-latitude increments, then limited them to the species breeding range within the province. We extracted the total number of pixels designated as each land cover type and filtered these to only include the relevant habitats to curlews, including grassland, agricultural, and wetland cover, as well as urban cover. Urban cover was included because urban encroachment of native grasslands is an important driver behind habitat loss, and we aimed to investigate how urban lands have changed within the curlew breeding range. We

then calculated the percent change of each land cover type at half-degree latitude intervals between 2000 and 2020. Results are presented as means \pm SD percent change for each habitat type for 2000 and 2020. We conducted a paired t-test on the pixel count of each habitat type at half-latitude segments from 2000 and 2020, and results are considered significant at an alpha of 0.05.

Curlew Detections by Land Cover Type

We also used the 2000 and 2020 AAFC data to examine land cover at curlew detection locations over the two time periods. We applied a 400m buffer around each curlew detection location to represent the area surveyed and the number of pixels of each land cover type (agriculture, wetland, and grassland) was extracted. We assigned the dominant habitat type at each survey location based on which habitat had the greatest pixel count. Results are presented as the percent of total curlew detections in each habitat type. These data were also used as the habitat covariates for Bayesian occupancy models, below.

Occupancy Modeling

We developed models to evaluate the covariates that best predicted curlew occupancy and detection probability based on our contemporary survey data (2022 and 2023). We only conducted repeat site visits for a subset of the 2023 surveys; as such, 2022 and part of the 2023 surveys did not include repeat site visits. As we wanted to account for detection probability but did not have data for all locations, we implemented a Bayesian approach using Stan in R (Carpenter et al., 2017; R Core Team 2021; Kellner et al., 2022) to develop occupancy models. The benefit of this approach is that it generates posterior distributions, allowing us to estimate the predictors for the missing data (Kellner et al., 2022). To accomplish this, we created a dataset that merged the 2022 and 2023 data and added empty site visits for the locations that were not visited more than once. Most of our repeat surveys were conducted three times, and as such, we chose to use three visits as the standard for our data. We created a dataset with three visits for each point count location, some with data from up to three visits, and most with only one visit filled. We calculated occupancy using a single-species Bayesian occupancy model in R using the ‘ubms’ package and the ‘stan_occu’ function (Kellner et al., 2022). For detection modeling, we included the time of each point

count transformed to minutes past midnight and for occupancy modeling we included the proportion (0-1) of agricultural land, grassland, and wetland cover, latitude, and year, with month as a random effect.

We ran a total of four models, including a null model, to find the model that best explained curlew occupancy. We ran individual models for each habitat cover covariate using the proportion of land cover (agricultural land, grassland, and wetland) to gain insight into how each habitat cover type was influencing curlew occupancy and determine whether the proportion of land cover had an effect on curlew occupancy. Each model was run with the same detection covariate (minutes past midnight) and non-habitat covariates (latitude and year). Models were run using 4 chains and 20,000 iterations. For each model, we assessed the goodness-of-fit with 1000 draws using the MacKenzie-Bailey chi-squared test. To compare the models, we performed leave-one-out cross-validation (LOO) which produced the expected log pointwise predictive density (elpd) (Kellner et al., 2022). The largest elpd value indicates the best-performing model (Kellner et al., 2022). We also obtained the LOO Information Criterion (LOOIC) which is analogous to AIC (Kellner et al., 2022).

RESULTS

Survey Data and Population Distribution

From the historical surveys, our analysis included data from 196 locations where curlews were detected (360 total individuals). From the contemporary surveys, our analysis included data from 1,241 point count locations in 2022, with curlews detected at 130 locations (227 total individuals; mean 0.18 individuals/location). Our analysis included data from 410 point count locations in 2023, with repeated surveys at 155 locations (37.89%), and we detected curlews at 92 locations (157 total curlews; mean 0.38 individuals/location).

We detected curlews further north than they have previously been reported in British Columbia (Figure 2.3). As far as we are aware, the previous northernmost curlew detection occurred in the Cariboo-Chilcotin region in 2002, at 52.82 degrees latitude (Figure 2.3). In 2023, the northernmost curlew we detected was at 54.42 degrees latitude in the Prince George-Nechako region (Figure 2.3). This is equivalent to a northward range expansion of ~177 km. Although surveys were not conducted in this expanded northern region in the early

2000s, eBird data (Figure 2.2) demonstrates a lack of observations in this region during that time, indicating that it was unlikely curlews were established in this northern range when the historical surveys were conducted.

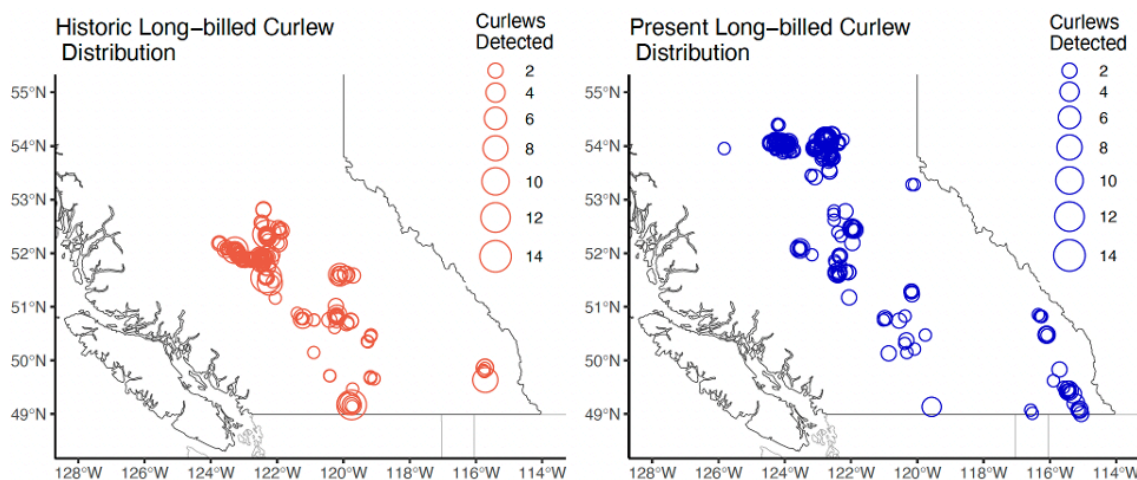


Figure 2.3. Left: Long-billed Curlew distribution and abundance map from 2000/02 using data obtained from the British Columbia Ministry of Environment. Right: Long-billed Curlew distribution and abundance map from 2022/23 using data obtained from Birds Canada and supplementary survey data conducted by K.F.

Land Cover Changes over Time

There was a decrease in grassland cover ($t = -2.34$, $p = 0.04$) and an increase in urban cover ($t = 4.74$, $p = 0.0008$) between 2000 and 2020 across the curlew breeding range (Figure 2.4). Grassland cover decreased by $1.15\% \pm 0.86$ (mean percent change \pm SD) and urban land increased by $37.86\% \pm 5.39$. We separated agricultural land cover into south (49 to 50.5°N) and north (51 to 54.5°N) for analyses as there was a clear divide between these latitudes in the direction of change (Figure 2.4). In the southern region, agricultural land cover decreased significantly ($t = -22.09$, $p = 0.0002$), and in the northern region, agricultural land cover increased significantly ($t = 2.54$, $p = 0.0002$). Agricultural land cover decreased by $13.15\% \pm 11.87$ in the south and increased by $2.17\% \pm 1.28$ in the north.

Curlew Detections by Land Cover Type

In the early 2000s, 48.68% of curlews detected were in grassland habitats, 46.03% of curlews detected were in agricultural habitats, and 3.70% of curlews detected were in wetland

habitats. In 2022 and 2023, 15.45% of curlews detected were in grassland habitats, 83.18% of curlews detected were in agricultural habitats, and 1.36% of curlews detected were in wetland habitats. If we restrict the contemporary survey period to 2022, which is more comparable to the historical surveys because the Prince George-Nechako region was the only region surveyed in 2023 and was only surveyed in that year, 25.58% of curlews detected were in grassland habitats, 72.10% of curlews detected were in agricultural habitats, and 2.33% of curlews detected were in wetland habitats. The agricultural habitats in which curlews were detected in were primarily pasturelands and hayfields; curlews were not detected in high-intensity row crops.

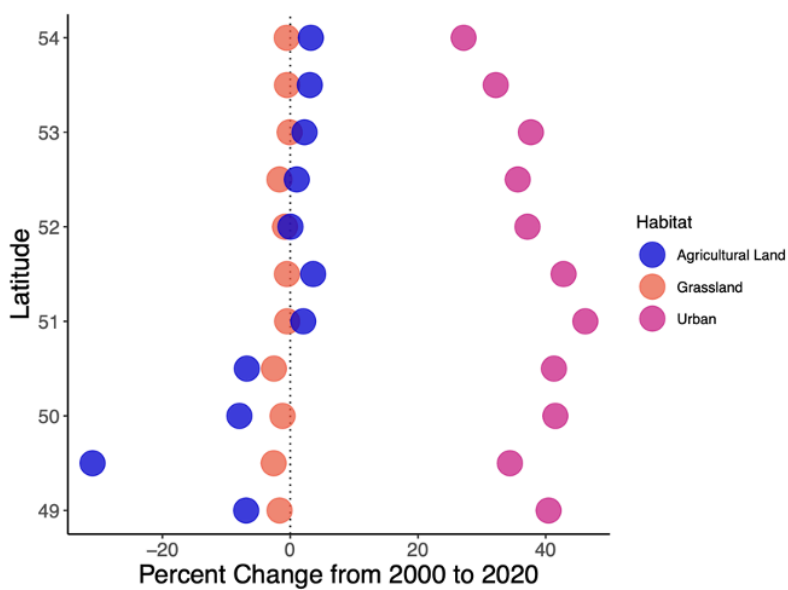


Figure 2.4. Change in agricultural land, grassland, and urban cover between 2000 and 2020 within the Long-billed Curlew breeding range in British Columbia.

Occupancy Modeling

MacKenzie Chi-squared tests indicated there was no lack of model fit for our agricultural land cover ($p=0.165$), grassland cover ($p=0.165$), and wetland cover ($p=0.227$). Overall, two of the four models explained curlew occupancy (LOOIC difference < 2). The top-ranked model included grassland cover as the habitat covariate and the second-ranked model included agricultural land cover as the habitat covariate (Table 2.2).

Table 2.2. Ranked Long-billed Curlew occupancy models based on survey data collected from British Columbia, Canada, from 2022-2023. Model selection was based on the expected log pointwise predictive density (elpd value), leave-one-out cross-validation weight (LOO weight), and LOOIC (LOO information criterion).

<i>Rank</i>	<i>Occupancy</i>	<i>Detection</i>	<i>elpd</i>	<i>elpd Difference</i>	<i>LOO Weight</i>	<i>LOOIC</i>
1	Grassland cover + latitude + year	Minutes past midnight	-675.861	0.000	0.805	1351.723
2	Agricultural land cover + latitude + year	Minutes past midnight	-676.187	-0.326	0.161	1352.375
3	Wetland cover + latitude + year	Minutes past midnight	-680.356	-4.494	0.000	1360.712
4	Null	Null	-736.275	-60.414	0.034	1472.550

When we examined the 95% credible intervals of the parameter estimates of the top-ranked model, grassland cover, year, and latitude had credible intervals that did not overlap zero (Figure 2.5). Curlews were less likely to occupy sites with higher levels of grassland cover. Additionally, curlews were more likely to occupy regions at higher latitudes. Minutes past midnight had no effect on curlew detection (Figure 2.5).

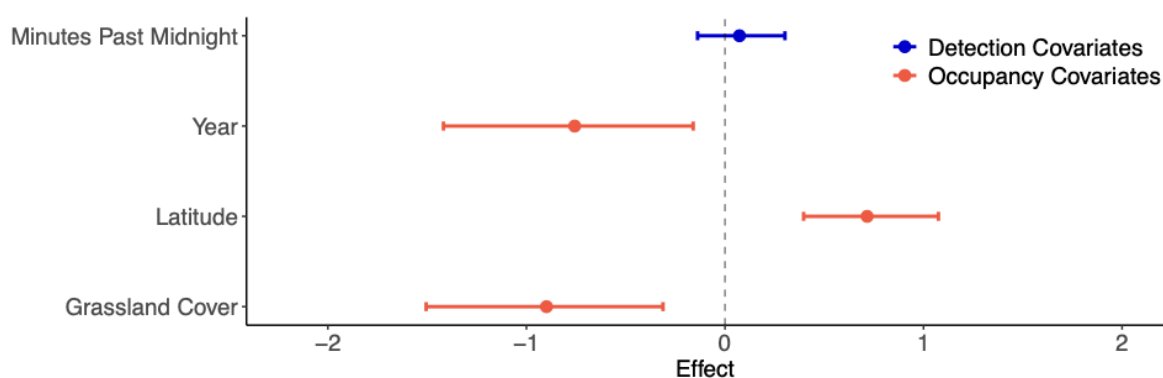


Figure 2.5. Parameter estimates and 95% credible intervals for occupancy and detection covariates from the top-ranked Bayesian occupancy model which includes grassland cover as the habitat covariate.

When we examined the 95% credible intervals of the parameter estimates of the second-ranked model, agricultural land cover, year, and latitude had credible intervals that did not overlap zero (Figure 2.6). Curlews were more likely to occupy sites with higher

levels of agricultural land cover. Additionally, curlews were more likely to occupy regions at higher latitudes. Minutes past midnight had no effect on curlew detection (Figure 2.6).

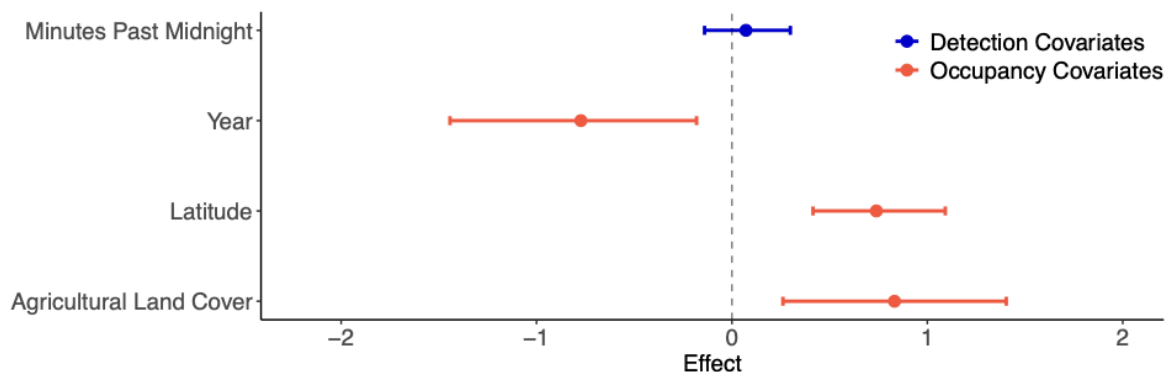


Figure 2.6. Parameter estimates and 95% credible intervals for occupancy and detection covariates from the second-ranked Bayesian occupancy model which includes agricultural land cover as the habitat covariate.

DISCUSSION

Using historical and contemporary survey and land cover data spanning two decades, we analyzed changes in British Columbia’s land cover and Long-billed Curlew detections by land cover type. We then explored the drivers behind contemporary curlew occupancy using occupancy models. Between the early 2000s and 2020s, we found an overall loss of grassland cover throughout the curlew range in British Columbia, as well as gains in agricultural land in the north, but decreases in the south. Curlews were detected more often in agricultural habitats in more recent years, and the species has apparently expanded its breeding range northward by ~177 km. Based on contemporary survey data, Long-billed Curlew occupancy was positively associated with agricultural land cover and negatively associated with grassland cover. These findings are possibly explained by habitat loss in southern British Columbia, coupled with habitat gain and warming temperatures in the north.

While our historical surveys did not include northern regions, eBird data supports the absence of curlews in the Prince George-Nechako region in the early 2000s (Figure 2.2). Checklists were being submitted within this region in the earlier 2000s, but no checklists included curlew observations until 2006, demonstrating there was likely a true absence of the species rather than a lack of survey effort in the region. It is possible few vagrant curlews

were nesting in this region before 2000, as Canning (1999) cited personal communications with landowners who had observed pairs of curlews from 1994-1997, but there is no documentation of curlews again until 2006. We consider this change as a northern range expansion rather than a range shift, as curlews are still being detected in the southern limits of British Columbia. However, detections in their southern interior range (Okanagan-Similkameen and Thompson-Nicola regions) appear to have decreased (Figure 2.3), likely due to a loss of available habitat from land conversion to both agricultural habitats and urban areas (Iverson, 2004). Our occupancy models based on contemporary survey data (2022-2023) show that curlews are more likely to occupy regions at higher latitudes, demonstrating that not only have curlews expanded their northern range limit, but that there are likely to be more curlews occupying this newly expanded region. These changes to the Long-billed Curlew distribution could be driven in part by a warming climate. Patterns of northern range expansion in response to climate change by bird populations have been well documented in temperate regions, including in North America (Hitch and Leberg, 2007; Chen et al., 2011; Nixon et al., 2016; Rushing et al., 2020) and Europe (Chen et al., 2011; Brommer et al., 2012), as well as specifically in grassland bird populations (Nixon et al., 2016). In British Columbia, the Prince George-Nechako region experienced an increase in average spring temperatures from 4.13°C in 2000-2002 to 5.03°C in 2020-2022 (Wang et al., 2016 from ClimateBC). This nearly 1°C change is equivalent to a shift of 100-133 km in latitude (Hughes, 2000). In addition to changing temperatures, habitat changes, namely an increase in agricultural land in the northern portion of the species range and a decrease of grasslands in the southern portion of the species range, could be contributing to their shift in distribution to the north. Warmer temperatures and earlier springs create more climatically suitable regions for species to shift into (Skagen and Adam, 2012; Jarzyna et al., 2016; Nixon et al., 2016). This idea is supported by work in Alberta, Canada, that showed generalist grassland birds are predicted to expand northward more quickly when there are existing agricultural habitats in their new climatically suitable breeding ranges (Nixon et al., 2016).

Conversely, changes in land use can impact species ranges as a result of habitat loss (Parry et al., 2007; Burgess et al., 2017; Pacifici et al., 2020; Britnell et al., 2023). In the southern interior regions of British Columbia (Okanagan-Similkameen and Thompson-Nicola regions), curlew observations appear to have decreased since the early 2000s,

corresponding to a substantial increase in urban land cover and a decrease in available native grasslands and agricultural habitats. It is also important to note that habitat loss is not the only driver behind the reduced availability of grassland habitats, woody encroachment resulting from fire suppression practices has created shrub-steppe habitats, which are sub-optimal for curlews (Cannings 1999). The reduced quality of grassland habitats is likely a large contributor to curlews' apparent avoidance of the remaining grassland habitats. A combination of habitat loss and degradation in the south and gain in the north is likely a contributing factor to the observed northern range expansion of curlews in British Columbia.

While climate change in the short-term has apparently benefited Long-billed Curlews in British Columbia, it is possible that the increased frequency of curlews on agricultural lands may have detrimental effects on the population in the future. Curlew productivity in agricultural habitats remains largely unknown (COSEWIC, 2002). However, agricultural habitats may act as population sinks, as nesting in agricultural habitats exposes curlews to threats from mowing, which can lead to direct mortality (COSEWIC, 2002; e.g. Green et al., 1997; Perlut et al., 2008), nest destruction (e.g. Green et al., 1997; Perlut et al., 2008; Kentie et al., 2015), nest abandonment (e.g. Bollinger et al., 1990), and increased predation rates (COSEWIC, 2002; e.g. Bollinger et al., 1990; Beja et al., 2014). Mowing and harvesting are particularly dangerous for curlews as they frequently nest in hay fields, which are mowed at regular intervals during the breeding season (Tews et al., 2013; Stanton et al., 2018). Since the 1950s, the timing of mowing in North America has advanced by 2-3 weeks, pushing it further into the grassland bird nesting period (Renfrew et al., 2015; Brown and Nocera, 2017; Stanton et al., 2018). This shift towards breeding primarily in agricultural habitats is especially concerning in the southern regions of British Columbia where the growing season is longer, resulting in more frequent hay harvesting (Agriculture and Agri-Food Canada, 2010; Grow BC, 2014). Fragmentation resulting from the conversion of grasslands to agricultural land can increase predation rates (Environment Canada, 2012). Fence posts and powerlines can provide perches for avian predators and corridors such as roads or trails can increase predation by mammalian predators such as coyotes or foxes (Environment Canada, 2012). In addition, curlews nesting in pastures or hayfields that rotationally graze livestock are at risk of nest destruction due to trampling (e.g. Mandema et al., 2013; Beja et al., 2014). Another threat associated with agricultural intensification is the increased use of pesticides,

which can both directly and indirectly cause mortalities to birds (Boatman et al., 2004; Stanton et al., 2018).

Future studies should focus on exploring the productivity of curlews in this newly expanded range to understand the viability of the population within agricultural lands. It is important to know how the increased use of agricultural lands will impact curlew reproduction, survival, and long-term abundance trends within British Columbia. Future management strategies should work to identify and protect remaining high-quality grassland habitats within southern British Columbia, as well as increase the habitat quality of these grasslands, restoring them to suitable nesting locations. Prescribed burns to reduce woody encroachment of the grasslands and limiting grazing pressures within the grasslands would be effective in increasing the quality of native grassland habitats for curlews. Furthermore, future work should aim to examine changes to the distribution of curlews throughout their entire North American breeding range. This work would provide further information as to how curlews are responding to climate change at both their northern and southern range limit and if other regions experiencing high levels of habitat loss are also experiencing changes in curlew distribution.

It is difficult to disentangle the impacts of climate change from those of habitat loss on species distribution and abundance, but our results highlight how changes in both climate and land use may interact to facilitate a rapid northward range expansion. Climate change and habitat loss independently can influence species distributions, but ultimately, it is the interactions between these forces that will drive changes in population trends and distributions (Mantyka-Pringle et al., 2019, Zhao et al., 2019).

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CHAPTER 3: BROAD AND FINE SCALE RANGE SHIFTS OF LONG-BILLED CURLEWS ACROSS NORTH AMERICA

ABSTRACT

Changes to the distributions of bird populations are becoming increasingly common as climate change and habitat loss continue to alter environments at a global scale. Grassland habitats have been disproportionately impacted by these stressors, leading to unprecedented declines of grassland bird species. Many grassland birds, such as the Long-billed Curlew (*Numenius americanus*) have large ranges across North America, and thus may face different threats and pressures in different parts of their range. Community science databases such as eBird provide large-scale, long-term temporal and spatial data, allowing for studies that examine changes in species distribution both regionally and range wide. Using thirteen years of eBird data we examined changes to the Long-billed Curlew's breeding range boundaries and centroid position in North America, and centroid position within eight Bird Conservation Regions (groupings of similar bird communities and habitats across North America) in which the species occurs. We found an overall northern range expansion of approximately 198 km and a northern shift of the centroid position by 228 km. At the Bird Conservation Region scale, BCR 10 (Northern Rockies) also showed a northern centroid shift, but BCR 11 (Prairie Potholes) showed the opposite pattern with a southeastern range shift. The shift in BCR 11 is likely related to the population decline of Long-billed Curlews in the Canadian portion of this BCR. Furthermore, we found a pattern of western centroid shifts in several BCRs, consistent with grassland loss in eastern North America. These results reinforce the importance of understanding both range-wide and regional population dynamics to effectively manage at risk species.

INTRODUCTION

Earth's temperatures are rising, impacting animal populations on a global scale (Parmesan and Yohe, 2003; Mac Nally et al., 2009; Chen et al., 2011; Mantyka-Pringle et al., 2012; Mantyka-Pringle et al., 2015) and shifting the distribution of many bird species towards more northern latitudes or higher elevations (Parmesan and Yohe, 2003; e.g. Hitch and Leberg, 2007; Nixon et al., 2016; Rushing et al., 2020). Combined with other anthropogenic stressors such as habitat loss and degradation, bird populations across North America are facing unprecedented declines (Mantyka-Pringle et al., 2012; Rosenberg et al., 2019; Jaureguiberry et al., 2022). Grasslands have been disproportionately impacted by land use change, with native habitat lost to agricultural conversion and urbanization (Vickery et al., 2000; Comer et al., 2018), resulting in the loss of over 60% of the native grasslands in North America (Comer et al., 2018). Furthermore, the remaining grasslands have been degraded through grazing pressure, invasive plants, and woody encroachment from fire suppression (Vickery et al., 2000; Stanton et al., 2018). Not surprisingly, grassland bird species have experienced the most drastic decline of all bird species since the 1970s (Rosenberg et al., 2019).

The Long-billed Curlew (hereafter 'curlew') is a large shorebird species that breeds throughout western North America in short grass and mixed grass prairies (Cannings, 1999; COSEWIC, 2002; Fellows and Jones, 2009). The North American Breeding Bird Survey has shown an overall negative trend in curlew abundance from 1980 to 2000 (Sauer et al., 2001, as reported by COSEWIC, 2002); however, analyses of BBS survey data from 2011 to 2021 indicate a slight increase in their breeding abundance (Smith et al., 2019). The curlew's breeding range historically spanned further east in the United States and Canada, but they have been extirpated from ~30% of their historical range (COSEWIC, 2002; Fellows and Jones, 2009). In Canada, curlews are listed as a species of "Special Concern" on Schedule 1 of the Species at Risk Act (Cannings, 1999; Jones et al., 2008). In the United States, curlews are listed as a U.S. Fish and Wildlife Service Bird of Conservation Concern (Fellows and Jones, 2009). The loss of short grass and mixed grass prairies (Wick et al., 2016), where much of North America's curlew population is found (COSEWIC, 2002), has reduced the curlew's range (COSEWIC, 2002; Fellows and Jones, 2009) and will likely continue to impact their abundance and distribution.

Detection and count data from bird surveys are crucial for modeling and understanding population trends (e.g. Sullivan et al., 2009; Sauer et al., 2014; Smith and Edwards, 2020), especially in light of anthropogenic change. While structured surveys such as the Breeding Bird Survey can provide insight into long-term trends (Sauer et al., 2014; Smith et al., 2019), especially at specific locations, these surveys can be limited by coverage (i.e., number and location of routes) as well as limitations imposed by species' behavior (Ankori-Karlinsky et al., 2021; e.g. Fellows and Jones, 2009; Bianchini and Tozer, 2023), such as their inconspicuous nature during nesting season, which is when BBS routes are typically completed (Fellows and Jones, 2009). As such, there is high value in community-driven data collection, such as through eBird, and this approach can provide the opportunity to answer a wide range of environmental questions about conservation, species distribution, and more (Sullivan et al., 2009; Sullivan et al., 2014). eBird is a community science database in which users can submit bird observations in a standardized way (Sullivan et al., 2009), providing large-scale spatial and temporal data that is effective for examining changes to populations such as their distributions and range limits (Sullivan et al., 2009; Sullivan et al., 2014).

As curlews have a large range throughout North America, this complicates researchers' ability to gain insight into their abundance and distribution across their entire range through traditional survey methods, making eBird a potentially valuable resource for understanding these patterns. eBird data has previously been used to examine how species distributions and migration patterns have changed over time (e.g. Sonnleitner et al., 2022; Prytula et al., 2023). For example, Sonnleitner et al., (2022) found that the breeding season population centroids of Western, Eastern, and Mountain Bluebirds have all shifted southward, while the migratory population centroids have shifted longitudinally toward the center of the continent. Similarly, a study on Vaux's and Chimney Swift using eBird data revealed that the breeding season population centroids of both species have shifted towards the centre of the continent, a pattern potentially driven by urban encroachment and habitat loss along both coasts (Prytula et al., 2023). These studies illustrate the power of eBird to allow us to detect unexpected, and sometimes surprising, shifts in distributions that may go undetected through the use of traditional methods alone.

While examining changes across an entire species range is important, understanding both large-scale and regional distribution dynamics is critical for the effective management of local populations. Species with large ranges distributed across different eco-regions will face different pressures from climate and land use (Jones, 2011, Conroy et al., 2012; e.g. Pavlacky et al., 2017). As such, a more nuanced approach to examining the differences in each eco-region, such as Bird Conservation Regions (BCRs), can be useful for understanding where populations may be the most vulnerable to climate change and habitat loss. BCRs are ecologically distinct regions that are defined by groupings of similar biotic communities, abiotic characteristics, and resource management issues (CEC, 1998; Bird Studies Canada, 2014). Examining changes to the climate and habitat of the varying BCRs in which a species occurs can provide a better understanding of the species distribution and abundance patterns on a broad scale (Pavlacky et al., 2017).

Here, we used eBird data to analyze curlew distribution dynamics across their entire North American range as well as within the eight Bird Conservation Regions (BCRs) that encompass the curlew's breeding range. We predicted that curlews would show an overall northern range expansion within their North American range in response to warming temperatures at their northern range periphery (Ch. 2). Furthermore, we predicted that curlew distributions would shift differently in response to the variable habitat loss and climatic stressors within each BCR. Specifically, we predicted that BCRs 10 (Northern Rockies) and 11 (Prairie Potholes) would show a northern centroid shift due to warming in the northern periphery of these BCRs (Chaikowsky, 2000; Wang et al., 2016 from ClimateBC). We also predicted that BCRs 11, 17 (Badlands and Prairies), 18 (Shortgrass Prairie), and 19 (Central Mixed Grass Prairie) would show western centroid shifts resulting from high levels of grassland loss to agricultural land on the eastern edge of the Great Plains (Wick et al., 2016; Lark et al., 2020; U.S. Fish and Wildlife Service, 2023).

METHODS

eBird Data

Long-billed Curlew data from 2010 to 2022 were acquired from the community science database, eBird (eBird, 2021). eBird provides checklists (single birding events) that include

the species observed, the number of individuals per species, the location, the date and time, and the effort, measured by variables including the distance traveled during “traveling” observations, the length of time each checklist was recorded for, and the number of observers. We used the “auk” package (Strimas-Mackey et al., 2023a) in R (R Core Team 2023) and followed eBird Best Practices to filter the data (Strimas-Mackey et al., 2023b). Specifically, we filtered the data to only include “stationary” or “traveling” protocols, omitting “incidental” and “historical” data. In addition, we removed traveling checklists that were greater than 5 km long and omitted checklists that lasted longer than 5 hours. We only included complete checklists, which refer to checklists in which all species seen or heard were recorded. Lastly, checklists that did not include curlew observations were zero-filled, to account for non-detection data. The resulting data were restricted to May 1st to July 31st, which encompasses the Long-billed Curlew breeding period (Dugger and Dugger et al., 2020), and within Bird Conservation Regions (BCRs) 9 (Great Basin), 10 (Northern Rockies), 11 (Prairie Pothole), 15 (Sierra Nevada), 16 (Southern Rockies Colorado Plateau), 17 (Badlands and Prairies), 18 (Shortgrass Prairie), and 19 (Central Mixed Grass Prairie), which encompasses the curlew breeding range within North America (Figure 3.1).

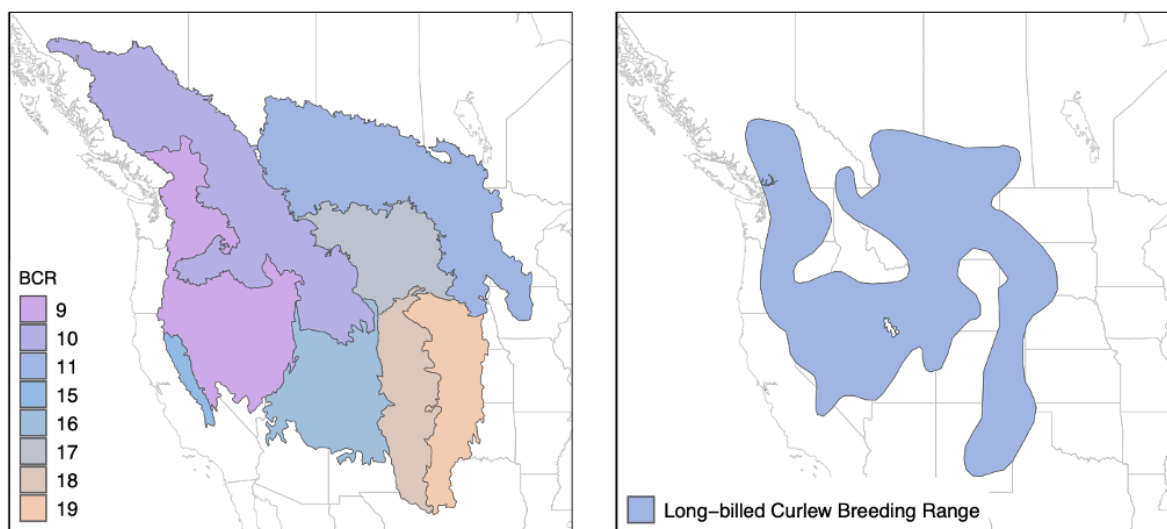


Figure 3.1. Left: Bird Conservation Regions within the Long-billed Curlew North American breeding range. Right: Long-billed Curlew Breeding Range.

Breeding Range Limits and Centroid Positions

We created 10 km by 10 km grids across the Long-billed Curlew breeding range and calculated the total number of complete checklists and checklists with curlew detections per year within each grid. We retained grid cells with at least 5 years of data to reduce any spatial bias of grid cells that were poorly sampled. We calculated the centroid (latitude and longitude) position of curlew detections each year for the entire range and within each BCR. The centroid represents the geometric center of mass of detections within each region. We also calculated the latitudinal and longitudinal bounds per year for the entire breeding range. Each of these directional measurements were calculated using all observations within the 100th percentile of the centroid. We chose to conduct data analyses using all data points as we are interested in the outermost range boundaries and these range expansions will be characterized by small peripheral populations. As such, using data less than the 100th percentile from the centroid eliminates the checklists from these peripheral range boundaries which does not provide a fair assessment of changes in the breeding range and would underestimate the absolute ranges.

Statistical Analysis

We conducted a series of linear regressions in R (R Core Team, 2023) using the ‘lm’ function to test for changes in the centroid position and range boundaries of curlews from 2010 to 2022. The linear regressions were calculated for the northern, eastern, southern, and western range limits, as well as the longitudinal and latitudinal centroid positions for the entire breeding range. We also conducted linear regressions for the longitudinal and latitudinal centroid position for each BCR. We calculated the distance of the estimated cumulative change (in kilometers) and yearly change (in degrees) in centroid positions and range limits using the slope of the linear regressions. Results are presented as mean \pm standard error.

RESULTS

Breeding Range Limits and Centroid Positions

North American Breeding Range

Based on eBird data collected between 2010 and 2022, the northern range limit of curlews shifted north by 0.148 ± 0.046 °/year, for a cumulative change of ~ 198 km ($r^2 = 0.48$, $p = 0.008$) and the centroid latitude shifted north by 0.171 ± 0.022 °/year (total change: ~ 228 km; $r^2 = 0.84$, $p = <0.001$) (Figure 3.2). The western range limit expanded west by 0.137 ± 0.058 °/year (total change: ~ 105 km; $r^2 = 0.34$, $p = 0.04$). There were no changes to the southern range limit, eastern range limit, or centroid longitude position (all $p > 0.05$).

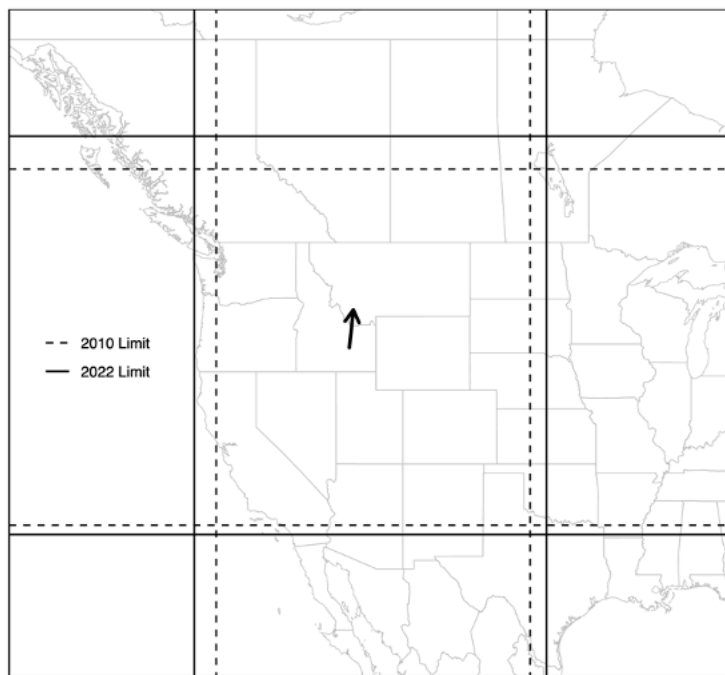


Figure 3.2. Breeding range limits of Long-billed Curlews in 2010 and 2022 for their entire North American breeding range. The arrow represents the movement of the centroid location between 2010 and 2022. Dotted lines represent 2010 range limits, solid lines represent 2022 range limits.

Bird Conservation Regions

The centroid latitude position shifted north in BCR 10 (Northern Rockies) by 0.063 ± 0.021 °/year, with a cumulative change of ~ 84 km ($r^2 = 0.44$, $p = 0.01$) and south in BCR 11 (Prairie Potholes) by 0.037 ± 0.016 °/year (total change: ~ 50 km; $r^2 = 0.32$, $p = 0.04$) between 2010 and 2022 (Table 3.1, Figure 3.3). The centroid longitudinal position shifted west in BCR 10 by 0.095 ± 0.029 °/year (total change: ~ 85 km; $r^2 = 0.50$, $p = 0.007$), east in BCR 11 by 0.089 ± 0.022 °/year (total change: ~ 77 km; $r^2 = 0.60$, $p = 0.002$), west in BCR 16 (Southern Rockies Colorado Plateau) by 0.102 ± 0.044 °/year (total change: ~ 108 km; $r^2 =$

0.33, $p = 0.04$), and west in BCR 18 (Shortgrass Prairie) by 0.043 ± 0.012 °/year (total change: ~45 km; $r^2 = 0.53$, $p = 0.005$). We detected no changes to the centroid latitude or longitude in BCRs 9 (Great Basin), 15 (Sierra Nevada), 17 (Badlands and Prairies), or 19 (Central Mixed Grass Prairie) (all $p > 0.05$).

Table 3.1. Changes to centroid latitude and longitude of the Long-billed Curlew breeding range from 2010-2022 within Bird Conservation Regions.

<i>Bird Conservation Regions</i>	<i>p-value</i>	<i>R²</i>	<i>Estimated total Distance and Direction Shifted</i>
<i>BCR 9 - Great Basin</i>			
Centroid Latitude	0.14	0.18	
Centroid Longitude	0.18	0.02	
<i>BCR 10 - Northern Rockies</i>			
Centroid Latitude	0.008	0.48	84 km N
Centroid Longitude	0.007	0.50	85 km W
<i>BCR 11 - Prairie Pothole</i>			
Centroid Latitude	0.04	0.32	50 km S
Centroid Longitude	0.002	0.60	77 km E
<i>BCR 15 - Sierra Nevada</i>			
Centroid Latitude	0.83	0.004	
Centroid Longitude	0.79	0.006	
<i>BCR 16 - Southern Rockies</i>			
<i>Colorado Plateau</i>			
Centroid Latitude	0.55	0.03	
Centroid Longitude	0.04	0.33	108 km W
<i>BCR 17 - Badlands and Prairies</i>			
Centroid Latitude	0.64	0.02	
Centroid Longitude	0.97	0.0001	
<i>BCR 18 - Shortgrass Prairie</i>			
Centroid Latitude	0.14	0.19	
Centroid Longitude	0.005	0.53	45 km W
<i>BCR 19 - Central Mixed Grass Prairie</i>			
Centroid Latitude	0.26	0.11	
Centroid Longitude	0.06	0.28	

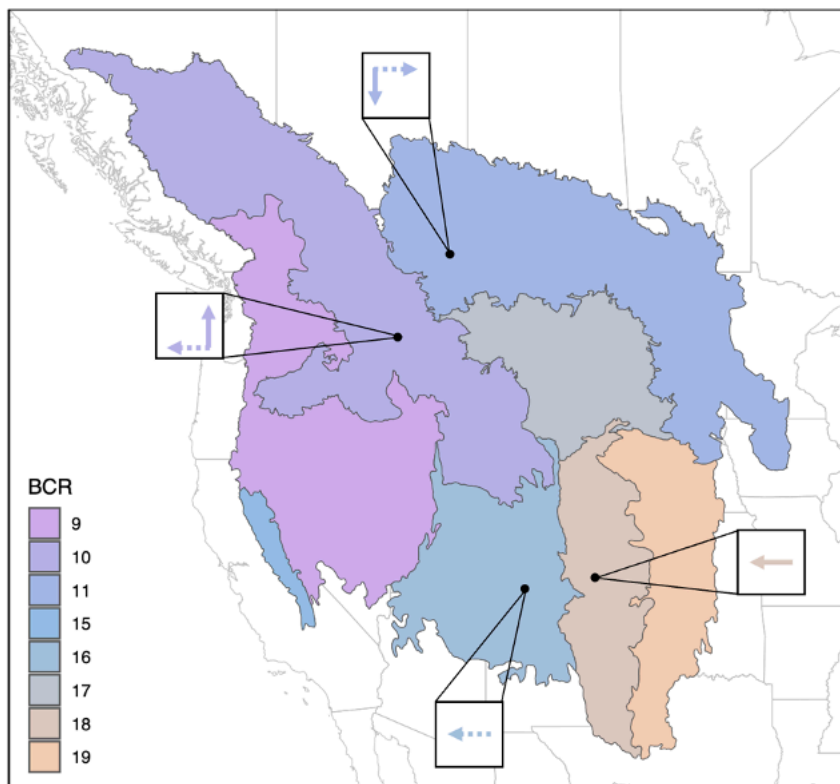


Figure 3.3. Changes to the centroid locations of Long-billed Curlews within Bird Conservation Regions (BCRs). The black dots represent the centroid position in 2022, and the arrows represent the direction of significant change. A dashed arrow represents $p < 0.05$ and a solid arrow represents $p < 0.01$.

DISCUSSION

Using eBird data spanning thirteen years, we analyzed changes to the North American distribution of Long-billed Curlews, as well as changes within the eight BCRs that overlap the curlew’s breeding range. Our results indicate that across the entirety of their breeding range, curlews have expanded their northern range limit—a pattern consistent with northern range expansions detected across taxa in response to warming temperatures resulting from climate change (Parmesan and Yohe, 2003). This pattern is also consistent with the patterns observed in Chapter 2. When we looked at shifts in population centroids within BCRs, we found high variability in the direction and magnitude of changes, indicating that warming temperatures may have different effects within different bioclimatic zones represented by BCRs and that other factors, such as differences in habitat loss across BCRs, may be driving patterns of distributional change at a regional scale.

Our results indicate that curlews expanded their northern breeding range limit by approximately 198 km over the last thirteen years. This result is similar to previous research that compared survey data from 2000 and 2022 within British Columbia (part of BCR 10 — Northern Rockies) and revealed an apparent ~177 km northward expansion that was attributed to climate and land use changes (Ch. 2). While curlews have expanded their northern range overall, they have not contracted their southern range, suggesting a range expansion rather than a range shift. Furthermore, we also detected northward movement of the centroid latitude position across the full breeding range (~228 km) and within BCR 10 (~84 km).

Warmer temperatures in the north allow for an earlier onset of spring and may create new climatically suitable regions for species to move into (Fraser, 1999; Skagen and Adam, 2012; Jarzyna et al., 2016; Nixon et al., 2016). Northern range expansions and changes in species distribution in response to a warming climate are becoming increasingly common among bird populations (Hitch and Leberg, 2007; Chen et al., 2011; Nixon et al., 2016; Rushing et al., 2020). This pattern has been observed in other grassland species within North America (e.g. Nixon et al., 2016). However, there needs to be suitable habitat for the species to shift into for these range shifts to occur (e.g. Nixon et al., 2016). The northern parts of BCR 10 (Northern Rockies) are composed mainly of agricultural land, which has increased in this region in recent years, providing suitable habitat to facilitate this northern range expansion (Ch. 2). In other words, the northern range expansion and centroid shift in North America, as well as the northern centroid shift in BCR 10 is likely due to the combined effects of agricultural land conversion and warming temperatures that have made previously unsuitable habitat now available (Ch. 2).

Surprisingly, the other BCR that comprises the northern extent of the curlew range — BCR 11 (Prairie Potholes)—showed the opposite pattern, with both a southern and eastern centroid shift. Breeding Bird Survey data showed a significant long-term (1970-2022) and short-term (2011-2022) negative trend of curlew abundance within the northern Canadian portion of BCR 11 (Smith and Edwards, 2020). This population decline of curlews within BCR 11 may explain the observed southern and eastern centroid shift as much of the northwestern portion of this BCR falls within Canada. Thus, if the Canadian portion is

declining, the centroid will shift towards the southeastern section of this BCR. Curlews were previously extirpated from around 30% of their eastern-most historical range (COSEWIC, 2002; Fellows and Jones, 2009), including the eastern regions of North and South Dakota. In recent years, agricultural conversion in the Dakotas has become intense (Lark et al., 2020) and if curlews are now potentially occupying agricultural lands in these regions, as they are in northern British Columbia (Ch. 2), the eastern centroid movement in BCR 11 may represent a re-colonization of their previously lost range. Much of the remaining grasslands of the Great Plains are now highly fragmented or have woody encroachment (Wick et al., 2016) making this habitat unsuitable for curlews (Cannings, 1999). The conversion of these unsuitable regions of grassland habitats to agriculture may provide curlews with habitat that appears to be of high quality. Similar to our findings in Chapter 2, occupation of agricultural habitat will likely be a short-term benefit to curlews as agricultural lands may act as population sinks.

In addition to a northern range expansion, we also observed a change to the western range limit of Long-billed Curlews breeding range—a pattern that is driven by shifts in BCR 10 (Northern Rockies), given that it is the westernmost BCR. The newly climatically suitable northern region that curlews have recently shifted into (Ch. 2) is northwest of their previously known breeding range. Therefore, this western range expansion is likely linked to the northern range expansion of a small peripheral population that was able to colonize a newly climatically suitable region in northern British Columbia (Ch. 2). In addition, we observed western centroid shifts in BCRs 16 (Southern Rockies Colorado Plateau) and 18 (Shortgrass Prairie). While the western centroid shift in BCR 10 is hypothesized to be linked to climate change and habitat gain through agricultural expansion, the western centroid shifts in BCRs 16 and 18 may be related to localized habitat loss within these regions. Both BCRs are characterized by arid environments with shortgrass prairies (Bird Studies Canada and NABCI, 2014). Shortgrass prairies in the mid and southwestern United States are facing heavy degradation and conversion by agricultural activities and urban development (Comer et al., 2018). These losses occur largely on the eastern limit of the curlews breeding range in the Great Plains and may be driving the observed western shift in curlew distribution.

Climate change and habitat loss continue to be omnipresent threats, influencing the distribution of species and threatening their persistence (Mantyka-Pringle et al., 2012;

Jaureguiberry et al., 2022). An estimated 62% of grasslands in North America have been lost (Comer et al., 2018). Habitat loss can influence a species' distribution directly and indirectly. Directly, losing large amounts of habitat may change a species' distribution as they shift to find suitable habitats. Indirectly, agricultural lands that are replacing grassland ecosystems may act as population sinks, ultimately leading to population declines, which in turn would influence a population's centroid position through effects on local abundance. While it appears Long-billed Curlew range dynamics on a large scale may be influenced by climate change, different patterns of distribution shifts at the Bird Conservation Region level indicate other factors, such as habitat availability, may be influencing local distribution and density and may interact with changes brought by climate change.

Future studies should aim to investigate changes in habitat and climate within each BCR to better understand the threats curlews are facing. In particular, these studies could focus on the eastern edge of the breeding range where native grassland loss has been most extreme, to better understand the variable eastward and westward centroid shifts that we detected in certain BCRs. The availability of habitat will largely influence how curlews are able to respond to climate change pressures and dictate whether they are able to continue expanding their range northward or if future range contractions will be expected. Our work demonstrates the importance of examining changes to distribution patterns at both regional and range-wide scales to better predict how future climate change and habitat loss scenarios may impact vulnerable species.

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CHAPTER 4: CONCLUSION

OVERVIEW OF THESIS

The goal of my thesis was to understand if Long-billed Curlews are altering their distributions in British Columbia and across their North American breeding range. I also aimed to provide insight into the drivers behind these changes, especially in light of global climate change and large-scale habitat loss and alteration. Climate change is influencing the distributions of bird populations at a global scale, typically driving poleward latitudinal shifts and pushing bird populations to higher elevations (Parmesan and Yohe, 2003; e.g. Hitch and Leberg, 2007; Nixon et al., 2016; Rushing et al., 2020). Furthermore, changes in land use can influence the distribution of species through alteration of the quality and availability of the habitats that birds rely on (Burgess et al., 2017; Pacifici et al., 2020; Britnell et al., 2023). Chapter 2 focused on understanding the role of land-use changes and climate change in altering British Columbia curlew populations using targeted survey data from 2000/02 and 2022/23. Chapter 3 focused on examining changes in curlew distributions using community science data over 13 years to test if their distributions were shifting on a large scale and additionally, test if populations in different eco-regions were experiencing different distributional changes. Broad distribution patterns can provide important insights, but management is often reflected at the regional scale, and as such understanding regional-level population changes is crucial to effectively managing populations. Additionally, understanding changes at a regional scale allows managers to better predict how the species may respond under various climate and habitat loss scenarios.

My Chapter 2 results uncovered an apparent northern range expansion by ~177 km of the curlew's distribution within British Columbia. Curlews were detected more frequently in agricultural lands and less frequently in grassland habitats. Furthermore, our occupancy models supported these findings as agricultural lands were positively associated with curlew occupancy and grassland habitats were negatively associated with curlew occupancy. These results are consistent with land use changes throughout British Columbia and with patterns of warming. We found a substantial increase in urban land throughout British Columbia. Urban development has likely contributed to grassland loss in the southern regions of British Columbia (Cannings 1999; COSEWIC, 2002). We also found a decrease in agricultural land

in the southern regions, potentially from urban encroachment on agricultural lands, and an increase in agricultural land in the northern regions. Thus, the observed northern range shift in curlews seems to be driven by habitat loss in the south and gain in the north, along with patterns of warming climates in this northern region, providing a climatically suitable region to shift into. Unexpectedly, it appears that climate change is currently beneficial to curlew populations in British Columbia, although this is almost certainly a short-term benefit, as curlews in the north are almost entirely found in agricultural lands, which are possibly lower-quality habitat compared to grasslands and a potential population sink - but this requires further study (see below).

My Chapter 3 results uncovered an overall northern range expansion and centroid shift across the curlew's entire breeding range, as well as a northern centroid shift in BCR 10 (Northern Rockies), consistent with our findings in British Columbia in Chapter 2. This range expansion and centroid shift is likely related to the combined habitat loss and climate pressures discussed in Chapter 2. Contrary to these findings, we found the opposite trend in the other northernmost BCR, BCR 11 (Prairie Potholes), which showed a southeastern centroid shift. This BCR extends from Canada south and east into the United States and curlews have undergone strong population declines in the Canadian portion of this BCR (Smith and Edwards, 2020), which would help explain the southeast centroid population shift towards the core of the species range. Additionally, potential habitat gains in the form of agricultural lands in the eastern portion of BCR 11 may further explain the eastern centroid movement in this BCR. If curlews are occupying this agricultural land, it will likely only be a short-term benefit to curlews as agricultural lands may act as population sinks. Lastly, we found western centroid shifts in BCRs 16 (Southern Rockies Colorado Plateau) and 18 (Shortgrass Prairie), both of which fall within the shortgrass prairies. The shortgrass prairies have declined by about 66% (Wick et al., 2016) and the observed western range shifts are likely related to regional losses that are more prominent on the eastern edge of the shortgrass prairies due to an east-west precipitation gradient, making this region more suitable for crops (National Research Council, 2005; Wick et al., 2016; Lark et al., 2020; Niemuth et al., 2022; U.S. Fish and Wildlife Service, 2023).

It would appear that curlew distribution, on a large scale, is driven by climate change, but on a regional scale, we can see localized differences in the pressures that drive curlew distributions. These results highlight the importance of examining species distribution dynamics at both scales to better predict how future climate change and habitat loss may impact species range-wide.

STRENGTHS OF RESEARCH

Examining the potential implications of both climate change and habitat loss on curlew distribution is a strength of Chapter 2. Many studies discuss either the impacts habitat loss or climate change has had on bird populations, but few studies account for the combined effects of both stressors. When only examining one stressor, it is easy to miss other important factors that may influence species distributions. When examining the results from Chapter 2, if we only examined habitat loss or made inferences based on current climate patterns, we could have easily determined either of these threats to independently be the driver behind the observed distribution shift. Instead, examining these together painted a clearer picture of the interactions climate change and habitat loss appear to have had on curlew distribution. Additionally, we filled a two-decade knowledge gap in the distribution of curlews within the province of British Columbia, which will contribute valuable information to current and future Species at Risk recovery planning documents. Listing decisions rely heavily on population trend and distributional information, so it is essential to have up-to-date data for appropriate conservation decisions and actions to be taken.

Using a community science database to examine both continent-wide and regional distribution trends across a broad temporal period and large spatial area is a strength of Chapter 3. Many species have widespread distributions which makes them difficult to study using small-scale, local surveys. The approach I took in Chapter 3 allowed us to gain insight into curlew distribution from 2010 to 2022 over their entire North American breeding range. Additionally, another strength is the use of Bird Conservation Regions to examine curlew distributions at a scale that has more ecological meaning than examining changes within political jurisdictions. This approach allows us to investigate regional distributions and identify potential drivers, such as habitat loss or climate pressures which provides useful information for management strategies.

LIMITATIONS OF RESEARCH

Due to the lack of targeted Long-billed Curlew surveys in British Columbia, I had to use datasets with varying effort levels, data collection methods, and survey regions in Chapter 2. For example, the early 2000s data did not include non-detection data, which limited our ability to use these data for occupancy modeling. Being able to model occupancy in the early 2000s could have provided additional evidence linking curlew range expansion to habitat loss and climate pressures. Additionally, the early 2000s surveys did not cover the Prince George-Nechako region which left our interpretation of the data open to potential bias. Although we can justify the lack of curlew presence in this region based on eBird data, we cannot completely rule out that curlews were absent from this region given that the curlew-specific surveys of the 2000s were not conducted there. Using eBird data may not provide the fairest assessment of whether a species was present or absent in the early 2000s due to the early stage of development the platform was in at that time. Lastly, in Chapter 2 we only had repeat surveys for 2023. This meant our occupancy model had to estimate the predictors for a large amount of missing data.

In Chapter 3, we used eBird data, which provides large-scale, long-term data useful for modeling species abundance and distribution (Sullivan et al., 2014; Sullivan et al., 2009). However, eBird data has limitations as well, including temporal, spatial, and detection biases, as well as variation in effort (Strimas-Mackey et al., 2023). Temporal biases arise from multiple sources. First, the rise in popularity of eBird has ultimately created a bias in the form of more data in recent years (Strimas-Mackey et al., 2023). This increases the number of detections in more recent years, which may result in an apparent population expansion. To overcome this bias, we used data from 2010 forward (following eBird best practices); however, this limited our analyses to just over a decade, which may have missed larger patterns that occurred before then. Secondly, observers are more likely to report observations during spring migration, leading to a bias in the data, favoring certain time periods (Courter et al., 2013; Sullivan et al., 2014; Strimas-Mackey et al., 2023). This bias can either under- or over-represent certain species, depending on their movement and distribution patterns relative to intense sampling. Spatial biases result from data often being collected around “hot spots”, easy-to-access locations, and large urban centers (Prendergast et al., 1993; Luck et al.,

2004; Kadmon et al., 2004; Strimas-Mackey et al., 2023). Detection biases result from certain birds being easier or harder to detect, which varies by season (Johnston et al., 2014; Johnston et al., 2018; Strimas-Mackey et al., 2023). Curlews are an inconspicuous species that are difficult to detect during nesting (Fellows and Jones, 2009), and as such, eBird checklists are unlikely to have high curlew detection rates during this time. Lastly, eBird can have biases in the sampling effort by observers (Ellis and Taylor 2018; Oliveira et al., 2018; Strimas-Mackey et al., 2023). This includes the distance traveled, time spent, number of observers, and even observer skill level (Ellis and Taylor 2018; Oliveira et al., 2018; Strimas-Mackey et al., 2023). Although these biases can be partially controlled by following eBird Best Practices (Strimas-Mackey et al., 2023), as I have done in Chapter 3, they still introduce bias into the data.

Lastly, in both chapters I am correlating these distributional shifts with both habitat and climate changes in the absence of testing the effects of these changes directly on curlew distribution. We are able to make strong inferences based on available climate and land cover data, as well as the changes in land use uncovered in Chapter 2, however, future work should directly test the effects of climate and land-use on curlew distributions.

IMPORTANCE, MANAGEMENT IMPLICATIONS, AND NEXT STEPS

The results from my thesis highlight potential interacting impacts of climate change and habitat loss on Long-billed Curlew populations, and this is widely applicable to other at-risk grassland species. It appears on a broad scale that climate change is influencing the distribution of curlews, moving the leading edge of their population further north. On a smaller scale, we can see that habitat loss is also influencing the regional distribution of curlews. This information is critical for effective management. Curlews are primarily using agricultural lands in British Columbia and this likely reflects the mismanagement of grassland ecosystems in the province. Agricultural lands have been shown to act as ecological traps or population sinks for other grassland species (e.g. Green et al., 1997; Perlut et al., 2008) and this may be true for curlews, highlighting an important research gap. Nesting in agricultural lands exposes birds to additional sources of mortality including livestock trampling (e.g. Mandema et al., 2013; Beja et al., 2014), machinery (Vickery et al., 2000; Perlut et al., 2008; Shustack et al., 2010), and pesticides (Boatman et al., 2004; Stanton

et al., 2018), as well as increased predation rates (Environment Canada, 2012). Future work should focus on curlew productivity in agricultural lands to understand the viability of the population in this newly expanded region. Furthermore, future work in North America should further investigate the drivers behind the observed changes in the regional patterns of curlew distribution. We can make correlational inferences on what may be driving these shifts, but additional work in the field is necessary to uncover the drivers properly. Lastly, future management strategies in British Columbia and North America as a whole should aim to protect critical grassland habitats.

Traditional Ecological Knowledge has been long ignored with western ecological knowledge at the forefront of modern-day conservation. Indigenous peoples were stewards of the land, protecting and respecting the environment for millennia before colonization. Yet we disregard the in-depth knowledge learned from lived-in experience over thousands of years for our limited knowledge over a significantly shorter timeframe. Since European colonization of North America, we have suppressed fire and this has significantly negatively impacted ecosystems (Backer et al., 2005; Bjorkman and Vellend, 2010). Fire is an essential process for regulating ecosystem services (McLauchlan et al., 2020), however, human needs were prioritized over environmental stewardship. Economic benefits were made to outweigh the ecological cost (Backer et al., 2005), highlighting the human supremacy idealism that settlers introduced to North America. Controlled burns were historically used for many reasons, including managing grassland habitats (Vickery et al., 2000). Indigenous communities in British Columbia used fire to suppress sagebrush and tree encroachment on the grasslands (Blackstock and McAllister, 2004). Without management, woody encroachment occurs leading to low-quality grassland habitats (Vickery et al., 2000), especially for grassland species such as the Long-billed Curlew. Curlews show a strong preference for shortgrass prairies with minimal encroachment and as such, shrub-steppe is largely avoided by curlews (Cannings, 1999). Ultimately, controlled burns of grassland habitats in collaboration with Indigenous partners in British Columbia and across the North American Great Plains should be strongly considered to revive suitable breeding habitats to ensure the long-term survival of Long-billed Curlews.

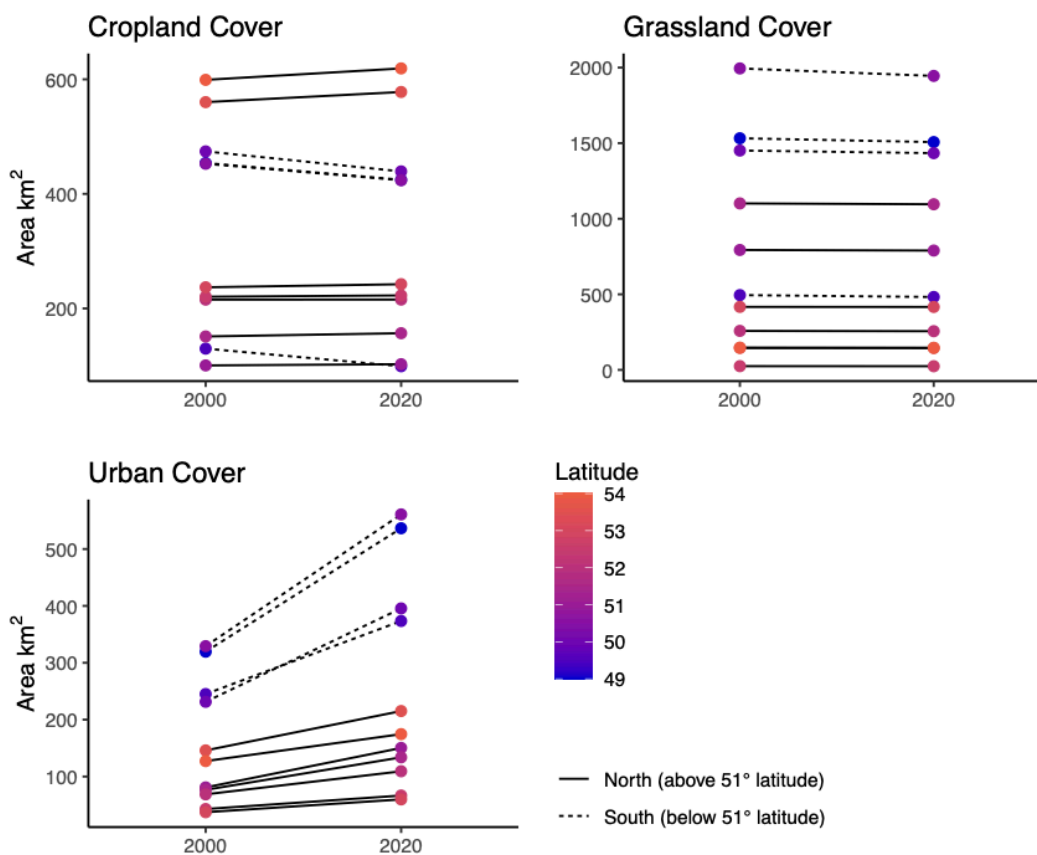
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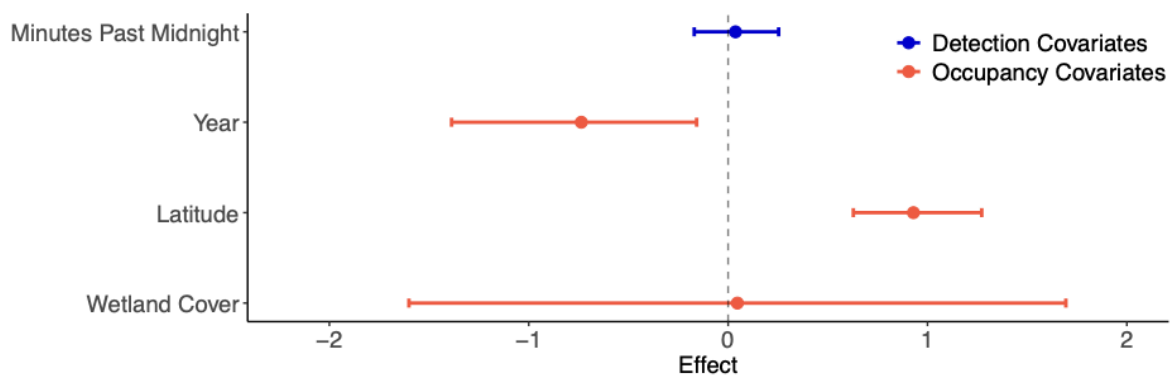
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APPENDIX



Appendix Figure 1. Change in agricultural land, grassland, and urban cover within British Columbia as limited to Long-billed Curlews breeding range from 2000 to 2020.



Appendix Figure 2. Parameter estimates and 95% credible intervals for occupancy and detection covariates from the Bayesian occupancy model with wetland cover as the habitat covariate.

Appendix Table 1. Occupancy and detection probabilities for the top-ranked model which included grassland cover as the habitat covariate. Parameter estimate, standard deviation (SD), and 95% credible intervals (CI).

<i>Grassland Cover Model</i>	<i>Estimate</i>	<i>SD</i>	<i>2.5%</i>	<i>97.5%</i>
<i>Occupancy</i>				
Intercept	-0.194	0.793	-1.741	1.443
Grassland Cover	-0.899	0.301	-1.505	-0.312
Latitude	0.716	0.173	0.396	1.075
Year	-0.757	0.321	-1.418	-0.160
sigma [1 Month.V1]	1.467	0.809	0.470	3.575
<i>Detection</i>				
Intercept	-0.3383	0.217	-0.731	0.111
Minutes Past Midnight	0.0729	0.112	-0.138	0.302

Appendix Table 2. Occupancy and detection probabilities for the second-ranked model which included agricultural land cover as the habitat covariate. Parameter estimate, standard deviation (SD), and 95% credible intervals (CI).

<i>Agricultural Land Cover Model</i>	<i>Estimate</i>	<i>SD</i>	<i>2.5%</i>	<i>97.5%</i>
<i>Occupancy</i>				
Intercept	-0.836	0.791	-2.302	0.855
Agricultural Land Cover	0.832	0.293	0.261	1.404
Latitude	0.739	0.171	0.415	1.092
Year	-0.773	0.322	-1.443	-0.181
sigma [1 Month.V1]	1.425	0.781	0.458	3.450
<i>Detection</i>				
Intercept	-0.3412	0.220	-0.736	0.120
Minutes Past Midnight	0.0718	0.111	-0.14	0.299

Appendix Table 3. Occupancy and detection probabilities for the third-ranked model which included wetland cover as the habitat covariate. Parameter estimate, standard deviation (SD), and 95% credible intervals (CI).

<i>Wetland Cover Model</i>	<i>Estimate</i>	<i>SD</i>	<i>2.5%</i>	<i>97.5%</i>
<i>Occupancy</i>				
Intercept	0.3888	0.787	-1.883	1.294
Wetland Cover	0.0465	0.84	-1.601	1.694
Latitude	0.9294	0.163	0.628	1.272
Year	-0.7363	0.31	-1.387	-0.158
sigma [1 Month.V1]	1.4894	0.813	0.462	3.615
<i>Detection</i>				
Intercept	-0.385	0.216	-0.778	0.0663
Minutes Past Midnight	0.037	0.108	-0.17	0.2535

Appendix Table 4. Linear regression comparing spatial locations of multiple directional measurements from 2010-2022 in curlews North American breeding range

Directional Changes in North American Breeding Range	<i>p-value</i>	<i>Multiple R-squared</i>	<i>Distance and Direction</i>
<i>Northern range limit</i>	0.008	0.48	198 km N
<i>Southern range limit</i>	0.65	0.02	
<i>Eastern range limit</i>	0.0692	0.2692	
<i>Western range limit</i>	0.04	0.34	130 km W
<i>Centroid Latitude Position</i>	9.3x10⁻⁶	0.84	228 km N
<i>Centroid Longitude Position</i>	0.27	0.11	