

Shelter from the storm: Identifying climate change refugia for British Columbia's coastal birds  
under future climate scenarios

by

Julie Galloway  
B.E.S., University of Waterloo, 2016

A thesis submitted in partial fulfillment  
of the requirements for the degree of

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*We acknowledge and respect the lək'wəḡən peoples on whose traditional territory the university stands and the Songhees, Esquimalt and WSÁNEĆ peoples whose historical relationships with the land continue to this day.*

## Supervisory Committee

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Supervisory Committee

Dr. Brian M. Starzomski, Supervisor  
School of Environmental Studies

Dr. Jason T. Fisher, Departmental Member  
School of Environmental Studies

## Abstract

The dual crises of biodiversity loss and climate change pose a complex challenge for conservation management. This study highlights the identification of climate change refugia for coastal birds in British Columbia (B.C.), Canada. Climate change refugia are areas of habitat that are predicted to be buffered from severe climate change impacts, thereby providing important areas of habitat into the future and supporting biodiversity. By identifying climate refugia, conservation managers can allocate resources towards those areas and better understand possible future environmental conditions.

Here, I use Maxent ecological niche models (ENMs) to identify potential climate change refugia for twelve species of coastal birds in B.C. under future climate scenarios. Model variables include the most recent climate change projections from the International Panel on Climate Change (IPCC) and data representing a suite of habitat characteristics (e.g., coastal slope and elevation, land use type, sea level rise projections, and more). The model outputs indicate the relative probability of bird occurrence across their B.C. range through time and under different climate conditions. I show that under the four IPCC climate scenarios studied, outcomes for B.C.'s coastal birds may vary widely. Under the intensive fossil fuel development scenario (SSP5-8.5), the area (square kilometres) of “optimal habitat” (i.e., where probability of occurrence is between 60-100% per 1x1 kilometre grid cell) declines between mid and late century for eight of twelve species studied. For eight of the twelve species, the SSP5-8.5 scenario also has the lowest overall percent cover of optimal habitat at late century when compared to the other scenarios. However, under the other three climate scenarios, species fare better. Under SSP1-2.6 and SSP3-7.0, eleven out of twelve species gain or have no difference in optimal habitat coverage between mid and late century. Under the “middle of the road” scenario (SSP2-

4.5), all twelve species gain optimal habitat between mid and late century. For half of the species studied, models indicate that areas of optimal habitat shift northward over time and under warmer scenarios. For most species, the models do not indicate range expansion outside of birds' current ranges, but the models do indicate the importance of parks and protected areas as climate refugia into the future.

## Table of Contents

<i>Supervisory Committee</i> .....	<i>ii</i>
<i>Abstract</i> .....	<i>iii</i>
<i>Table of Contents</i> .....	<i>v</i>
<i>List of Tables</i> .....	<i>vii</i>
<i>List of Figures</i> .....	<i>viii</i>
<b>Chapter 1: General Introduction</b> .....	<b>1</b>
Literature Cited:.....	<b>9</b>
<b>Chapter 2: Identifying Climate Refugia for British Columbia’s Coastal Birds under Future Climate Scenarios</b> .....	<b>16</b>
<b>2.1 Abstract</b> .....	<b>16</b>
<b>2.2 Introduction</b> .....	<b>18</b>
<i>The Case for Coastal Bird Conservation</i> .....	19
<b>2.3 Methods</b> .....	<b>21</b>
<i>Overview</i> .....	21
<i>Bird Observation Data</i> .....	23
<i>Spatial-temporal Subsampling</i> .....	25
<i>Environmental Variable Selection</i> .....	26
<i>Climate Model Selection</i> .....	29
<i>Environmental Variable Preparation and Addressing Collinearity</i> .....	30
<i>Ecological Niche Modelling</i> .....	31
<b>2.4: Results</b> .....	<b>35</b>
<i>Results Summary</i> .....	35
<i>Comparing Model Outputs by Climate Scenario</i> .....	36
<i>Comparing Model Outputs through Time: Mid versus Late-Century Outcomes</i> .....	<b>36</b>
<i>Model Statistics</i> .....	45
<i>Evidence of Range Expansion in the Ecological Niche Models</i> .....	49
<i>Comparison of Model Outputs and Existing Protected Areas</i> .....	51
<i>Study Limitations and Next Steps</i> .....	52
<b>Chapter 3: Conclusion</b> .....	<b>55</b>
<b>Appendix A: Breakdown of Results by Species</b> .....	<b>59</b>
<i>Black-bellied Plover (Pluvialis squatarola)</i> .....	59
<i>Black Turnstone (Arenaria melanocephala)</i> .....	61
<i>Black Oystercatcher (Haematopus bachmani)</i> .....	63
<i>Dunlin (Calidris alpina)</i> .....	65
<i>Red Knot (Calidris canutus)</i> .....	67
<i>Rock Sandpiper (Calidris ptilocnemis)</i> .....	69
<i>Semipalmated Plover (Charadrius semipalmatus)</i> .....	71
<i>Short-billed Dowitcher (Limnodromus griseus)</i> .....	73
<i>Surfbird (Aphriza virgata)</i> .....	75
<i>Western Grebe (Aechmophorus occidentalis)</i> .....	77
<i>Western Sandpiper (Calidris mauri)</i> .....	79

<i>Whimbrel (Numenius phaeopus)</i> .....	81
<b><i>Appendix B: Supplemental Material</i></b> .....	<b>83</b>
<b><i>Appendix C: Full Ecological Niche Modelling</i></b> .....	<b>85</b>
<b>Ecological Niche Modelling: Black Oystercatcher (<i>Haematopus bachmani</i>)</b> .....	<b>86</b>
<b>Ecological Niche Modelling: Dunlin (<i>Calidris alpina</i>)</b> .....	<b>109</b>
<b>Ecological Niche Modelling: Red Knot (<i>Calidris canutus</i>)</b> .....	<b>117</b>
<b>Ecological Niche Modelling: Rock Sandpiper (<i>Calidris ptilocnemis</i>)</b> .....	<b>125</b>
<b>Ecological Niche Modelling: Short-billed Dowitcher (<i>Limnodromus griseus</i>)</b> .....	<b>133</b>
<b>Ecological Niche Modelling: Semipalmated Plover (<i>Charadrius semipalmatus</i>)</b> .....	<b>141</b>
<b>Ecological Niche Modelling: Surfbird (<i>Aphriza virgata</i>)</b> .....	<b>149</b>
<b>Ecological Niche Modelling: Western Grebe (<i>Aechmophorus occidentalis</i>)</b> .....	<b>162</b>
<b>Ecological Niche Modelling: Western Sandpiper (<i>Calidris mauri</i>)</b> .....	<b>170</b>
<b>Ecological Niche Modelling: Whimbrel (<i>Numenius phaeopus</i>)</b> .....	<b>178</b>
<b><i>Appendix D: Literature Cited</i></b> .....	<b>186</b>

## List of Tables

Table 1: Candidate Species. Global listings include G5 (abundant), G4 (secure), G3 (vulnerable), and G2 (imperiled). B.C. listings include yellow (not at risk), blue (special concern) and red (threatened or endangered). Federal listings could include listing in the Species at Risk Act (SARA), either threatened/endorsed, or listing by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC). Data accessed through the B.C. Conservation Data Centre. The column on the far right (Final # Obs.) indicates the number of observations per species after pre-processing (thinning to one observation per km <sup>2</sup> and eliminating duplicates). .....	24
Table 2: Environmental predictor variables considered for Maxent modelling .....	27
Table 3: Final suite of environmental variables included in Maxent modelling. ....	30
Table 4: Comparison of late-century (2080) model outputs for each species, detailing the amount of optimal habitat (where detection is 60-100% per grid cell) across each species' current range. ....	37
Table 5: Area (square kilometers) of “Optimal Habitat” (60-100% probability of occurrence in each 1x1km grid cell) that overlaps with parks and other protected areas in the late century models. I obtained the spatial layer of all protected areas in B.C. from the Canadian Protected and Conserved Areas Database.....	51

## List of Figures

Figure 1: Study area within Bird Conservation Region 5 (Northern Pacific Rainforest).....	22
Figure 2: Sample Maxent model output showing the original study area (full polygon of Bird Conservation Region 5), compared to the model clipped to the existing range for Black Turnstone (range maps provided by Birdlife International) .....	34
Figure 3: Late-century (2080) model outputs for Black Oystercatcher, contrasting the "middle of the road" SSP2-4.5 output versus the fossil-fuel intensive (SSP5-8.5) output. ....	39
Figure 4: Late-century (2080) model outputs for Black-bellied Plover, contrasting the "middle of the road" SSP2-4.5 output versus the fossil-fuel intensive (SSP5-8.5) output. ....	39
Figure 5: Late-century (2080) model outputs for Dunlin, contrasting the "middle of the road" SSP2-4.5 output versus the fossil-fuel intensive (SSP5-8.5) output.....	40
Figure 6: Late-century (2080) model outputs for Black Turnstone, contrasting the "middle of the road" SSP2-4.5 output versus the fossil-fuel intensive (SSP5-8.5) output.....	40
Figure 7: Late-century (2080) model outputs for Red Knot, contrasting the "middle of the road" SSP2-4.5 output versus the fossil-fuel intensive (SSP5-8.5) output.....	41
Figure 8: Late-century (2080) model outputs for Rock Sandpiper, contrasting the "middle of the road" SSP2-4.5 output versus the fossil-fuel intensive (SSP5-8.5) output. ....	41
Figure 9: Late-century (2080) model outputs for Black Oystercatcher, contrasting the "middle of the road" SSP2-4.5 output versus the fossil-fuel intensive (SSP5-8.5) output.....	41
Figure 10: Late-century (2080) model outputs for Surfbird, contrasting the "middle of the road" SSP2-4.5 output versus the fossil-fuel intensive (SSP5-8.5) output.....	42
Figure 11: Late-century (2080) model outputs for Semipalmated Plover, contrasting the "middle of the road" SSP2-4.5 output versus the fossil-fuel intensive (SSP5-8.5) output.....	42
Figure 12: Late-century (2080) model outputs for Short-billed Dowitcher, contrasting the "middle of the road" SSP2-4.5 output versus the fossil-fuel intensive (SSP5-8.5) output. ....	43
Figure 13: Late-century (2080) model outputs for Western Grebe, contrasting the "middle of the road" SSP2-4.5 output versus the fossil-fuel intensive (SSP5-8.5) output. ....	43
Figure 14: Late-century (2080) model outputs for Western Sandpiper, contrasting the "middle of the road" SSP2-4.5 output versus the fossil-fuel intensive (SSP5-8.5) output. ....	44
Figure 15: Late-century (2080) model outputs for Whimbrel, contrasting the "middle of the road" SSP2-4.5 output versus the fossil-fuel intensive (SSP5-8.5) output.....	44
Figure 16: Late-century (2080) range expansion mapping under the SSP2-4.5 scenario .....	50
Figure 17: Late-century (2080) range expansion mapping under the SSP5-8.5 scenario .....	50
Figure 18: Black-bellied Plover range map created by the author using data from BirdLife International. ....	59
Figure 19: Black Turnstone range map created by the author using data from BirdLife International. ....	61
Figure 20: Black Oystercatcher range map created by the author using data from BirdLife International. ....	63
Figure 21: Dunlin range map created by the author using data from BirdLife International. ....	65
Figure 22: Red Knot range map created by the author using data from BirdLife International... ..	67
Figure 23: Rock Sandpiper range map created by the author using data from BirdLife International. ....	69

Figure 24: Semipalmated Plover range map created by the author using data from BirdLife International. ....	71
Figure 25: Short-billed Dowitcher range map created by the author using data from BirdLife International. ....	73
Figure 26: Surfbird range map created by the author using data from BirdLife International. ....	75
Figure 27: Western Grebe range map created by the author using data from BirdLife International. ....	77
Figure 28: Range map for Western Sandpiper. Yellow indicates migratory habitat. Accessed from the Cornell “All About Birds” database: 5 <a href="https://www.allaboutbirds.org/guide/Western_Sandpiper/maps-range">https://www.allaboutbirds.org/guide/Western_Sandpiper/maps-range</a> .....	79
Figure 29: Whimbrel range map created by the author using data from BirdLife International. .	81

## Chapter 1: General Introduction

On February 18<sup>th</sup>, 2019, after years of unsuccessful attempts to rediscover the species in the wild, the Australian government formally declared the Bramble Cays melomys (*Melomys rubicola*) extinct (Roycroft et al., 2021). This small rodent was endemic to a low-elevation island near the northern tip of the Great Barrier Reef, an area that had experienced rising sea levels and severe flooding for over two decades (Waller et al., 2017). In its report, the state government of Queensland attributed the species' extinction to anthropogenic climate change, making it the first species to have formally gone extinct due to this cause (Roycroft et al., 2021). In their 2017 paper which first recorded the species' likely extinction, Waller et al. state the following:

“This event highlights the immediate need to mitigate predicted impacts of sea-level rise and ocean inundation on other vulnerable species occurring on low lying islands and in susceptible coastal zones through captive breeding and reintroduction or other targeted measures.” (Waller et al., 2017).

Though this was the first species to have been declared extinct due to climate change, it will almost certainly not be the last. The Sixth Assessment Report (AR6) from the Intergovernmental Panel on Climate Change (IPCC), released in April 2022, formally recognizes that the world has now experienced  $\sim 1^{\circ}\text{C}$  of global warming from pre-industrial levels due to human activity (Lynn & Peeva. 2021). Without immediate action to halve global emissions by 2030, rapidly transition energy systems from reliance on fossil fuels, and implement nature-based solutions for climate adaptation, the world will likely experience greater than 1.5 degrees of warming in the next two decades (Thierry et al, 2022). Once  $1.5^{\circ}\text{C}$  of global warming is surpassed, the severity and frequency of adverse climate impacts will increase; these include extreme heat, drought, shifting precipitation patterns, and sea-level rise, among others (Masson-Delmotte et al, 2022).

Unfortunately, even if warming is limited to 1.5°C, some of the impacts of climate change will be irreversible (Masson-Delmotte et al, 2022). Sea level rise is expected to continue beyond the year 2100 even if the optimistic target of 1.5°C is reached (Masson-Delmotte et al, 2022).

According to the AR6, mean global sea level rise is projected to increase by 0.26-0.77 metres by the year 2100 if the world experiences 1.5°C of warming (Masson-Delmotte et al, 2022).

Catastrophic sea-level rise of multiple metres is likely to occur with “medium confidence” over hundreds to thousands of years if the 1.5°C limit is surpassed due to major glacial melting, including the loss of the Greenland ice sheet and Antarctic marine ice (Masson-Delmotte et al, 2022).

Undoubtedly these are dire warnings, but political efforts to instigate meaningful change (e.g., reducing emissions from major emitters) are often thwarted by competing interests, largely economic in nature (Pascual et al, 2022; Westerhoff et al., 2018). To mitigate the worst effects of climate change, the IPCC has clearly stated that we must halve global emissions in seven and a half years (Pascual et al, 2022). Ambitious climate goals were set at COP26 in Glasgow in 2021, but efforts to meet these goals seem to have been thwarted by the multiple coinciding global events that have unfolded over the past few years, with the COP27 proceedings falling short of making significant commitments to phase out fossil fuels (Masood et al., 2022).

Meanwhile, the ongoing global biodiversity crisis presents its own set of complex challenges. A staggering three billion birds have been lost in North America since 1970, with habitat loss cited as the leading cause (Rosenberg et al., 2019). Climate change is likely to exacerbate these declines; according to the National Audubon Society, two thirds of North American bird species will be under threat of extinction due to climate change under an unmitigated climate scenario (RCP 8.5 in the IPCC AR5 climate scenarios) (Bateman et al.,

2020; Wilsey et al., 2019). This figure sounds extreme, but the drastic declines we are witnessing in bird populations speak to it being a possibility, especially among some of the fastest declining groups – aerial insectivores, marshland birds, shorebirds, and range-restricted species (Bateman et al., 2020). Regrettably, in spite of the impending threat of the climate crisis and widespread biodiversity loss, many jurisdictions worldwide lack sufficient legislation to protect species at risk (Westwood et al., 2019). In a Canadian context, British Columbia (B.C.) does not have adequate species at risk legislation and climate change vulnerability is not a formally recognized criteria for species at risk protection (Westwood et al., 2019). Biologists have called for the B.C. government to implement standalone species at risk legislation, noting that B.C. is the most biodiverse province in Canada and yet only portions of its vast landscape are protected under federal legislation (Westwood et al., 2019). According to the 2021 Canadian Protected and Conserved Areas Database, 19.6% of B.C.'s land base is under some form of protection, either as protected areas or OECMs (other effective area-based conservation measure) (Government of Canada, 2023).

Though not the sole intention of this work, my interest in species at risk conservation (and its relationship with climate change) spurred me to investigate which species of B.C. birds might be most affected by climate change, and how this vulnerability might contribute to future development of species at risk legislation in the province. Federally, the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) species specialist subcommittee (SSC) for birds identifies species that are up for assessment due to population decline and other factors (Ray et al., 2021). At the time I began this MSc back in 2017, 32 candidate species were up for status assessment; of these, seven of the eleven high-priority candidates were shorebirds, including commonly observed species such as Sanderling (*Calidris alba*), Dunlin (*Calidris alpina*), and

Killdeer (*Charadrius vociferus*). Currently, only the Wandering Tattler (*Tringa incana*) remains on the high-priority candidate species list, with the Red Knot, *roselaari* type (*Calidris canutus roselaari*) listed as threatened in 2021. Several of the target species in this study have been recognized as species of conservation concern in federal and provincial databases (see Table 1).

Why are coastal bird populations declining at such a rapid rate? Many shorebirds and their allies are long-distance migrants, which are susceptible to changing environmental conditions across their various staging, stopover, and breeding habitats (Both et al., 2010). In coastal habitats, the magnitude of climate-related threats may exceed species' capacity to adapt to environmental change, especially due to the limited geographic extent of coastal habitat (Sims et al., 2013) and the additive effects of human disturbance (Craft et al., 2009; Gittman et al., 2016), land development (Johannessen & Macdonald, 2009), and recreation (Drever et al., 2016), all of which have impacted coastal bird populations. Coastal habitats in British Columbia are expected to experience a range of climate impacts in the future, including extreme heat, ocean acidification (and subsequent die-off of marine invertebrates), seasonal flooding, and sea-level rise (Galbraith et al., 2014). Additionally, many of the staging and stopover habitats for birds in coastal B.C. coincide with dense areas of human settlement, including the Fraser River delta, which provides migratory habitat to approximately 1.5 million migratory birds each year (Cannings, 2005). There is an urgent need for continued research on the projected effects of climate change on coastal habitats and the species which occupy them, particularly coastal birds, as they are considered by many to be indicators of the overall 'health' of coastal ecosystems (Canham et al., 2021; Piersma & Lindström, 2004).

Climate change may impact coastal bird populations in a variety of ways, including nest loss and overtopping from flooding on breeding grounds (van de Pol et al., 2010), changes in the

spatial and temporal availability of food resources (Niehaus & Ydenberg, 2006), and seasonal habitat loss from inundation, leading to increased foraging competition (Kirby et al., 2008). Higher mean temperatures in breeding areas may affect abundance by decreasing chick growth rates and recruitment (Piersma & Lindström, 2004), while rainfall temporarily affects population densities at foraging sites (Murray et al., 2018). Additionally, birds that migrate long distances are threatened by habitat loss and environmental change at all stages of their yearly life cycle, from their nesting sites in the arctic to their wintering habitat in the southern United States and South America (Lyons et al., 2016). For these long-distance migratory species, climate-related phenological change may lead to a mismatch between the timing of arrival at migratory staging grounds and the timing of peak food availability (Both et al., 2010). If long-distance migrants are unable to adapt to changes in the distribution and availability of their prey along their migratory route, this could lead to further population decline (Both et al., 2010). Food availability and its relation to habitat suitability is outside the scope of this research, but it remains an important consideration when determining how coastal birds may be impacted by climate into the future (Niehaus & Ydenberg, 2006). Resident species which remain in temperate coastal habitats year-round may also experience climate-related effects, including inundation in mudflats and intertidal areas, leading to increased foraging competition (Galbraith et al., 2002). Important prey items including intertidal invertebrates (Lawrence & Soame, 2004) and mollusks (VanDusen et al., 2012) display high levels of phenotypic plasticity in response to environmental change, and shorebirds must readily adapt to shifts in the peak abundance of these primary food sources (Adamík & Pietruszková, 2008). In addition to invertebrate prey, biofilm composition and distribution may be affected by rising temperatures; this slimy intertidal substance, comprised mainly of diatoms and bacteria, is a primary food source for migratory shorebirds (Mathot et al.,

2007). This "decoupling" of crucial phenological relationships between predator and prey species may result in further alteration to population-level processes and could be exacerbated by human disturbance (Bruggeman et al., 2015). Although this study did not investigate the impacts of climate change on the quality or distribution of food sources for coastal birds, climate sensitivity analysis from the Pacific Northwest Climate Sensitivity Database indicated that species with restricted diets were more vulnerable to the effects of climate change than generalist species (Correll et al., 2017). Species such as Black Oystercatcher (*Haemotopus bachmani*), though a common sight along coasts of the Pacific Northwest, was ranked "highly vulnerable" to climate impacts in the Pacific Northwest Climate Sensitivity Database due to its restriction to rocky intertidal habitats and its specialized diet (Case et al., 2014).

Through this thesis, I aim to contribute to the growing field of climate refugia and climate change vulnerability studies. As defined by Dr. Toni Lyn Morelli, climate change refugia are "areas relatively buffered from contemporary climate change over time that enable persistence of valued physical, ecological, and socio-cultural resources" (Morelli et al., 2016). This buffering may be due to a combination of geographical and physical characteristics and the unique habitat requirements of a particular species (Morelli et al., 2016). Identifying climate change refugia allows for conservation efforts and resources to be allocated to areas that could provide suitable habitat into perpetuity. George E.P Box's quote that "all models are wrong, but some are useful" (Box, 1976) must be taken into consideration here; though these models are only approximations of future conditions, they are a tool for conservation managers and policy makers to identify which areas may provide a buffer from the worst impacts of climate change (Wilsey et al., 2019). Throughout this thesis, I refer to habitat and areas of "optimal habitat"; here, I define habitat as the spatial manifestation of a species' ecological niche, either during breeding or migration, as

based on standard definitions in the field of ornithology (Hall et al., 1997). For a spatial representation of each species' range, I used the species distribution maps prepared BirdLife International and the Handbook of the Birds of the World (BirdLife International, 2022).

In Chapter 2, I use climate projections from the IPCC's AR6 to develop Maxent ecological niche models (ENMs) for twelve species of coastal bird species in British Columbia, focusing on a suite of species that represent a variety of coastal habitats (from rocky intertidal dwelling species to those that inhabit mudflats) as well as several at-risk species at the federal or provincial level. I developed ENMs at two time periods (middle and end of 21<sup>st</sup> century) for four climate scenarios (referred to as Shared Socioeconomic Pathways in the AR6), ranging from a sustainable development scenario (SSP1-2.6) to an intensive fossil-fuel use scenario where emissions are not reduced (SSP5-8.5) (Cai et al., 2022). By comparing the model outputs and extracting areas where species were most likely to occur (Cobos et al., 2019), we can begin to identify areas of climate refugia along British Columbia's coasts. Overall, I find that under four climate scenarios studied, outcomes for B.C.'s coastal birds may vary widely. Under the scenario with continued warming and intensive fossil fuel use (SSP5-8.5), the area (square kilometres) of optimal habitat (where probability of bird occurrence is between 60-100% per 1x1km grid cell) declines between mid-century (2050) and late-century (2080) for eight of twelve species studied. For eight of the twelve species studied, the SSP5-8.5 scenario also has the lowest overall percent cover of optimal habitat at late century when compared to the other scenarios. However, under the other three climate scenarios, species fare better. Under SSP3-7.0, eleven out of twelve species gain habitat in the optimal category between mid and late century, and under SSP1-2.6, ten species gain habitat in the optimal category while one species has no change. Under the "middle of the road" scenario (SSP2-4.5), all twelve species gain habitat in the optimal category

between mid and late century. For half of the species studied, models indicate that areas of optimal habitat shift northward over time and under warmer scenarios. For most species, the models do not indicate range expansion outside of birds' current ranges, but the models do indicate the importance of parks and protected areas as climate refugia into the future.

From a conservation perspective, I recognize the importance of understanding the impacts of climate change on the entire migratory route of bird species, including impacts to their northern breeding sites and their southern overwintering sites. Given time and resources, I would have expanded this study to encompass birds' full annual migratory habitat. However, for the sake of feasibility and policy applicability, British Columbia was selected as a management unit so that the findings from this work could be relevant to provincial land management decisions, species at risk protection plans, and climate adaptation strategies.

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## Chapter 2: Identifying Climate Refugia for British Columbia's Coastal Birds under Future Climate Scenarios

### 2.1 Abstract

British Columbia's coasts are areas of high biodiversity, providing migratory or breeding habitat for over 1.5 million birds each year. However, in coastal habitats, the magnitude of climate-related threats may exceed species' capacity to adapt to environmental change, especially due to the limited geographic extent of coastal habitat and the additive effects of human disturbance, land conversion, and catastrophic events like disease outbreak and oil spills. In the future, the large densities of birds that migrate along the Pacific Flyway will rely on parcels of coastal habitat that are buffered from the worst climate impacts. These are referred to as climate change refugia. Here, I use Maxent ecological niche models (ENMs) to identify potential climate change refugia for twelve species of coastal birds in British Columbia (B.C.) under future climate scenarios. Variables included in the models include the most recent climate change projections from the International Panel on Climate Change (IPCC) and a suite of habitat characteristics (e.g., coastal slope and elevation, land use type, sea level rise projections, and more). The final model outputs show the relative future likelihood of a bird being present across their current range. I show that under the four most recent climate change scenarios presented by the IPCC, outcomes for B.C.'s coastal birds may vary widely. Under the intensive fossil fuel development scenario (SSP5-8.5), the area (km<sup>2</sup>) of "optimal" habitat (where probability of occurrence is between 60-100% per 1x1km grid cell) declines between mid and late century for eight of twelve species studied. However, under the other three climate scenarios, species fare better. Under SSP1-2.6 and SSP3-7.0, eleven out of twelve species gain habitat in the optimal category between mid and late century. Under the "middle of the road" scenario (SSP2-4.5), all twelve species gain habitat in the optimal category between mid and late century. For half of the

species studied, models indicate that areas of optimal habitat shift northward over time and under warmer scenarios. For most species, the models do not indicate range expansion outside of birds' current ranges, but the models do indicate the importance of parks and protected areas as climate refugia into the future.

## 2.2 Introduction

The worldwide decline in biodiversity is a cause for major concern. A staggering three billion birds have been lost in North America since 1970 (Rosenberg et al., 2019), and according to the National Audubon Society, two thirds of North American bird species will be under threat of extinction due to climate change under an unmitigated climate scenario (RCP 8.5) (Bateman et al., 2020; Wilsey et al., 2019). Habitat loss, thought to be one of the leading causes of avian population decline, is likely to be exacerbated by climate change in the coming decades (Sims et al., 2013). The projected impacts of global climate change, including extreme heat, drought, and ocean acidification, are predicted to impact nest success and survival in birds worldwide (Morelli, 2016). As their environment changes, birds will rely on crucial parcels of habitat that are buffered from the worst impacts of climate change; these are known as climate change refugia (Barrows et al., 2020). By identifying potential climate change refugia, conservation managers can allocate resources to areas that may provide optimal habitat for communities of species into perpetuity (Balantic et al., 2020; Stralberg et al., 2019). In this study, I aim to identify climate change refugia for twelve species of coastal birds in British Columbia (B.C.).

Coastal habitats in B.C. are areas of high biodiversity, sustaining over 1.5 million migratory shorebirds each year and providing habitat for over 300 species of birds (Drever & Hrachowitz, 2017; Johannessen & Macdonald, 2009; Cannings, 2005). However, the cumulative impacts of habitat loss, land use change, and human disturbance have changed the landscape for B.C.'s migratory birds; these impacts are likely to be exacerbated by climate change in the coming decades (Ethier et al., 2020). Winter storms may occur with increasing frequency and magnitude (Mekis et al., 2018), potentially disturbing important areas of migratory stopover habitat (Latimer et al., 2021). Many of the shorebirds that migrate along B.C.'s coasts are range

restricted, relying on small parcels of coastal habitat for foraging and resting during their long migrations (Canham et al., 2021). In southern B.C., popular stopover sites for birds are situated in highly urbanized landscapes with dense coastal infrastructure, engineered coastlines, and a large human population in the surrounding area (Henderson et al., 2013).

The questions I sought to address in this study were threefold:

- 1) For target species, what percentage of their established ranges will provide suitable habitat under future climate scenarios (assuming no range expansion)?
- 2) Will new areas of climate refugia develop outside of these established ranges (e.g., is there evidence for range expansion past the ranges defined by Birdlife International)?
- 3) What percentage of climate refugia overlap with already established protected areas?

Can the findings of this study (i.e., newly identified climate change refugia) feed into the identification of candidate protected areas?

### ***The Case for Coastal Bird Conservation***

Why do shorebirds and their coastal allies matter, and why should the conservation of climate refugia be prioritized? From a philosophical and moral standpoint, one could argue the inherent value of nature for nature's sake, though here I would like to emphasize the importance of coastal birds as indicators of ecosystem health (Sims et al., 2013). The coastal and wetland habitats these birds rely on provide countless ecosystem services for humans, including erosion control, protection from flooding and storms, and carbon sequestration (Galbraith, 2002). As we witness the global decline of bird populations (and biodiversity loss at large), this should raise alarm bells, as biodiversity loss is a symptom of underlying ecological distress; what threatens birds, threatens us (Skidmore et al., 2021; Scmeller et al., 2020). It is crucial that we continue working to understand the extent and cause of avian population decline both globally and at a

regional scale, particularly regarding the added dimension of climate change (Bateman et al., 2019).

Temporally, climate-related hazards are predicted to impact coastal bird habitat throughout the year, affecting many aspects of birds' annual cycles (Kirby et al., 2008). At a regional level, the anticipated effects of climate change in British Columbia include higher mean temperatures, drier summers, increased precipitation in the winters, and increased severity of subtropical winter storms (Pacific Climate Impacts Consortium (PCIC), 2015). Annual precipitation is projected to increase 6% provincewide, while northern coastal B.C. may experience a 6-26% increase in precipitation by the 2080s (PCIC, 2015). In the Lower Mainland, recent climate projections estimate an average sea-level rise of one metre by the year 2100, which will have wide-ranging effects on both the natural and built environment (Fraser Basin Council (FBC), 2016). Although the snowpack in the southern Coastal Mountains is expected to decrease over time, increased temperatures will lead to faster snowmelt, which will increase both the frequency and magnitude of Fraser River floods (PCIC, 2015). Provincewide, increased temperatures will lead to more frequent and higher magnitude flood events, which may cause inundation of breeding habitat and nest failure for coastal species, as well as impacts to foraging habitat availability and quality (Murchison et al., 2016). During the winter months of October to February, subtropical storms and storm surge may lead to damage or loss of wintering foraging habitat for resident species; migratory bird habitat may also be damaged during northward migration season (typically in April and May). Wind conditions, tide, and sea level impact the spatial extent of mudflat and intertidal habitat, which in turn affects the spatial extent of foraging and breeding habitat (Austin & Rehfish, 2003; Galbraith et al., 2002). Drought and extreme heat events are also a major

concern during the nesting season for breeding species, as heat stress to chicks is a major impediment to survival and recruitment (Coxen et al., 2017; Yasué & Dearden, 2006).

Climate experts have emphasized that it is not too late to prevent the worst impacts of climate change, but that the window to prevent  $>1.5^{\circ}\text{C}$  of warming is rapidly closing (IPCC, 2022). There is an urgent need for continued research on the projected effects of climate change on coastal habitats and the species which occupy them, particularly coastal birds, as they are considered by many to be global sentinels of environmental change (Canham et al., 2021; Piersma & Lindström, 2004).

## **2.3 Methods**

### ***Overview***

Through Maxent ecological niche modelling, this study examines whether climate change and climate-related hazards, such as increased wave height, sea-level rise, changing precipitation, and higher temperatures would impact the spatial extent and suitability of coastal bird habitat. To develop Maxent ecological niche models, I followed the workflow described by Cobos et al. in their 2019 paper which followed the release of the *kuenm* package in R (Cobos et al., 2019).

### ***Study Area***

As defined by the U.S North American Bird Conservation Initiative (NABCI), Bird Conservation Region 5 (North Pacific Rainforest; BCR5) includes the entire portion of the Pacific coast of North America, reaching from the Gulf of Alaska to northern California. This study focuses on the portion of coastal B.C. that falls within BCR5 (Figure 1). Coastal habitat in BCR5 is varied, consisting of rocky intertidal areas, mudflats, estuaries, and freshwater wetlands. The southern portion of the conservation region includes some of the most populated areas of the

province, including the Lower Mainland ecoregion, which is particularly vulnerable to the effects of climate-related hazards due to its low elevation, heavily modified coastline, and dense coastal infrastructure (Gustavson et al., 1999).

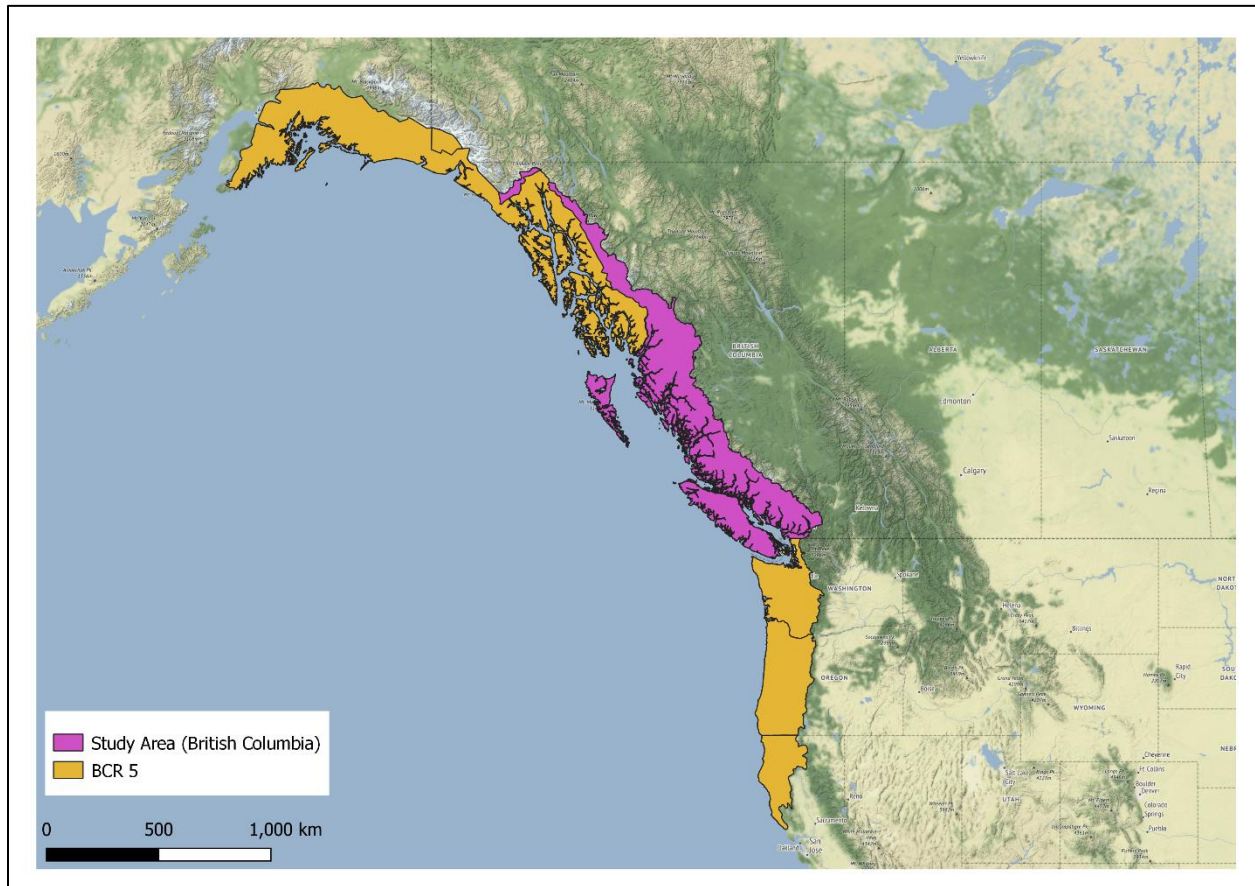


Figure 1: Study area within Bird Conservation Region 5 (Northern Pacific Rainforest)

The original models used the entire B.C. portion of Bird Conservation Region 5 (North Pacific Rainforest, BCR5) as a boundary (Whitehorne et al., 2013), an area spanning approximately 203,000km<sup>2</sup>. I chose BCR5 as a boundary to standardize my outputs, allowing for easier model processing since all the layers that feed into the Maxent model must match in terms of resolution and spatial extent. I also hypothesized that using the same boundary for each species would allow me to identify new areas of range expansion, or to identify climate refugia

outside of each species' established range. However, upon reviewing the results I decided to clip the model output for each species to their B.C. range using range maps produced by Birdlife International<sup>1</sup>. I concluded that for some species, looking at changes within their range may be more biologically meaningful due to the unsuitability of much of the habitat within BCR5, which lies inland and away from the coast.

### ***Bird Observation Data***

The first step in my modelling workflow was to compile a database of bird occurrence data with spatial coordinates. Drawing from eBird community science data, I compiled georeferenced bird occurrences for target species through the Auk package in R (Version 4.1.0), which allows for quick extraction and indexing of the full eBird dataset (Sullivan et al., 2009). Several of the target species were those identified by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) Avian Specialist Subcommittee as high-priority candidates for conservation status assessment. These species include Wandering Tattler (*Tringa incana*) from the 2021 high-priority species list, and Dunlin (*Calidris alpina*), Killdeer (*Charadrius vociferus*), and Whimbrel (*Numenius phaeopus*) from the 2019 high priority list. Additionally, several target species were chosen based on their provincial conservation status rank, though not exclusively shorebirds. These include Short-billed Dowitcher (*Limnodromus griseus*), which is blue-listed (special concern in the provincial database) and Western Grebe (*Aechmophorus occidentalis*), Red Knot (*Calidris canutus*), Whimbrel (*Numenius phaeopus*) and Hudsonian Godwit (*Limosa haemastica*), which are red-listed (endangered or threatened in the provincial database) (B.C. Conservation Data Centre, 2022). I also selected several common coastal species in the Northern

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<sup>1</sup> BirdLife International and Handbook of the Birds of the World (2020) Bird species distribution maps of the world. Version 2020.1. Available at <http://datazone.birdlife.org/species/requestdis>.

Pacific Rainforest that are likely to be indicators of environmental change in the conservation region (Golumbia, 1999; Hazlitt, 2002). These include Black Oystercatcher (*Haematopus bachmani*), Black-bellied Plover (*Pluvialis squatarola*), and Western Sandpiper (*Calidris mauri*) (see Table 1).

To reduce variability and address spatial autocorrelation in the data, eBird lists were filtered to include only checklists that were less than five-hour observation periods, had less than ten observers, and were less than five kilometres in length, according to Cornell’s best practices for eBird data in research (Johnston et al., 2019). All data filtering, modelling and spatial analyses were conducted in R (Version 1.4.1717) and QGIS (Version 3.18.2).

*Table 1: Candidate Species. Global listings include G5 (abundant), G4 (secure), G3 (vulnerable), and G2 (imperiled). B.C. listings include yellow (not at risk), blue (special concern) and red (threatened or endangered). Federal listings could include listing in the Species at Risk Act (SARA), either threatened/endangered, or listing by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC). Data accessed through the B.C. Conservation Data Centre<sup>2</sup>. The column on the far right (Final # Obs.) indicates the number of observations per species after pre-processing (thinning to one observation per km<sup>2</sup> and eliminating duplicates).*

<b>Common Name</b>	<b>Scientific Name</b>	<b>BC List</b>	<b>eBird Presences</b>	<b>Breeding/ Migratory</b>	<b>Federal Listing</b>	<b>Final # Obs.</b>
Black Oystercatcher	<i>Haematopus bachmani</i>	Yellow	8449	B	None	226
Black Turnstone	<i>Arenaria melanocephala</i>	Yellow	2339	M	None	83
Black-bellied Plover (Grey Plover)	<i>Pluvialis squatarola</i>	Yellow	10828	M	None	188
Dunlin	<i>Calidris alpina</i>	Yellow	12688	M	None	260
Hudsonian Godwit	<i>Limosa haemastica</i>	Red	157	M	COSEWIC - T	10
Killdeer	<i>Charadrius vociferus</i>	Yellow	29821	B	None	920
Red Knot	<i>Calidris canutus</i>	Blue	735	M	SARA - E/T	27
Rock Sandpiper	<i>Calidris ptilocnemis</i>	Yellow	136	M	None	18

Semipalmated Plover	<i>Charadrius semipalmatus</i>	Yellow	3898	B	None	150
Short-billed Dowitcher	<i>Limnodromus griseus</i>	Blue	2308	M	None	104
Surfbird	<i>Calidris virgata</i>	Yellow	2737	M	None	102
Wandering Tattler	<i>Tringa incana</i>	Blue	408	M	None	32
Western Grebe	<i>Aechmophorus occidentalis</i>	Red	6060	B	None	328
Western Sandpiper	<i>Calidris mauri</i>	Yellow	11964	M	None	297
Whimbrel	<i>Numenius phaeopus</i>	Red	2606	M	None	109

### ***Spatial-temporal Subsampling***

Spatial autocorrelation and sampling bias are common issues with community science data, particularly for birds, since observations generally tend to be clustered along roadways and popular birdwatching destinations and are correlated at certain times of day (Johnston et al., 2019; Munson et al., 2010). Since eBird observations are opportunistic and do not abide by stringent sampling criteria, it is necessary to correct for spatial autocorrelation (Johnston et al., 2019). To address this, I first clipped the observation data to the extent of the climate data coverage. I then subsampled the observation data using the R “spThin” package, which uses pairwise distance calculations to randomly select observation points according to a user-specified distance in R (in this case, 1km) (Aiello-Lammens et al., 2015). This step deleted individual bird observations with duplicate coordinates (a common occurrence in eBird records) and drastically reduced the number of observation points for each (see Table 1). Deleting duplicate records is necessary to reduce bias in the Maxent models, since we are interested in presence/absence, not abundance; if duplicates exist, the algorithm will weight these locations more than others, even though these locations might be popular geotags used by birdwatchers and not true observances (Newbold, 2010; Elith et al., 2010). Several species that were initially included for analysis (e.g.,

Wandering Tattler and Hudsonian Godwit) had very few records after subsampling and therefore were not included in the next round of modelling.

### ***Environmental Variable Selection***

A variety of environmental factors impact site selection in shorebirds, including substrate, elevation, and land use, along with interspecific competition and food availability (VanDusen, 2012; Hazlitt, 2002). When selecting environmental variables, I aimed to include as many biologically meaningful variables as possible, though food availability and competition were outside the scope of this research. Including the climate data described in the following section, I compiled thirty-five environmental variables (see Table 2 for full descriptions, rationale, and data sources). Raster data were resampled to the cell size and extent of the climate data rasters for consistency and ease of modelling. Certain layers with large spatial coverage, such as the SRTM digital elevation model or the MODIS landcover raster, were downloaded in separate tiles, merged into one raster, and clipped to the study area. Vector data were converted to raster layers, either as binary layers (0/1) (e.g., agricultural land/not agricultural land), or as categorical rasters (e.g., types of protected areas or categories of freshwater wetlands).

Table 2: Environmental predictor variables considered for Maxent modelling

Name	Description	Hypothesis/Rationale for Inclusion
MODIS Land Cover	A LIDAR-derived classification of global land cover available annually between 2001-2017 at a resolution of 500m	This layer provides information on land use, breaking each pixel into sixteen land cover classes. Land cover plays a key role in avian coastal habitat suitability, as certain areas (e.g., urbanized areas, croplands, forests) are unsuitable habitat for coastal birds (Murchison et al., 2016).
Shuttle Radar Topography Mission 1 Arc-Second Global	Worldwide digital elevation model available from NASA at 1 arc-seconds, or 30m resolution	Elevation affects habitat suitability for coastal birds, with most shorebird species preferring to forage and roost above the high-tide line (Hazlitt, 2002). I predicted that elevation would be highly correlated with shorebird presences since most observations would likely be in low-elevation areas, near sea level.
Murray Global Tidal Flat Classification Dataset	Global classification of tidal flat ecosystems	This layer categorizes the full study area into tidal flat, permanent water, or other. I predicted that bird occurrences would be associated with tidal flat areas. According to Murray et al., tidal flats around Vancouver, B.C. have remained relatively stable over the past 33 years, while others worldwide decreased significantly (Murray et al., 2019). However, sea level rise and coastal development may change the extent of intertidal areas in the future (Murray et al., 2019).
Change in Sea Level 2006-2020, and 2006-2099	Geological Survey of Canada (CanCoast) More information on these layers can be found <a href="#">here</a> .	The 2006-2020 dataset shows relative sea level-change in the early 21st century. The 2006-2099 dataset uses a model of global sea level projections for RCP8.5 (James et al., 2019) combined with a model of vertical land motion generated by the Canadian Geodetic Survey (Robin et al., 2019).
Significant Wave Height Including Sea Ice Effects 1996-2005		This dataset shows mean significant wave height under RCP8.5 for 1996-2005.
Coastal Sensitivity Index V2.5.6 (2000s/2090s)		This is an index of coastal sensitivity based on a combination of decadal mean wave height, change in relative sea level, ground ice, coastal materials, backshore slope, and tide range.
Coastal Slope		In this layer, slopes were derived from a digital elevation model created by Natural Resources Canada in 2017.
Linear Coastline features	Linear flood protection features for the province of B.C.	This contains all existing flood protection works, including bank protection and dike crests (Joshua Chan, p. comm.). The shapefile was converted to raster format, with the maximum value (height) of linear features recorded for each cell. I predicted that linear shoreline

		features would be negatively associated with shorebird presences.
Agricultural Land Reserve (ALR) Areas	Areas of the province that have been designated for agricultural use	Shorebirds often use agricultural areas for foraging (Evans Ogden et al., 2007). I predicted that birds would be associated with these areas, but since agriculture was not included as a land use classification type in the MODIS data, I used B.C.-specific data.
Freshwater atlas wetlands and waterbodies	This is a spatial layer of all waterbodies in the province.	I hypothesized that bird observations would be associated with wetlands and waterbodies. This layer broke waterbody types into rivers, lakes, manmade features, and wetlands.
Parks and protected areas	Spatial layer of all protected areas in the province broken down into federal and provincial parks, recreation areas, ecological reserves, wildlife management areas, and NGO conservancies.	I hypothesized that areas of optimal habitat would be strongly associated (and overlap with) parks and protected areas in the province.
Important Bird Areas	IBAs are areas which provide crucial habitat for breeding or non-breeding birds based on key criteria (e.g., areas inhabited by species at risk, endemic species, species that are representative of a biome, or sites which contain notable concentrations of birds). I hypothesized that bird presences would be associated with IBAs.	

### *Climate Model Selection*

The next step in my modelling workflow was to create a baseline ecological niche model for each species. To do this, I used the bird observation data described previously, the environmental variables, and an ensemble General Circulation Model (GCM) of 1991-2020 climate ‘normals’ (based on Prism and Worldclim data) (Mahony et al., 2022). I then projected this model into future climate scenarios, measuring GCM-averaged changes from baseline conditions. For each climate scenario, I used an ensemble model of 13 (GCMs) from the IPCC’s most recent climate models, the Coupled Model Intercomparison Project phase 6 (CMIP6), at two thirty-year periods (2041-2070 and 2071-2100). An ensemble model is the combination of multiple individual climate model runs, averaged into one model. They are often used in climate research as they have less individual variability than individual model runs (Mahony et al., 2022). The climate data used in this study is available through AdaptWest, a spatial database providing open-source climate data (Mahoney et al., 2022). The GCMs in the ensemble models have been statistically downscaled to a finer resolution than the original IPCC data outputs to best represent the range of possible future conditions in North America (Mahony et al., 2022).

I included four emission scenarios (known as Shared Socioeconomic Pathways (SSPs) in CMIP6): SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5. SSP2-4.5 is like the RCP 4.5 scenario from the previous (fifth) phase of the CMIP (CMIP5); both represent  $\sim 3^{\circ}\text{C}$  of warming, but SSP2-4.5 shows higher overall emissions than RCP 4.5 and a slower rate of emissions reduction (Gidden et al., 2019). SSP1-2.6 represents a scenario where warming is limited to below  $2^{\circ}\text{C}$ , while SSP3-7.0 and SSP5-8.5 are the “middle-of-the road” and “fossil fuel intensive” scenarios, respectively (Gidden et al., 2019).

### ***Environmental Variable Preparation and Addressing Collinearity***

I assessed the habitat covariates for collinearity using the *ENMTools* package in R and the *MOLUSCE* plugin in QGIS (Version 2.18). Although machine learning algorithms like Maxent handle collinearity well (Phillips & Dudík, 2008), eliminating correlated variables in Maxent's overall performance and increases the statistical validity of the models (Morales et al., 2017). Highly correlated variables were eliminated based on Pearson correlation coefficients (>0.5) to reduce collinearity in the final suite of variables; I eliminated wave height and ocean depth, since elevation is more relevant than ocean depth and the coastal sensitivity index includes wave height. All habitat covariates were resampled to a 1-km resolution, which matches the resolution of the AdaptWest climate data and approximates the scale at which habitat patterns are believed to impact shorebird habitat selection, estimated to be between 1.25-2km (Albanese et al., 2012). Likewise, several climate variables were eliminated due to lack of relevance to the study species or correlation. Climate variables used in further analyses were selected based on their level of correlation and their biological relevance. The final suite of climate variables is included in Table 3 below.

*Table 3: Final suite of environmental variables included in Maxent modelling.*

<b>Code</b>	<b>Description</b>
MAT	Mean annual temperature (°C)
MAP	Mean annual precipitation (mm)
AHM	Annual heat moisture index, calculated as $(MAT+10)/(MAP/1000)$
MWMT	Mean temperature of the warmest month (°C)
MCMT	Mean temperature of the coldest month (°C)
SHM	Summer heat moisture index, calculated as $MWMT/(MSP/1000)$
MSP	Mean summer (May to Sep) precipitation (mm)
TD	Difference between MCMT and MWMT, as a measure of continentality (°C)
EXT	Extreme maximum temperature over 30 years
Modis	Land use classification
	Wave height (1996-2005)

Sea level change (2006-2020)  
Coastal slope  
Intertidal areas  
Coastal sensitivity index (2000s)  
Important bird areas  
Protected areas  
Freshwater wetlands

### ***Ecological Niche Modelling***

I used Maxent as an ecological niche modelling method due to its overall robustness and high degree of customization, particularly with the open-source release of the software (Phillips et al., 2017). Maxent is one of the most popular open-source tools for ecological niche modelling and there is a wealth of literature available to inform which parameters should be used and how best to interpret and use the results (Guillera-Arroita et al., 2014; Merow et al., 2013). I used the *kuenm* package in R to develop the Maxent models as it allows for the automation of candidate models and statistical evaluation of the top models based on AICc<sup>3</sup>, ROC<sup>4</sup>, and AUC<sup>5</sup> (Cobos et al., 2019). For each model, I randomly split the observation data into training (80% of data) and testing (20% of data) datasets. Using the *kuenm* package, I created a set of 585 candidate models for each species to test a broad range of parameter combinations in Maxent, including different sets of environmental variables, various regularization multiplier values, and different feature classes. These candidate models used the baseline climate data and the final suite of

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<sup>3</sup> AICc: Akaike Information Criterion (AIC), corrected for small sample sizes. AIC is a value indicating the best-fit model from a series of possible models, based on the number of independent variables and how well the model reproduces the data.

<sup>4</sup> ROC: Receiver Operating Characteristic – a statistic used to show the performance of any kind of classification model, including machine learning models. The name comes from its military origin (relating to radar). When graphed, the ROC is a curve which plots true positives vs. false positives.

<sup>5</sup> AUC: area under the ROC curve, another statistic used to determine how well a machine learning model is performing. Measured from 0 to 1. A model with no wrong predictions has an AUC value of 0 and a model with only wrong predictions has a value of 1.

environmental predictor variables. Instead of using the default regularization multiplier values in the *kuenm* parameters, I used a recommended suite of values which is better suited to smaller sample sizes (1,2,5,10,15,20), following recommendations from Morales et al. (Morales et al., 2017). I selected the raw Maxent output type for the candidate models (Phillips et al., 2017). The formula for the raw Maxent output is  $f_1(\mathbf{z})/f(\mathbf{z})$ , where  $f_1(\mathbf{z})$  is the “conditional density of the covariates at the presence sites” and  $f(\mathbf{z})$  is the “marginal density of the covariates across the study area” (Elith et al., 2010). As Maxent is a machine learning algorithm, its inputs differ from conventional modelling methods (logistic regression, etc.).

After running the candidate models, I used the “*kuenm\_ceval*” function to evaluate the best models for each species based on statistical significance (partial ROC), prediction ability (omission rates) and model complexity (evaluated using AICc) (Cobos et al., 2019). The top model for each species is listed in Table 5. Unfortunately, due to the large size of the dataset and lack of processing power, the Killdeer model did not successfully run after many attempts, and this species could not be included in the next steps.

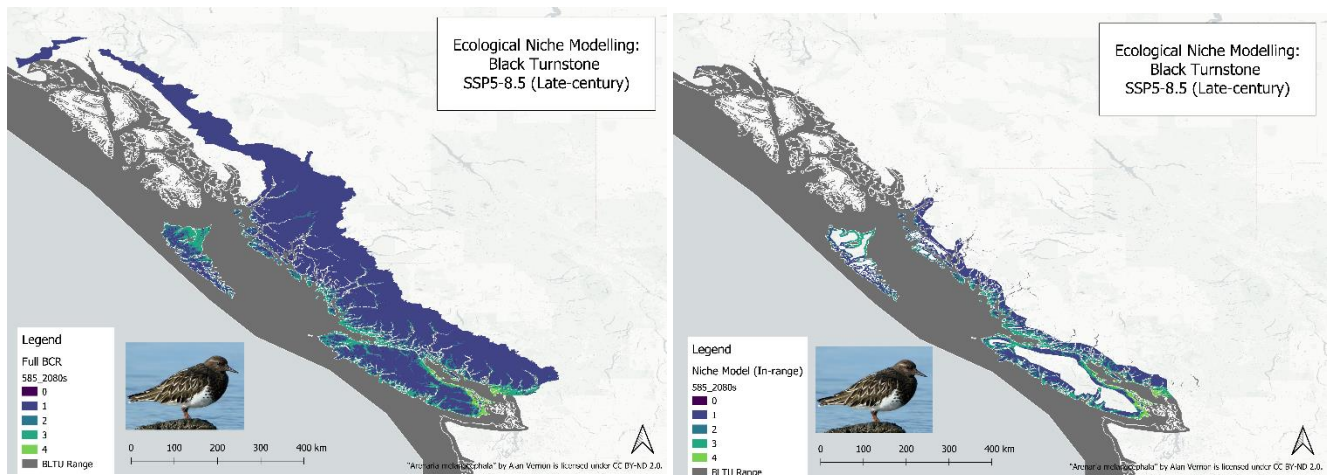
The top model for each species from the previous step (identified through AICc, ROC and omission rates, see Table 4) was used to create the final suite of models for each species, each with ten replicates, using bootstrap replication and the jackknife function to compare variable importance. At this stage, I projected the final models to the future climate scenarios and time periods, which was a considerable computational task. I used the “clamping” option in Maxent to restrict the range of values in the environmental variables to the values used in the training models, which reduces uncertainty in the final models by preventing extrapolation beyond the range of observed data. These final models (created with the “*cloglog*” transformation with bootstrap replication and ten replicates) represent an estimate of occurrence

probability on a scale of 0-1 (e.g., each 1x1km grid cell was given a value between 0 and 1). After running the final models, I used the post-processing model statistics function in the *kuenm* package to calculate the mean values of each grid cell across the ten model runs. I then reclassified the output rasters, binning the data to a six-point scale based on occurrence probability (see Table 5 below). I then converted the outputs to vectors. Before binning, probability of occurrence scores ranged from 0-1. Since I wanted to compare the likelihood of bird occurrence in each grid cell across time periods and climate scenarios, and this feat was difficult given the size of the study area, I binned the cells together into three categories: marginal habitat (0-19% probability of occurrence), moderate (20-59%), and optimal (60-100%). 0% probability of occurrence in the model does necessarily mean there is no chance of a bird occurring in that location; because the outputs were clipped to the formally established range for each species, technically a bird could be found throughout that entire range, but the probability of occurrence is relative. I then calculated the spatial coverage (in terms of area, km<sup>2</sup>) for each habitat class polygon, which allows us to compare between the mid- and late-century outputs for each climate model.

*Table 4: Habitat classes and their respective values (% probability of occurrence, e.g., probability of one individual bird being present in each 1x1km grid cell)*

<b>Model Value</b>	<b>Category</b>	<b>Habitat Class</b>	<b>Explanation</b>
0 – 0	Marginal	0	0% probability of occurrence ( )
0.01 – 0.19		1	<19% probability of occurrence
0.20 – 0.39	Moderate	2	20-39% probability of occurrence
0.40 – 0.59		3	40-59% probability of occurrence
0.60 – 0.79	Optimal	4	60-79% probability of occurrence
0.80 – 1.0		5	80-100% probability of occurrence

I clipped the final model output to the current range for each species using range maps produced by Birdlife International (Birdlife International, 2022). These maps are more useful and intuitive than looking at the entire BCR5 polygon due to the unsuitability of much of the habitat within BCR5, which lies inland and away from the coast. See for instance a comparison of the model outputs for Black Turnstone, with the full BCR5 model on the left (in colour) and the range identified by Birdlife International on the right (dark grey). Clipping the model output allowed me to better understand climate effects in the species' actual habitat, as described in the following sections.



*Figure 2: Sample Maxent model output showing the original study area (full polygon of Bird Conservation Region 5), compared to the model clipped to the existing range for Black Turnstone (range maps provided by Birdlife International)*

As a final step, I overlaid the model outputs for each species with geospatial layers from the Canadian Protected and Conserved Areas Database (CPCAD). This database is managed by Environment and Climate Change Canada (ECCC) in collaboration with federal, provincial, and territorial jurisdictions. This database contains recent (2021) data on marine and terrestrial protected areas and other effective area-based conservation measures (OECM) in Canada. I was curious about what percentage of “optimal” habitat in the Maxent models (where there was 60-

100% likelihood of bird occurrence) would overlap with existing parks and protected areas in B.C. over time and under different climate scenarios. This information helps to inform whether existing protected areas will serve as climate change refugia in the future.

## **2.4: Results**

### ***Results Summary***

Using Maxent (Merow et al., 2013), I developed ecological niche models for twelve species of coastal birds at two time periods (mid and late 21<sup>st</sup> century), using four of the most recent climate scenarios presented by the International Panel of Climate Change (IPCC) in their Sixth Assessment Report (IPCC, 2022). I binned the cells into six habitat classes to better facilitate comparisons in spatial coverage (area sq km<sup>2</sup>) of each class between climate scenarios and over time (see Table 4). By binning the rasters into habitat classes (0-5) and then aggregating these scores into broader descriptive categories (e.g., Marginal, Moderate, and Optimal), this facilitates easier comparison of the model outputs over time and between climate scenarios. Here, I also aimed to simplify the data visualization process, because it is easier to visually depict changes in an area over time (and between climate scenarios) if the values are binned into a smaller, but still meaningful number of categories. This also facilitates easier identification of climate refugia. I then clipped each species' final model to their corresponding range map within B.C. (Birdlife International, 2021). The final model outputs are displayed in [Appendix C](#), with each map showing the likelihood of a bird being present in each 1x1km grid cell.

There are two ways to interpret the differences in the models: by climate scenario (e.g., by comparing the differences in habitat class coverage at mid and late century under each climate scenario); or by looking at a particular time period (for instance, the late-century outcomes) and comparing the outputs of the four models at that time period.

### ***Comparing Model Outputs by Climate Scenario***

Overall, I found that under the four most recent climate change scenarios presented by the IPCC, outcomes for B.C.'s coastal birds may vary widely. Under the intensive fossil fuel development scenario (SSP5-8.5), the area (km<sup>2</sup>) of “optimal” habitat (where probability of occurrence is between 60-100% per 1x1km grid cell) declines between mid and late century for eight of twelve species studied. However, under the other three climate scenarios studied, species fare better. Under the “sustainability” (SSP1-2.6) and “divided” (SSP3-7.0) scenarios, eleven out of twelve species gain habitat in the optimal category between mid and late century (i.e., the spatial coverage of the optimal habitat category increases). Under the “middle of the road” scenario (SSP2-4.5), all twelve species gain habitat in the optimal category between mid and late century. There was evidence that optimal habitat (where there is 60-100% probability of encountering a bird) will shift northward over time for more than half of the species studied, while optimal habitat in southern portions of their range shrinks. There was little evidence of range expansion outside of the birds' current ranges.

### ***Comparing Model Outputs through Time: Mid versus Late-Century Outcomes***

Another way to interpret the model outputs is to choose a particular time period and compare each of the four climate scenarios to determine which scenario may have the most drastic effect on the amount of “optimal” habitat available at that time. The table below provides the amount of optimal habitat (where probability of detecting a bird in each grid cell ranges between 60-100%) in the 2080 model outputs for each species. For eight of the twelve species, the SSP5-8.5 model has the lowest coverage of optimal habitat when contrasted with the other models at late century. To put it simply, there is evidence here that habitat suitability for shorebirds can be linked to climate change; under the intensive fossil-fuel development scenario,

where warming is not limited to 1.5°C, three-quarters of shorebirds in this study would have less “optimal” habitat available to them than under the less severe scenarios. Observers would be less likely to detect birds within the bounds of their current range, and the remaining areas of “optimal” habitat would become climate refugia where habitat remains suitable.

<b>Species Name</b>	<b>SSP1 – 2.6</b>	<b>SSP2 – 4.5</b>	<b>SSP3 – 7.0</b>	<b>SSP5 – 8.5</b>
<b>Black-bellied Plover</b>	16%	6%	8%	1%
<b>Black Oystercatcher</b>	27%	27%	24%	15%
<b>Black Turnstone</b>	16%	24%	30%	4%
<b>Dunlin</b>	2%	3%	3%	1%
<b>Red Knot</b>	7%	14%	15%	0%
<b>Rock Sandpiper</b>	15%	25%	38%	48%
<b>Semipalmated Plover</b>	5%	3%	15%	0%
<b>Short-billed Dowitcher</b>	80%	80%	62%	52%
<b>Surfbird</b>	6%	8%	10%	11%
<b>Western Grebe</b>	21%	29%	33%	10%
<b>Western Sandpiper</b>	3%	4%	5%	6%
<b>Whimbrel</b>	8%	12%	15%	19%

*Table 4: Comparison of late-century (2080) model outputs for each species, detailing the amount of optimal habitat (where detection is 60-100% per grid cell) across each species' current range.*

On the following pages, I provide a sample of the Maxent ecological niche modelling outputs for each species included in this study. The full suite of models is accessible in [Appendix C](#). The maps below show the contrast between late-century (2080) model outputs for SSP2-4.5 (the “middle-of-the-road” climate scenario) and SSP5-8.5 (fossil-fueled development). There are several notable findings in the model outputs. For instance, in the Black Oystercatcher models,

there is evidence that the northern coast of British Columbia and Haida Gwaii will become areas of climate refugia under a warmer, fossil-fuel intensive climate scenario (evidenced by the amount of Class 4 habitat in these areas, in green), while much of Vancouver Island will become less suitable for Black Oystercatcher under the warmer scenario. It is important to note here that this does not mean that areas in their current range will be entirely unsuitable, but that according to the models, the likelihood of encountering a bird will be less when compared to other areas in their range. Similar patterns can be found in the model outputs for Black-bellied Plover, Black Turnstone, Dunlin, Semipalmated Plover, Red Knot, and Western Grebe, with many of the yellow areas identified as optimal habitat in 2080 under the moderate climate scenario models (SSP2-4.5) presenting as less suitable in the SSP5-8.5 models. For other species, such as Western Sandpiper and Whimbrel, the late-century models indicate that under the unmitigated climate scenario, conditions on the southern coast of British Columbia and Vancouver Island may become more suitable than before, perhaps allowing for new areas of habitat to form. Likewise, the Surfbird model shows negligible change in most areas, with only Haida Gwaii presenting as more suitable in the late-century SSP5-8.5 model. The models for Rock Sandpiper and Short-billed Dowitcher present the strangest results, likely owing to the small number of samples that fed into the initial models; these models seem to overestimate the amount of suitable habitat available.

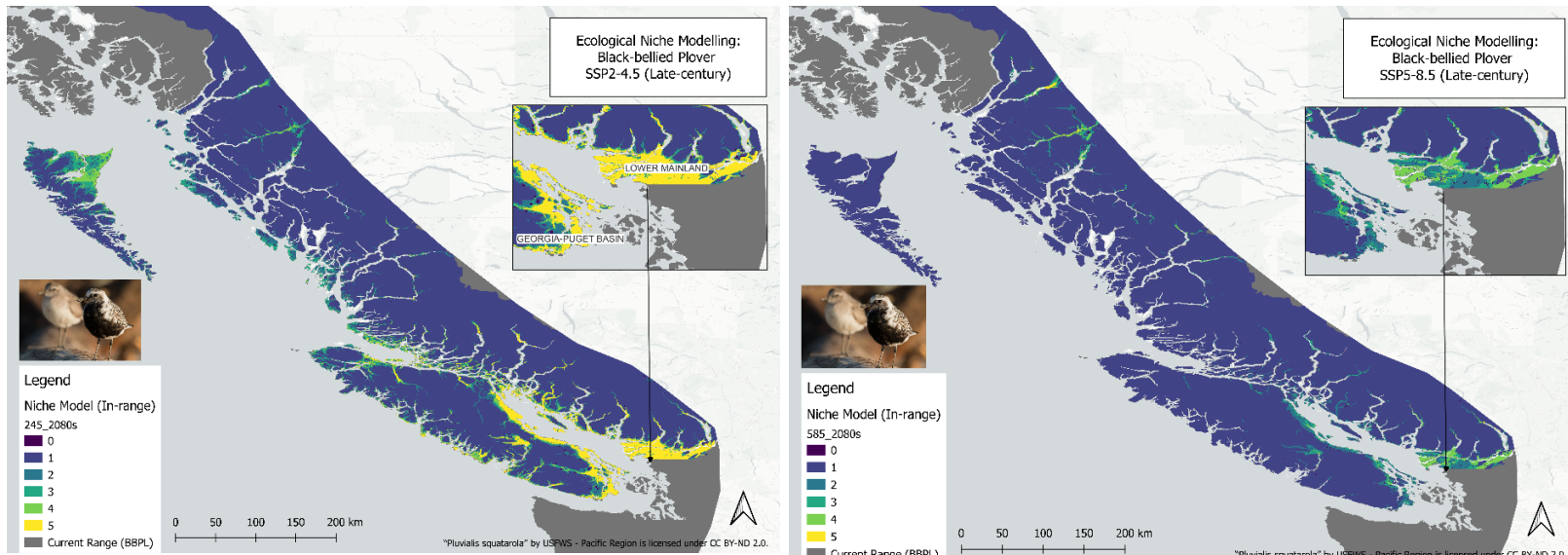


Figure 4: Late-century (2080) model outputs for Black-bellied Plover, contrasting the "middle of the road" SSP2-4.5 output versus the fossil-fuel intensive (SSP5-8.5) output.

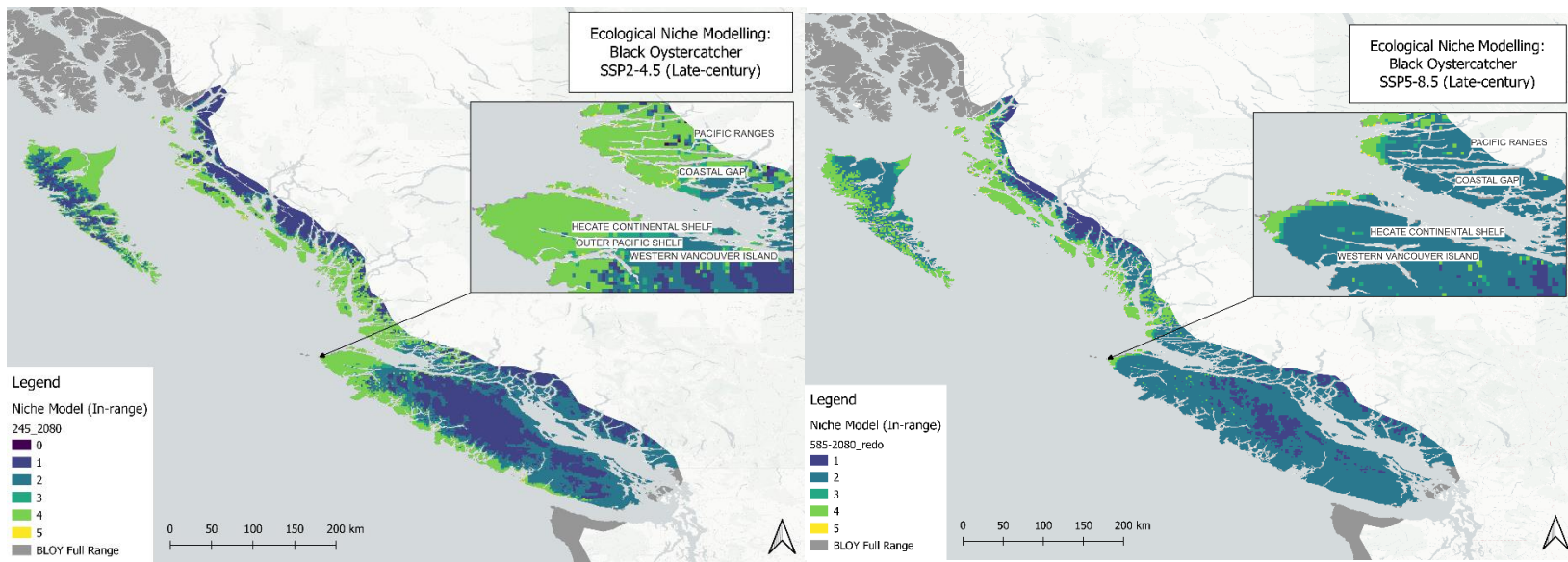


Figure 3: Late-century (2080) model outputs for Black Oystercatcher, contrasting the "middle of the road" SSP2-4.5 output versus the fossil-fuel intensive (SSP5-8.5) output.

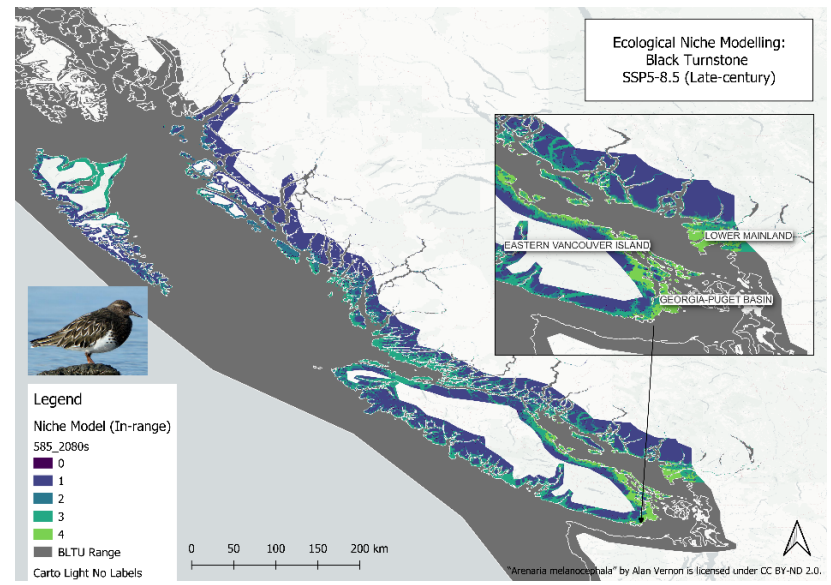
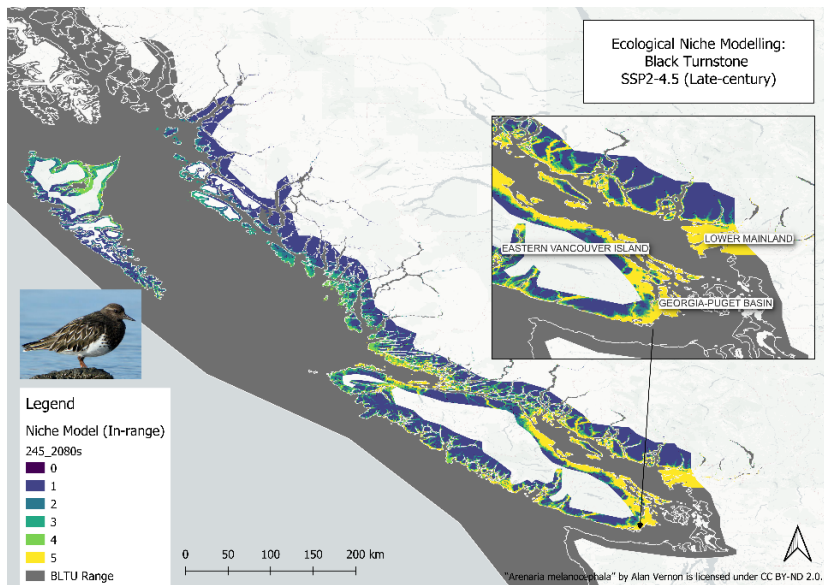


Figure 6: Late-century (2080) model outputs for Black Turnstone, contrasting the "middle of the road" SSP2-4.5 output versus the fossil-fuel intensive (SSP5-8.5) output.

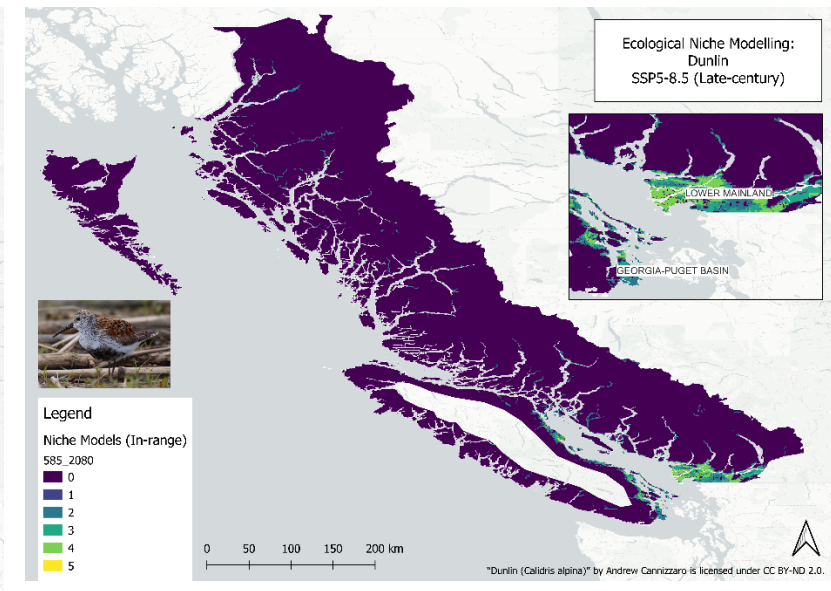
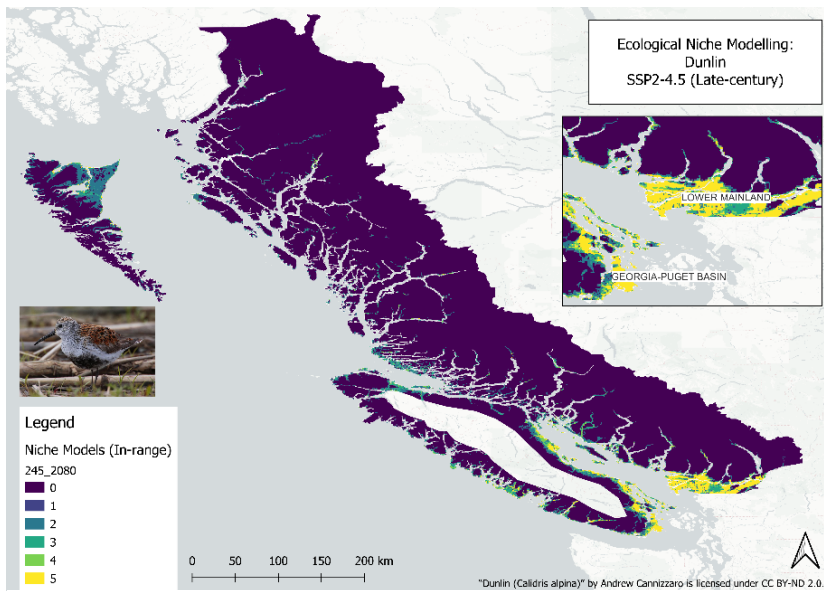


Figure 5: Late-century (2080) model outputs for Dunlin, contrasting the "middle of the road" SSP2-4.5 output versus the fossil-fuel intensive (SSP5-8.5) output.

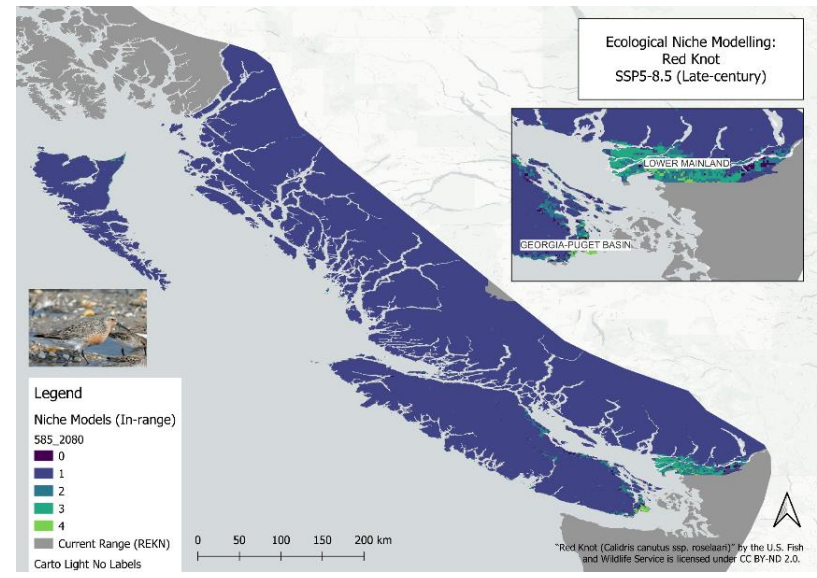
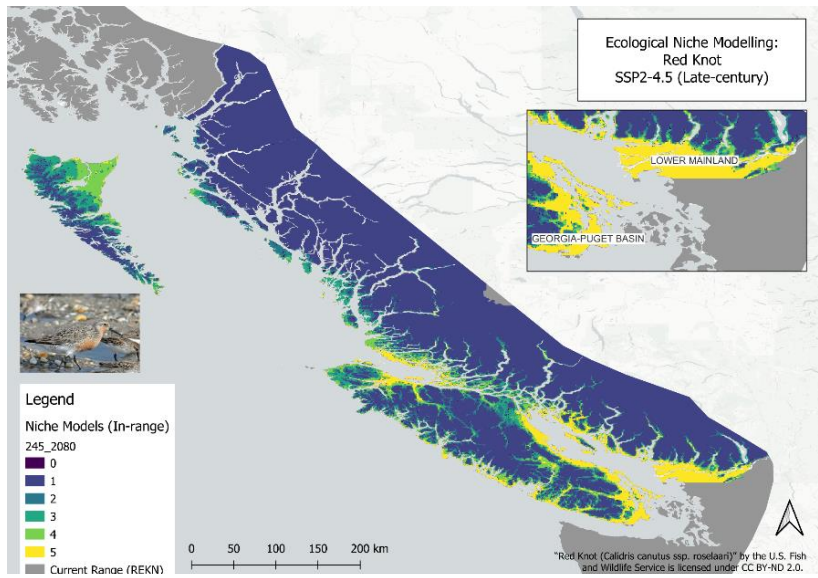


Figure 7: Late-century (2080) model outputs for Red Knot, contrasting the "middle of the road" SSP2-4.5 output versus the fossil-fuel intensive (SSP5-8.5) output.

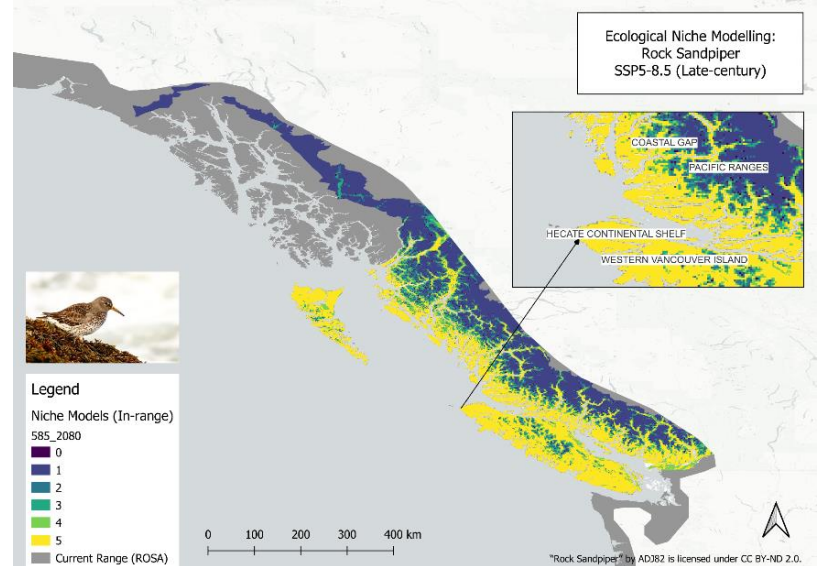
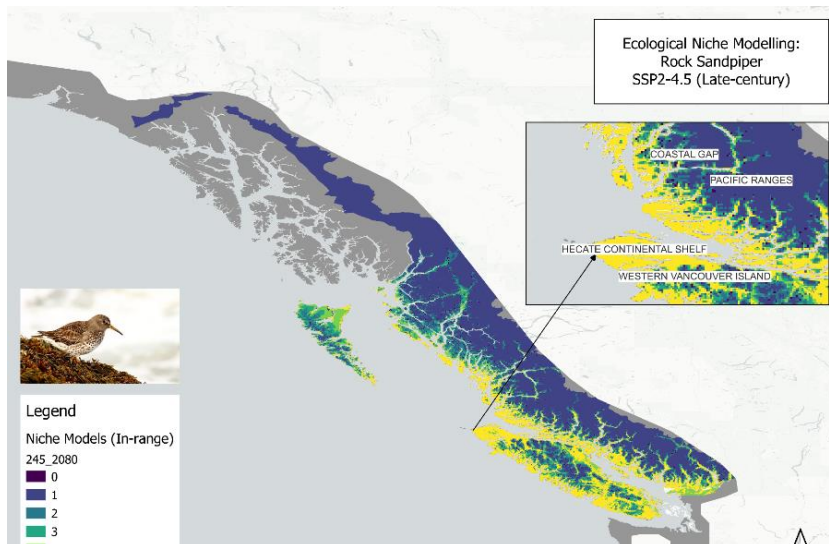


Figure 8: Late-century (2080) model outputs for Rock Sandpiper, contrasting the "middle of the road" SSP2-4.5 output versus the fossil-fuel intensive (SSP5-8.5) output.

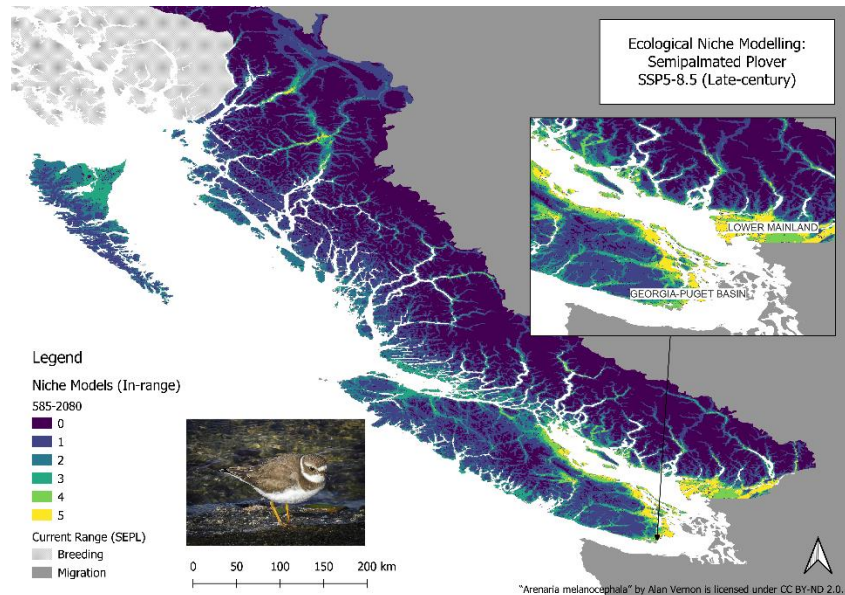
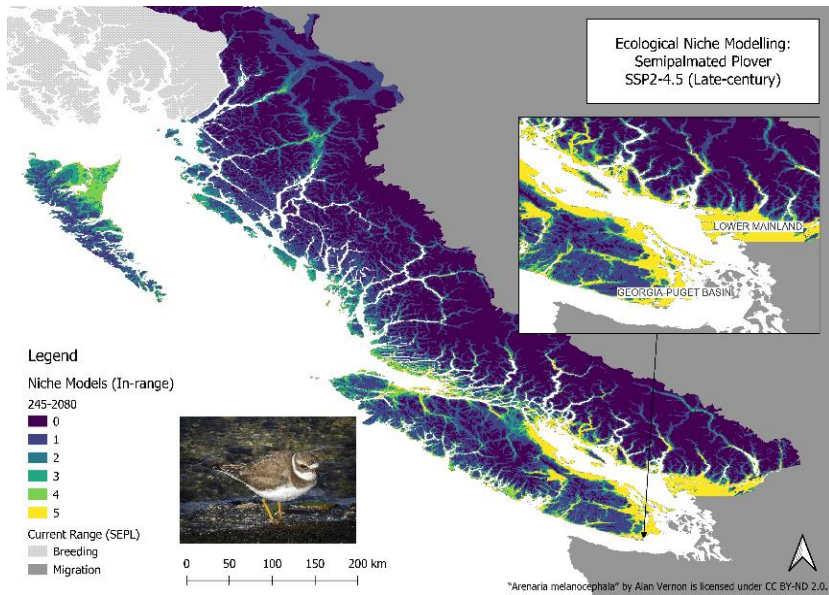


Figure 11: Late-century (2080) model outputs for Semipalmated Plover, contrasting the "middle of the road" SSP2-4.5 output versus the fossil-fuel intensive (SSP5-8.5) output.

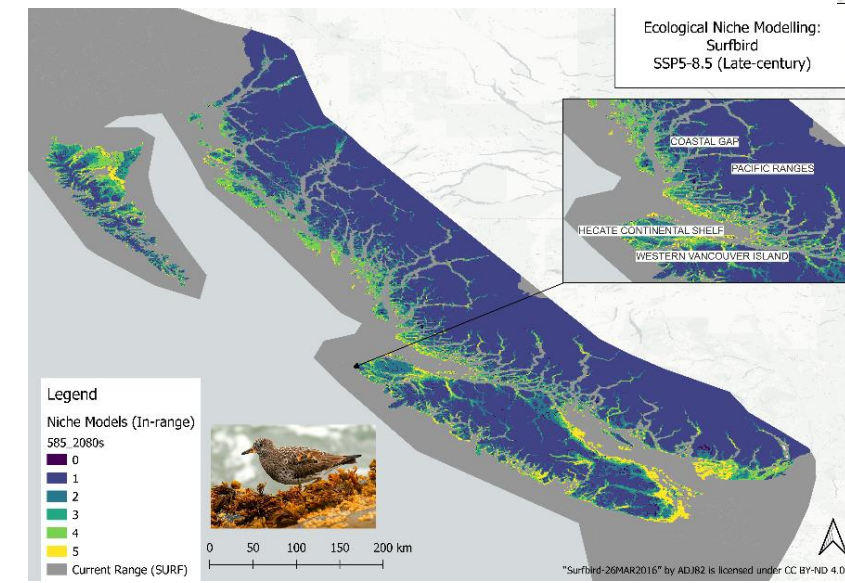
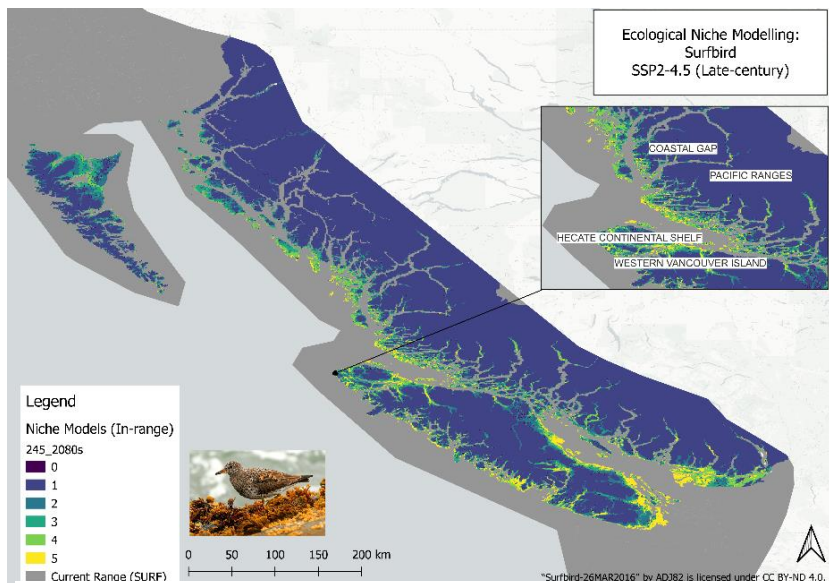


Figure 10: Late-century (2080) model outputs for Surf Screeper, contrasting the "middle of the road" SSP2-4.5 output versus the fossil-fuel intensive (SSP5-8.5) output.

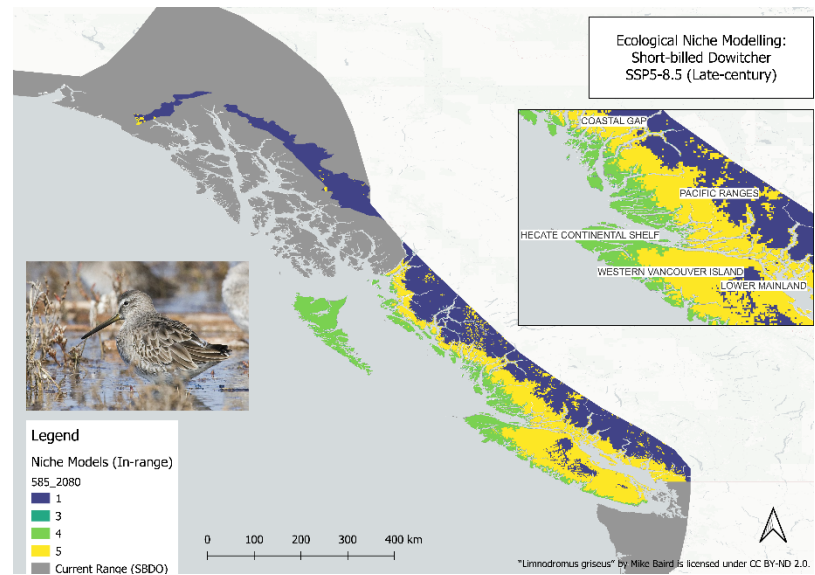
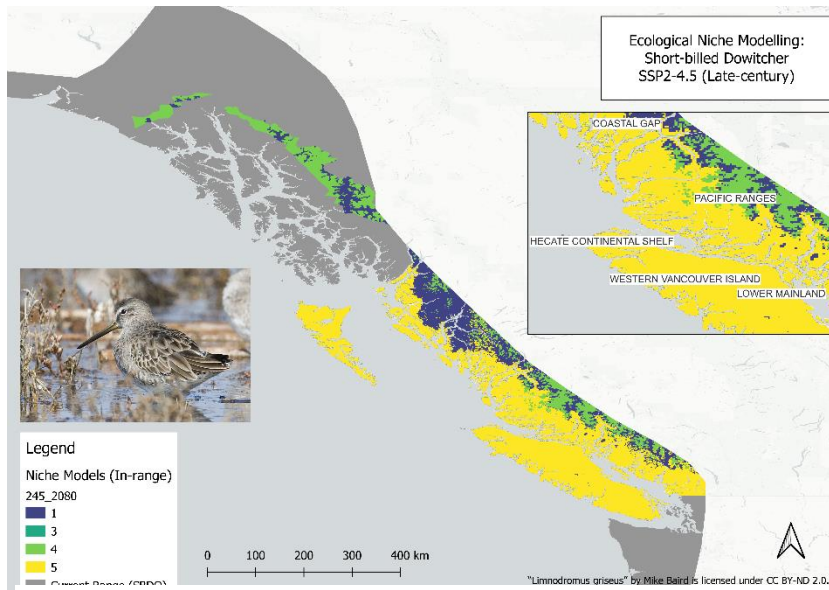


Figure 12: Late-century (2080) model outputs for Short-billed Dowitcher, contrasting the "middle of the road" SSP2-4.5 output versus the fossil-fuel intensive (SSP5-8.5) output.

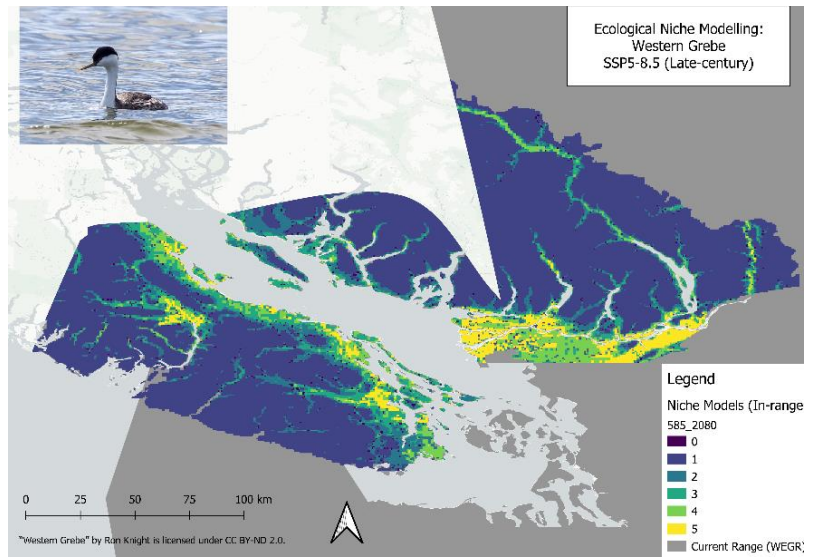
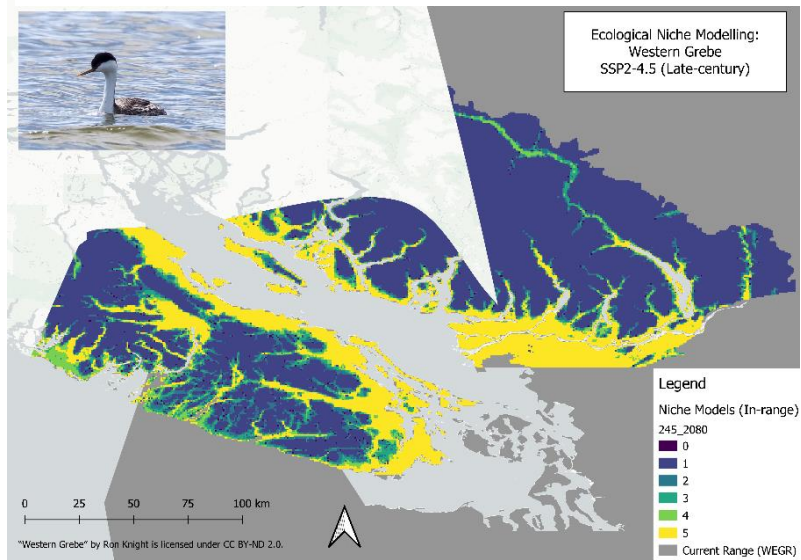


Figure 13: Late-century (2080) model outputs for Western Grebe, contrasting the "middle of the road" SSP2-4.5 output versus the fossil-fuel intensive (SSP5-8.5) output.

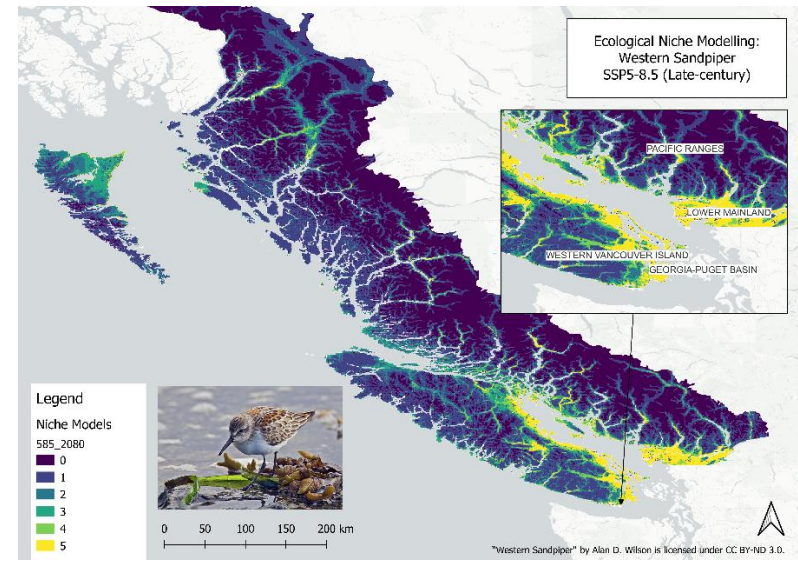
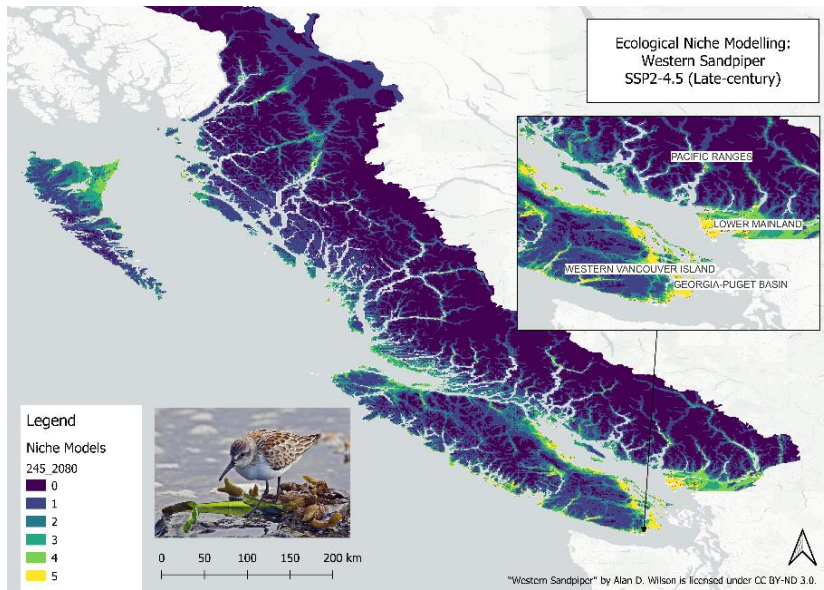


Figure 14: Late-century (2080) model outputs for Western Sandpiper, contrasting the "middle of the road" SSP2-4.5 output versus the fossil-fuel intensive (SSP5-8.5) output.

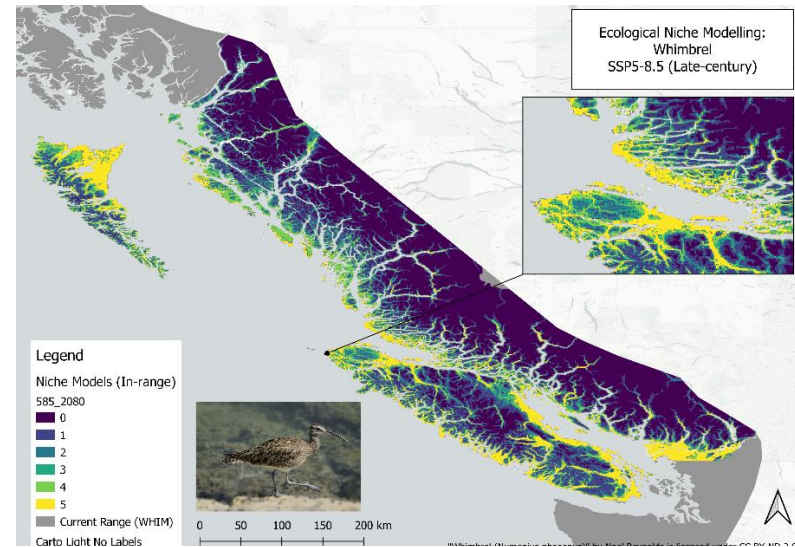
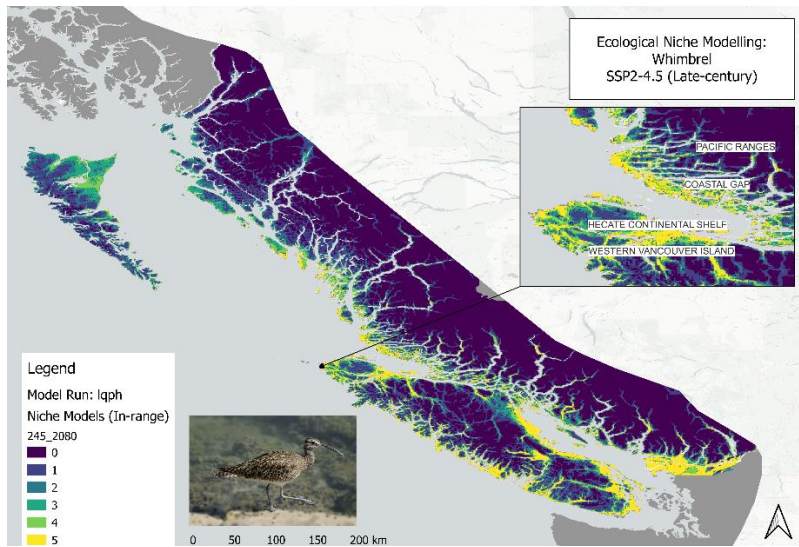


Figure 15: Late-century (2080) model outputs for Whimbrel, contrasting the "middle of the road" SSP2-4.5 output versus the fossil-fuel intensive (SSP5-8.5) output.

## *Model Statistics*

Each of the final models performed well (based on mean AUC and omission rates). The model selection algorithm in the *kuenm* package is designed to evaluate these metrics as an ensemble when selecting the best model for the dataset. For each species, the *kuenm* algorithm evaluated 558 candidate models based on differing combinations of parameters (combinations of 6 regularization multiplier settings, 31 feature class combinations, and 3 distinct sets of environmental variables). Model performance was evaluated based on statistical significance (Partial\_ROC), omission rates (OR), and the Akaike information criterion corrected for small sample sizes (AICc)<sup>6</sup>. Model performance plots will be included in the supplemental data package accompanying this thesis.

AUC scores indicate how well a machine learning algorithm can make accurate predictions. Generally, a mean AUC score of 0.5 would be equivalent to a random choice (e.g., flipping a coin). The AUC scores in each of the models are close to 1, indicating that the algorithm could very accurately predict whether presences were “true” (i.e., there was a real-life bird in the grid cell according to eBird records). Omission rates tell us the percent of presences (real-life bird observations) in the “test” category that would be falsely identified as absences by the training dataset; this is a measure of how well the model is able to predict presences, and how well it performs. A low omission rate (close to 0) indicates that fewer test observations would be miscategorized as absences in the training model. All twelve models had omission rates of less than 1% (see Table 5).

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<sup>6</sup> From Cobos et al., 2019: “Model selection is based on significance, predictive ability, and complexity, in that order of priority: i.e., models are filtered first to detect those that are statistically significant; the omission rate criterion is applied to this reduced set of models; finally, among the significant and low-omission candidate models, those with values of delta AICc lower than two are selected.”

*Table 5: Model performance metrics of the final models. Final models were selected from the other candidates based on AICc, omission rates, and mean AUC scores. Please note: The full list of all model statistics which ranks the AICc scores for each of the candidate models will be provided in the supplemental data package.*

<b>Species</b>	<b>AICc Scores of Top Model</b>	<b>Delta AICc</b>	<b>Mean AUC of Final Replicates (Average of Last 3 Runs)</b>	<b>Omission Rate</b>
<b>Black-bellied Plover</b>	3552.71	0	0.986	0.061
<b>Black Oystercatcher</b>	3912.57	0	0.986	0.053
<b>Black Turnstone</b>	1498.24	0	0.986	0.045
	1498.72	0.479852	0.986	0.045
<b>Dunlin</b>	4754.14	0	0.981	0.044
<b>Red Knot</b>	476.39	0	0.992	0
<b>Rock Sandpiper</b>	280.92	1.381197	0.979	0
	279.53	0	0.979	0
<b>Short-billed Dowitcher</b>	2256.72	0	0.942	0
<b>Semipalmated Plover</b>	2878.31	1.33845	0.974	0.051
<b>Surfbird</b>	1740.68	0	0.989	0.037
<b>Western Grebe</b>	6234.40	0	0.978	0.04819277
<b>Western Sandpiper</b>	5688.31	0	0.984	0.024
<b>Whimbrel</b>	1909.218	0	0.991	0.071

## 2.5: Discussion

British Columbia's coasts are areas of high avian biodiversity, providing habitat for globally significant congregations of migratory and breeding birds (Drever et al., 2016). However, in the future, the low-elevation coastal habitats these birds depend upon are predicted to be under threat from climate-related hazards including flooding, storm surge, and sea-level rise (Galbraith et al., 2014). Through Maxent ecological niche modelling, I show that the spatial extent of habitat where coastal birds are likely to occur along British Columbia's coasts may shrink under an unmitigated climate scenario (SSP5-8.5), with eight of twelve species projected to lose habitat (in terms of area – km<sup>2</sup>) in the “optimal” zones of their current range by 2080 (i.e., where there is 60-100% chance of encountering a bird per 1x1km grid cell). However, under the other three scenarios, species fare better, and the predicted outcomes are not so bleak. Under SSP1-2.6 and SSP3-7.0, eleven out of twelve species gain habitat in the optimal category between mid and late century. Under the “middle of the road” scenario (SSP2-4.5), all twelve species gain habitat in the optimal category between mid and late century.

The Maxent output for each species provides estimates of relative contributions of the environmental variables to the Maxent model. For nine out of twelve species studied, a temperature variable (either mean annual temperature, continentality, or mean temperature of the warmest month) was identified as the variable explaining the most variability in the model (and contributing the most to its predictions) based on jackknife variable contribution analysis. The coastal areas where shorebird observations were recorded likely had higher temperatures relative to the surrounding inland areas. The Maxent algorithm may have interpreted these warmer areas as the most likely zones for shorebird presence, which is logical; however, once a temperature threshold is reached (e.g., in the unmitigated climate scenario with the most warming), the

algorithm would consider these same zones to be uninhabitable when compared to baseline conditions. Under the moderate or middle-of-the-road climate scenario (SSP2-4.5), there may have been larger areas which matched the temperatures that the model identified with high likelihood of shorebird presence. If temperature truly is a key driver of shorebird presences (and an indicator of suitable habitat), these models may support the notion that extreme heat and long durations of heat would make coastal habitats challenging for birds. We do know that extreme heat has wide-ranging effects on marine life, leading to invertebrate death and ocean acidification, as well as causing heat stress to many animals (Stillman, 2019). Black Oystercatcher and other coastal bird species have been known to engage in belly-soaking as a method of keeping cool in extreme heat events (Ryeland et al., 2021), and adult birds are of course not sessile, meaning that they would be able to move about to thermoregulate, using vegetation and beach wrack to cool (Davis et al., 2021). However, nestlings and eggs may be negatively impacted by extreme heat events (Albright et al., 2010).

For Black-bellied Plover, Short-billed Dowitcher, and Semipalmated Plover, elevation was identified as the variable that contributed most to the Maxent model (and therefore could be interpreted as one of the key variables explaining the distribution of occurrences). These species are true shorebirds and would likely have only been observed very close to sea level, though this applies to many of the other species studied as well. The MODIS landcover variable was identified as one of the contributing variables for Black Turnstone, Dunlin, Red Knot, Semipalmated Plover but there were many species for which it did not contribute to variability in the model at all (e.g., Short-billed Dowitcher and Surf-bird). If time and resources allowed, a secondary piece of analysis could be to determine which specific land cover classes within the MODIS model were associated with shorebird presences. Several species had unusual variables

identified as key contributors, though these were all small contributors (e.g., <5% relative contribution). For instance, the Agricultural Land Reserve (ALR) layer contributed to the Rock Sandpiper model, the wave height model contributed to the Semipalmated Sandpiper and Dunlin models, slope contributed to the Surfbird and Western Grebe models, and the Important Bird Areas polygon was a key contributor to the Whimbrel model. The Coastal Sensitivity Index layer was a contributing layer in the Black Oystercatcher model.

### ***Evidence of Range Expansion in the Ecological Niche Models***

For the twelve species studied, there was very little meaningful evidence of range expansion beyond the bounds of each species' current range (as described by Birdlife International). I overlaid the ecological niche models I generated for the full Bird Conservation Region 5 polygon (the Northern Pacific Rainforest boundary) against each species' range map. I then selected only Moderate and Optimal Habitat for easier visualization, eliminating unsuitable areas. For most species, areas that were identified as suitable habitat outside their current range were likely similar to their actual range in terms of temperature and conditions (e.g., coastal inlets and freshwater drainages were often identified as suitable, even though these areas are too far inland and would likely not be suitable in actuality). This is an example of where the model outputs must be considered amongst the real-life conditions in order to determine their usefulness. As a visualization, I have included below the Whimbrel range expansion mapping for 2080 under two climate scenarios, SSP2-4.5 and SSP5-8.5. Note the lack of significant range expansion outside of the Birdlife International range polygon.

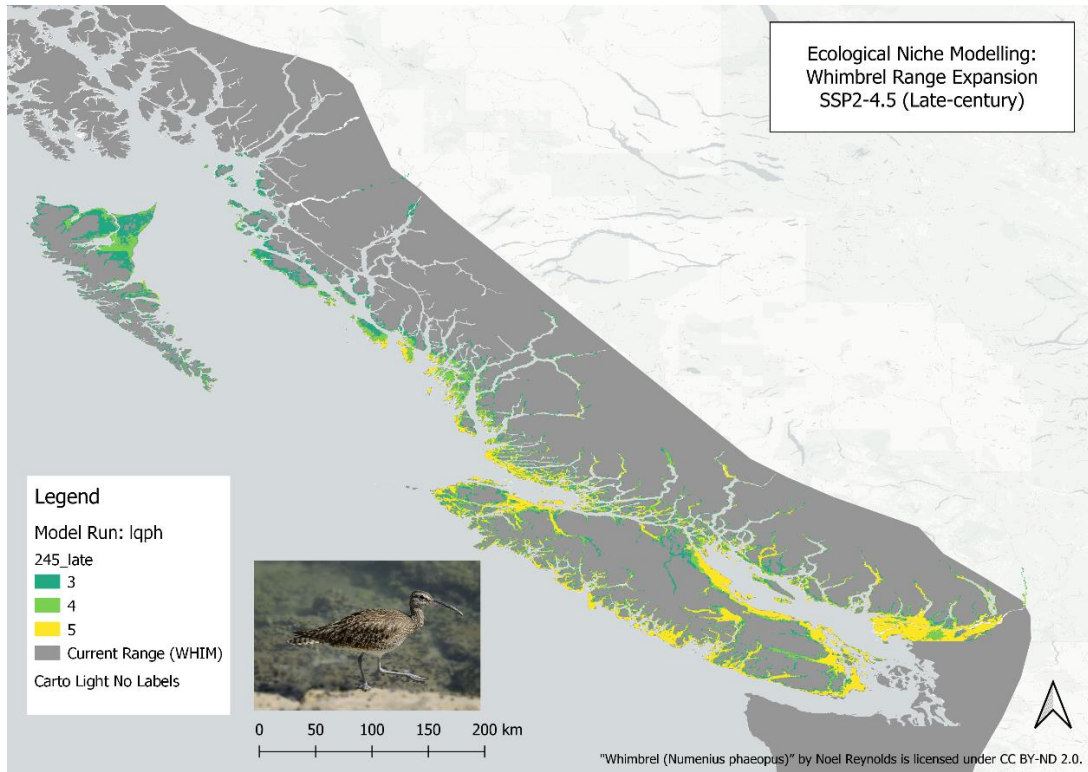


Figure 16: Late-century (2080) range expansion mapping under the SSP2-4.5 scenario

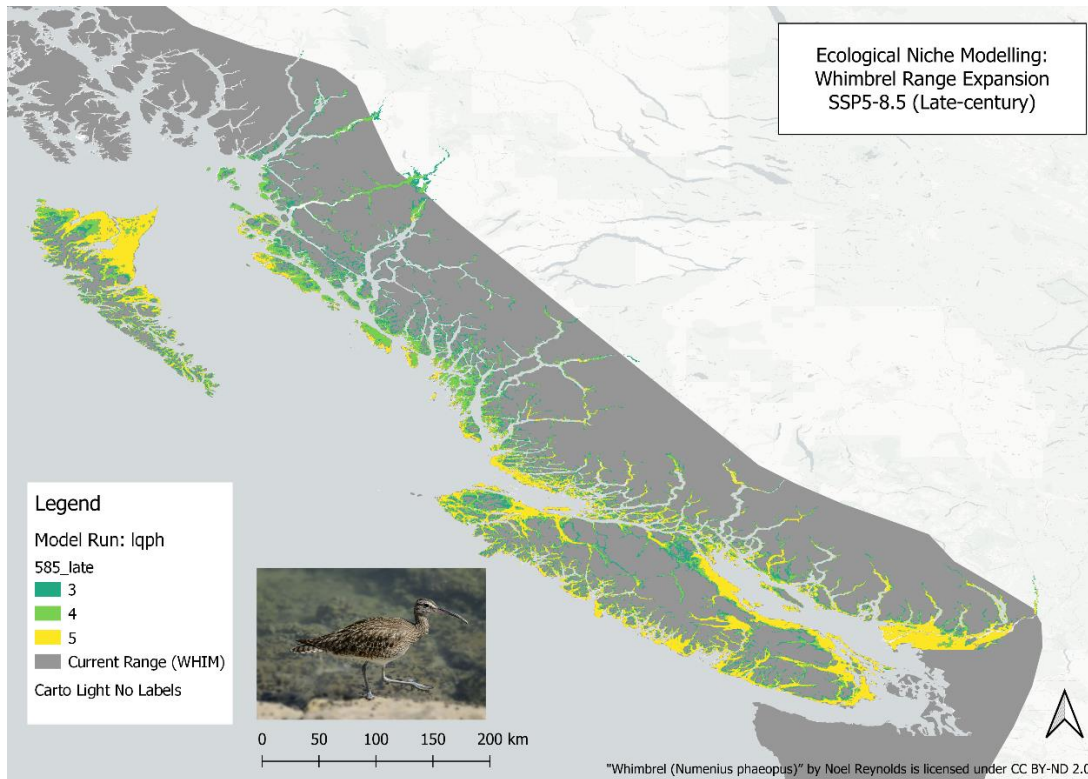


Figure 17: Late-century (2080) range expansion mapping under the SSP5-8.5 scenario

### *Comparison of Model Outputs and Existing Protected Areas*

As an additional line of investigation, I analyzed the percentage of parks and protected areas in B.C. that overlap with areas of optimal habitat from the ecological niche models (i.e., areas where there is 60-100% probability of encountering a bird in each grid cell). For eight out of twelve species, the amount of “optimal” habitat that overlaps with protected areas under SSP5-8.5 at late century covers less spatial area than the amount of optimal habitat that overlaps with parks under less severe climate scenarios (SSP3-7.0 or SSP2-4.5). Here, the key message is that parks and protected areas may become climate refugia in the future, but some parks may have suitable habitat for some species under severe climate scenarios. Climate change will impact habitat for these species throughout the province, including within parks and protected areas. This may necessitate the expansion of protected areas beyond their current boundaries, or the establishment of new protected areas in currently unprotected parts of species’ ranges. However, this line of inquiry was ultimately not very informative, and I did not do further analysis in this area.

*Table 5: Area (square kilometers) of “Optimal Habitat” (60-100% probability of occurrence in each 1x1km grid cell) that overlaps with parks and other protected areas in the late century models. I obtained the spatial layer of all protected areas in B.C. from the [Canadian Protected and Conserved Areas Database](#).*

<b>Species:</b>	<b>SSP1-2.6</b>	<b>SSP2-4.5</b>	<b>SSP3-7.0</b>	<b>SSP5-8.5</b>
<b>Black-bellied Plover</b>	516.97	601.59	464.53	203.29
<b>Black Oystercatcher</b>	5700.365	5700.365	6571.71	4397.505
<b>Black Turnstone</b>	765.93	1568.61	2676.162	1446.271
<b>Dunlin</b>	172.09	343.18	461.68	30.75
<b>Red Knot</b>	1044.96	2476.47	3462.81	1.767
<b>Rock Sandpiper</b>	3319.385	8084.168	13900.53	18901.93
<b>Semipalm. Plover</b>	1145.54	2237.65	3255.85	391.37
<b>Surfbird</b>	818.497	1684.66	2404.117	2814.108
<b>Western Grebe</b>	380.12	666.99	828.711	124.73
<b>Western Sandpip.</b>	853.875	1638.74	2157.51	1302.58
<b>Whimbrel</b>	1263.93	2731.07	4516.08	5893.591

### *Study Limitations and Next Steps*

There were several limitations to this study. For instance, due to computational capacity I chose to only develop models using annual data. Ideally, I would expand my analysis to include biologically meaningful seasonal data, for instance data for the spring and fall months to focus on migration season, or breeding season for locally-breeding birds. However, this would have required much more processing power and model runtime. Additionally, many of the climate layers I used were available only at the annual scale.

Additionally, a drawback to the study was my sole use of community science data. To verify my results, it would be beneficial to rerun the models using true presence-absence data, such as Breeding Bird Survey data or personally collected point count data that used a stratified sampling protocol. eBird data, like other community science datasets, is limited by the spatial aggregation of its datapoints as they are clustered around popular bird-watching destinations and time periods. I aimed to correct for this in the data processing stage, but it is likely that some spatial autocorrelation of the data still exists, and the north coast of the province is not well represented in eBird data due to accessibility. However, if I did use true presence-absence data, such as point counts, Maxent would not have been an appropriate method (Guillera-Aroita et al., 2014) and I would have been required to use random forests or another machine learning algorithm. The Maxent algorithm was a good choice for this study, but because I used the *kuenm* R package and it has its own model selection framework built in, I had slight difficulty interpreting how it ranked the models and finding the criteria. Machine learning models are also notorious as being black box models, so the learning curve was steep.

In addition, I could have used more granular environmental data, but because everything had to be reclassified to the resolution of the climate data, this limited my ability to use higher-

resolution layers. Microclimates were not considered in my analysis; even though the climate data was downscaled, it was coarse (1x1km resolution). Climate data is often being updated, so ideally these models should be re-run periodically as new IPCC models become available. Instead of using an ensemble GCM, I could have followed recommendations from Dr. Colin Mahony et al. to use specific models that are best suited to regional areas (Mahony et al., 2022). However, because I was studying the entire coast of the province, a downscaled ensemble GCM seemed to be the most appropriate choice, as I would need to study each region separately and that quickly would become computationally challenging. Storage was also a major challenge since each species' set of models was approximately fifty gigabytes.

Overall, the model performed best for species with abundant observation data relative to less common and cryptic species, after accounting for processing and thinning of the data. Although Maxent is touted as an excellent method for modelling the ecological niche of cryptic species, including marsh birds and other species that are seldom recorded, my work indicates that care must be taken to use appropriate model parameters and not to conflate the model outputs with true presence-absence points. The model outputs for Short-billed Dowitcher and Rock Sandpiper, both of which had relatively fewer observation points initially, seem to overestimate the amount of optimal habitat for the species, with inland areas and urban areas showing as optimal. I had tried to fine-tune my model parameters to make the model more appropriate for smaller sample sizes, following guidance from Morales et al. (Morales et al., 2017), but even after running these models a second time, the results appear overinflated and should be interpreted with caution.

By including the entire coast of B.C. in the study, I hoped to provide evidence for climate-related range shifts. Although I do have evidence that areas of suitable habitat for some

species will shift northward within their currently established ranges, there is not sufficient evidence to support the notion that the ranges themselves will expand due to climate change. Ideally, this study could be expanded to include the full migratory range of each species, including their arctic nesting grounds and southern migratory grounds. Data access at the international scale and compatibility of the different environmental variables would be a challenge, but with a database like eBird as the input observation data, this could be possible. If time and resources allowed, I also could have increased the number of species and the diversity of species studied. I selected a suite of different bird species for analysis, including several species were identified by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) Avian Specialist Subcommittee as high-priority candidates for conservation status assessment, several species that are provincially listed as at-risk in British Columbia, and several common, iconic species along B.C.'s coasts that are included in federal and provincial monitoring regimes. However, this work could be easily replicated in different regions and using data for other species.

In spite of the limitations to the study, I believe that my work here may support future policy and conservation decision-making, including species at risk protection plans and the evaluation of candidate protected areas based on climate change refugia and habitat suitability.

### **Chapter 3: Conclusion**

The International Union for the Conservation of Nature (IUCN) states that species are most vulnerable to the effects of climate change when they have high sensitivity to change, low adaptive capacity, and their habitats are likely to experience severe climate-related hazards (Foden et al., 2013). In coastal habitats, the magnitude of climate-related threats may exceed species' capacity to adapt to environmental change, especially due to the limited geographic extent of coastal habitat (Sims et al., 2013) and the additive effects of human disturbance (Craft et al., 2009; Kress, 1997), land development (Johannessen & Macdonald, 2009), and recreation (Drever et al., 2016). Migratory species that are range-restricted to particular coastal habitat types or those that rely on particular food sources have higher sensitivity to climate impacts and lower adaptive capacity than habitat generalists (Pollux et al., 2009); likewise, resident species with high site fidelity (i.e., Black Oystercatchers) have lower adaptive capacity than species that have a wider variety of suitable nesting habitats (Hazlitt, 2002). For species that are the most vulnerable to the impacts of climate change, climate refugia will be essential for their survival into the future (Morelli et al., 2020). These are areas of habitat that are sheltered from the worst impacts of climate change due to a combination of their environmental characteristics and geography (Morelli et al., 2020).

Anticipated climate-related threats to coastal bird populations include seasonal habitat loss from inundation, leading to increased foraging competition (Kirby et al., 2008), nest loss and overtopping from flooding on breeding grounds (van de Pol et al., 2010), and changes in the spatial and temporal availability of food resources (Niehaus & Ydenberg, 2006). Changing weather patterns and climatic differences are also predicted to have direct effects on coastal bird populations. For instance, higher mean temperatures in breeding areas may affect abundance by

decreasing chick growth rates and recruitment (Piersma & Lindström, 2004), while rainfall temporarily affects population densities at foraging sites (Murray et al., 2018). For migratory species, climate-related phenological change may lead to a mismatch between the timing of arrival at migratory staging grounds and the timing of peak food availability (Both et al., 2010).

If long-distance migrants are unable to adapt to changes in the distribution and availability of their prey along their migratory route, this could lead to further population decline (Both et al., 2010). Resident species which remain in temperate coastal habitats year-round may also experience climate-related effects, including inundation in mudflats and intertidal areas, leading to increased foraging competition (Galbraith et al., 2002). Important prey items including intertidal invertebrates (Lawrence & Soame, 2004) and mollusks (VanDusen et al., 2012) display high levels of phenotypic plasticity in response to environmental change, and shorebirds must readily adapt to shifts in the peak abundance of these primary food sources (Adamík & Pietruszková, 2008). In addition to invertebrate prey, biofilm availability may be affected by seasonal temperature and flooding; this is a primary food source for migratory shorebirds (Mathot et al., 2007). This "decoupling" of crucial phenological relationships between predator and prey species may result in further alteration to population-level processes and could be exacerbated by human disturbance (Bruggeman et al., 2015). Although the relationships between food availability, timing, and bird migration were not addressed in this study, this could be an area for future research. Gaining a better understanding of how climate change may affect the quality or distribution of coastal bird prey would allow managers to better support species at high risk (van der Kolk et al., 2020). For example, climate sensitivity analysis conducted by Partners in Flight indicates that species with restricted diets were more vulnerable to the effects of climate change than generalist species (Langham et al., 2015). For instance, the eastern subspecies of the

Red Knot (*Calidris canutus rufa*) is known to be at decline due in part to overharvest of horseshoe crabs, whose eggs the Red Knot depend upon during migration (Krisfalusi-Gannon et al., 2018). Climate change may exacerbate these impacts due to increasing storms, sea-level rise and flooding in their foraging habitat (Warnock, 2010).

The assessment for coastal birds outlined in Chapter 2 of this study aims to build upon ongoing work in the province of British Columbia and builds on the recommendations of the 2016 *Fish and Wildlife Climate Change Vulnerability Assessment for BC*. Phase 2 of the study, published in 2017, recommended that additional species be assessed using the province's framework; due to the relative availability of bird data, it was recommended that birds be the next group for assessment. Although this work was tabled for some time due to the Covid-19 pandemic, there may be renewed interest. The framework itself builds upon NatureServe's Climate Change Vulnerability Index (Young et al., 2015), as well as the Pacific Northwest Climate Sensitivity Database (Mims et al., 2018) and the CCVA framework recommended by the IUCN (Foden et al., 2013). Within this framework, vulnerability lies at the intersection of exposure, sensitivity, and adaptive capacity. Here, exposure is quantified as the level of change to habitat suitability for each species.

My findings support my initial hypothesis that climate change will impact habitat suitability for coastal birds. Under the intensive fossil fuel development scenario (SSP5-8.5), the area (km<sup>2</sup>) of "optimal" habitat (where probability of occurrence is between 60-100% per 1x1km grid cell) declines between mid and late century for eight of twelve species studied. In the SSP5-8.5 scenario, a push for economic development will lead to further fossil fuel use and warming is not limited to less than 1.5°C. However, under SSP1-2.6 (the lowest-emission scenario) and SSP3-7.0 (global inequality in climate adaptation), eleven out of twelve species gain habitat in

the optimal category between mid and late century. Under the “middle of the road” scenario (SSP2-4.5), where challenges to adaptation and mitigation are moderate worldwide, all twelve species gain habitat in the optimal category between mid and late century. Overall, these findings support the notion that unmitigated climate change could have dire consequences for B.C.’s coastal bird populations, but under less severe scenarios, these species stand a fighting chance. The models I developed in Chapter Two could potentially inform future climate change vulnerability assessments by the provincial government and could potentially feed into future species at risk protection plans and the evaluation of candidate protected areas. It is crucial that this work continue in the province.

## Appendix A: Breakdown of Results by Species

### *Black-bellied Plover (Pluvialis squatarola)*



“*Pluvialis squatarola*” by USFWS - Pacific Region is licensed under CC BY-ND 2.0.

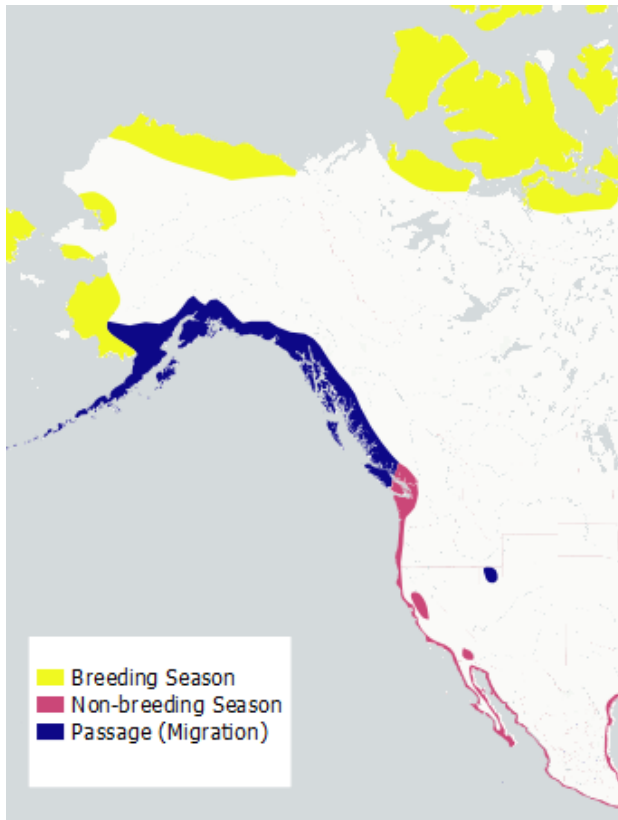


Figure 18: Black-bellied Plover range map created by the author using data from BirdLife International.

The established range for Black-bellied Plover (BBPL) within British Columbia covers ~ **174,330.7 km<sup>2</sup>** and is exclusively migratory (i.e., they do not breed in the province). Their population is ranked as globally secure (G5) and provincially not at risk (yellow). Full niche modeling for the species can be viewed here.

#### Overall Findings:

- Under a low-emissions climate scenario (SSP1-2.6), BBPL **gain habitat** in optimal habitat classes (Classes 4 and 5, where BBPL have 60-100% probability of occurrence in each grid cell) between the mid-century model and the late-century model. BBPL also gain habitat in the optimal habitat category under SSP2 and SSP3. The amount of habitat in “marginal” classes (0-19% probability of occurrence) declines between mid and late century under SSP1, 2 and 3.
- Under an unmitigated climate scenario (SSP5-8.5), BBPL **lose habitat** in the optimal habitat classes, from 24% in the mid-century model down to 15% in the late-century model. The amount of marginal habitat increases from 85 to 94%. Variable importance statistics from the Maxent model output indicate that the variables that individually contribute the most to the model (and explain the most variation) are elevation (64.6%) and mean temperature of the warmest month (28.5%).

Climate Scenario	Class	Mid-century (2050) – Coverage in Km <sup>2</sup> and % of Current Range		Late Century (2080) - Coverage in Km <sup>2</sup> and % of Current Range	
SSP1 – 2.6	0	967.0630011 (1%)	<b>90%</b> Marginal Habitat	717.1 (1%)	<b>60%</b> Marginal Habitat
	1	154,301 (89%)		28429.0 (59%)	
	2	8782.2 (5%)	<b>7%</b> Moderate Habitat	6699.7 (14%)	<b>24%</b> Moderate Habitat
	3	4328.4 (2%)		5118.4 (10%)	
	4	2343.2 (1%)	<b>3%</b> Optimal Habitat	3191.2 (7%)	<b>16%</b> Optimal Habitat
	5	3608.9 (2%)		4355.2 (9%)	
SSP2 – 4.5	0	542.4 (0%)	<b>95%</b> Marginal Habitat	1139.3 (1%)	<b>85%</b> Marginal Habitat
	1	165984.0 (95%)		146457.0 (84%)	
	2	4423.1 (3%)	<b>4%</b> Moderate Habitat	9599.3 (6%)	<b>10%</b> Moderate Habitat
	3	2332.2 (1%)		6095.4 (4%)	
	4	584.6 (0%)	<b>0%</b> Optimal Habitat	4237.0 (2%)	<b>6%</b> Optimal Habitat
	5	110.8 (0%)		6475.1 (4%)	
SSP3 – 7.0	0	1092.2 (1%)	<b>87%</b> Marginal Habitat	1541.4 (1%)	<b>81%</b> Marginal Habitat
	1	149441.0 (86%)		139078.0 (80%)	
	2	9132.2 (5%)	<b>8%</b> Moderate Habitat	11899.5 (7%)	<b>11%</b> Moderate Habitat
	3	5592.8 (3%)		6463.0 (4%)	
	4	3286.8 (2%)	<b>5%</b> Optimal Habitat	5851.9 (5%)	<b>8%</b> Optimal Habitat
	5	5416.5 (3%)		9167.4 (3%)	
SSP5 – 8.5	0	1170.8 (1%)	<b>85%</b> Marginal Habitat	576.2 (0%)	<b>94%</b> Marginal Habitat
	1	146735.0 (84%)		163770.0 (94%)	
	2	9618.4 (6%)	<b>9%</b> Moderate Habitat	5117.9 (3%)	<b>4%</b> Moderate Habitat
	3	6022.9 (3%)		2557.0 (1%)	
	4	3995.9 (2%)	<b>6%</b> Optimal Habitat	1792.1 (1%)	<b>1%</b> Optimal Habitat
	5	6419.3 (4%)		164.9 (0%)	

***Black Turnstone (Arenaria melanocephala)***



“Arenaria melanocephala” by Alan Vernon is licensed under CC BY-ND 2.0.

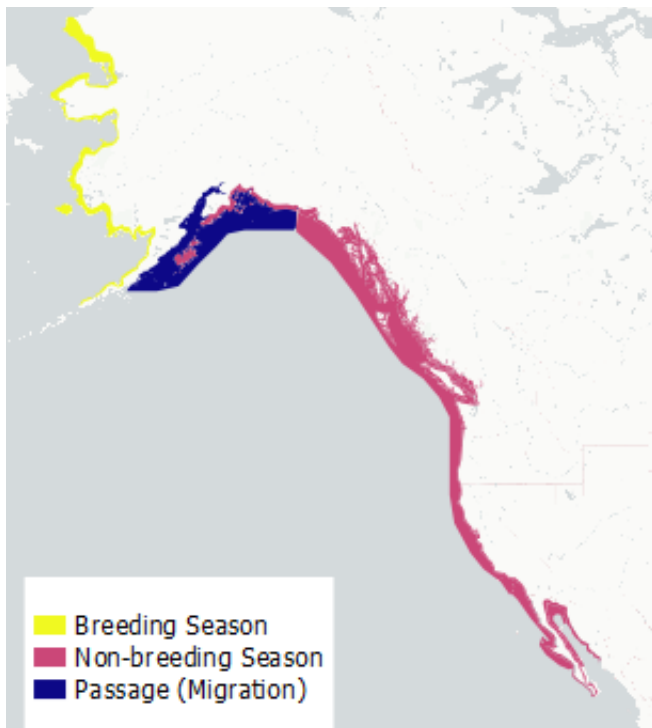


Figure 19: Black Turnstone range map created by the author using data from BirdLife International.

The established range for Black Turnstone within British Columbia covers ~45,000 km<sup>2</sup> and is exclusively migratory. Their population is ranked as globally secure (G5) and provincially not at risk (yellow). Like many species of shorebirds, they migrate long distances to breed in the high arctic, where their nesting habitat might experience climate impacts in the future from increased warming. Full niche modeling for the species can be viewed here.

**Overall Findings:**

- Under a low-emissions climate scenario (SSP1-2.6), BLTU gain habitat in the optimal habitat classes (4 and 5, 60-100% probability of occurrence in each grid cell), while the amount of habitat in the marginal category (0-19%) is reduced.
- Under the high-emissions scenario (SSP5-8.5) the amount of habitat in the marginal category increases from 54% to 56%, while optimal habitat decreases from 22% down to 4%.
- The Maxent model output indicates that the variables that individually contribute the most to the model (and

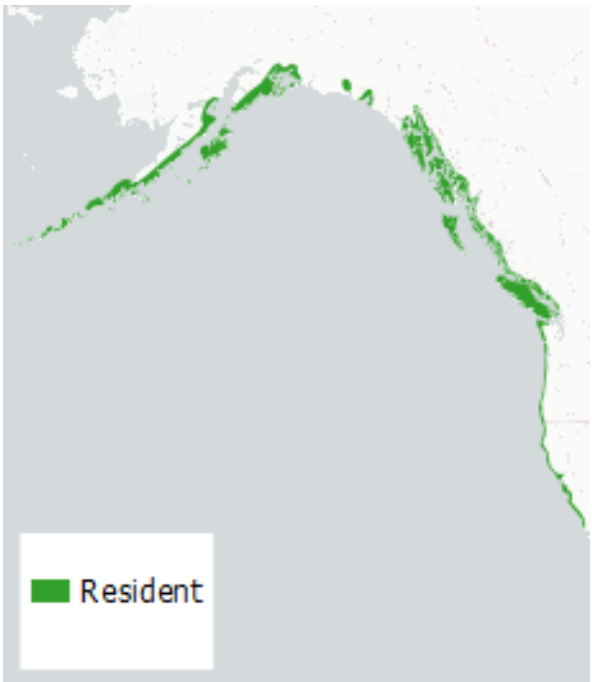
explain the most variation) are ‘td’ (with 42.9%) and mean temperature of the warmest month (31%). The ‘td’ variable is the difference between mean temperature of the warmest month and mean temperature of the coldest month, a measure of continentality.

Climate Scenario	Class	Mid-century (2050) – Coverage in Km <sup>2</sup> and % of Current Range		Late Century (2080) - Coverage in Km <sup>2</sup> and % of Current Range	
SSP1 – 2.6	0	922.2 (2%)	<b>79%</b> Marginal Habitat	717.1 (1%)	<b>60%</b> Marginal Habitat
	1	37613.2 (77%)		28429.0 (59%)	
	2	7727.3 (16%)	<b>18%</b> Moderate Habitat	6699.7 (14%)	<b>24%</b> Moderate Habitat
	3	2571.8 (2%)		5118.4 (10%)	
	4	0 (0%)	<b>0%</b> Optimal Habitat	3191.2 (7%)	<b>16%</b> Optimal Habitat
	5	0 (0%)		4355.2 (9%)	
SSP2 – 4.5	0	983.1 (2%)	<b>69%</b> Marginal Habitat	682.8 (1%)	<b>53%</b> Marginal Habitat
	1	32264.0 (67%)		25247.7 (52%)	
	2	9185.4 (19%)	<b>30%</b> Moderate Habitat	5880.1 (12%)	<b>33%</b> Moderate Habitat
	3	5157.5 (11%)		5404.6 (11%)	
	4	904.5 (2%)	<b>2%</b> Optimal Habitat	4692.6 (10%)	<b>24%</b> Optimal Habitat
	5	0 (0%)		6602.9 (14%)	
SSP3 – 7.0	0	685.0 (1%)	<b>57%</b> Marginal Habitat	607.0 (1%)	<b>47%</b> Marginal Habitat
	1	26935.7 (56%)		22453.1 (46%)	
	2	6315.6 (13%)	<b>24%</b> Moderate Habitat	5718.0 (12%)	<b>22%</b> Moderate Habitat
	3	5425.0 (11%)		4953.1 (10%)	
	4	3805.5 (8%)	<b>19%</b> Optimal Habitat	5893.9 (12%)	<b>30%</b> Optimal Habitat
	5	5299.8 (11%)		8886.2 (18%)	
SSP5 – 8.5	0	644.6 (1%)	<b>54%</b> Marginal Habitat	1004.408 (2%)	<b>56%</b> Marginal Habitat
	1	25478.6 (53%)		26154.69 (54%)	
	2	5985.0 (12%)	<b>23%</b> Moderate Habitat	8626.328 (18%)	<b>40%</b> Moderate Habitat
	3	5394.5 (11%)		10651.92 (22%)	
	4	4455.0 (9%)	<b>22%</b> Optimal Habitat	2056.759 (4%)	<b>4%</b> Optimal Habitat
	5	6508.7 (13%)		0 (0%)	

**Black Oystercatcher (*Haematopus bachmani*)**



*Black Oystercatcher by Alan D. Wilson is licensed under CC BY-ND 3.0.*



*Figure 20: Black Oystercatcher range map created by the author using data from BirdLife International.*

The established range for Black Oystercatcher (BLOY) within British Columbia covers ~68,000km<sup>2</sup>. Their population is ranked as globally secure (G5) and provincially not at risk (yellow). However, BLOY are restricted to rocky intertidal habitats and as such has been noted as a species of conservation concern by Partners in Flight due to potential habitat loss stemming from climate change (Partners in Flight, 2017).

**Overall Findings:**

- Under a low-emissions climate scenario (SSP1-2.6), BLOY **gain habitat** in optimal habitat classes (Classes 4 and 5, where BLOY have 60-100% probability of occurrence in each grid cell) between the mid and late century. BLOY also gain habitat in the optimal category under SSP2 and SSP3.
  - Under an unmitigated climate scenario (SSP5-8.5), BLOY **lose habitat** in the optimal habitat classes, from 24% in the mid-century model down to 15% in the late-century model.
- Overall models indicate that optimal habitat may

shift northward under high-emissions climate scenarios where temperatures will be warmer overall. Full niche modeling for the species can be viewed [here](#). Mean annual temperature was the variable with the highest percent contribution to the Maxent model (71.6%).

Climate Scenario	Class	Mid-century (2050) – Coverage in Km <sup>2</sup> and % of Current Range		Late Century (2080) - Coverage in Km <sup>2</sup> and % of Current Range	
SSP1 – 2.6	0	140.6 (0%)	<b>59%</b> Marginal Habitat	35.2 (0%)	<b>36%</b> Marginal Habitat
	1	40229.0 (59%)		24405.5 (36%)	
	2	15831.1 (23%)	<b>25%</b> Moderate Habitat	23329.6 (34%)	<b>36%</b> Moderate Habitat
	3	1138.6 (2%)		1658.0 (2%)	
	4	10629.2 (16%)	<b>16%</b> Optimal Habitat	18223.2 (27%)	<b>27%</b> Optimal Habitat
	5	266.6 (0%)		330.2 (0%)	
SSP2 – 4.5	0	106.6 (0%)	<b>52%</b> Marginal Habitat	35.2 (0%)	<b>59%</b> Marginal Habitat
	1	35541.0 (52%)		24405.5 (36%)	
	2	17929.7 (26%)	<b>27%</b> Moderate Habitat	23329.6 (34%)	<b>36%</b> Moderate Habitat
	3	898.3 (1%)		1658.0 (2%)	
	4	13188.5 (19%)	<b>19%</b> Optimal Habitat	18223.2 (27%)	<b>27%</b> Optimal Habitat
	5	305.0 (0%)		330.2 (0%)	
SSP3 – 7.0	0	72.3 (0%)	<b>49%</b> Marginal Habitat	0.3 (0%)	<b>22%</b> Marginal Habitat
	1	33588.6 (49%)		15180.4 (22%)	
	2	18368.7 (27%)	<b>29%</b> Moderate Habitat	34046.3 (50%)	<b>53%</b> Moderate Habitat
	3	1286.6 (2%)		2187.7 (3%)	
	4	14311.3 (21%)	<b>21%</b> Optimal Habitat	16243.0 (24%)	<b>24%</b> Optimal Habitat
	5	316.7 (0%)		323.9 (0%)	
SSP5 – 8.5	0	34.9 (0%)	<b>40%</b> Marginal Habitat	0 (0%)	<b>12%</b> Marginal Habitat
	1	26929.9 (40%)		8448.3 (12%)	
	2	22705.9 (33%)	<b>35%</b> Moderate Habitat	47152.3 (69%)	<b>72%</b> Moderate Habitat
	3	1373.7 (2%)		1984.5 (3%)	
	4	16600.0 (24%)	<b>24%</b> Optimal Habitat	10190.5 (15%)	<b>15%</b> Optimal Habitat
	5	298.6 (0%)		191.7 (0%)	

## Dunlin (*Calidris alpina*)



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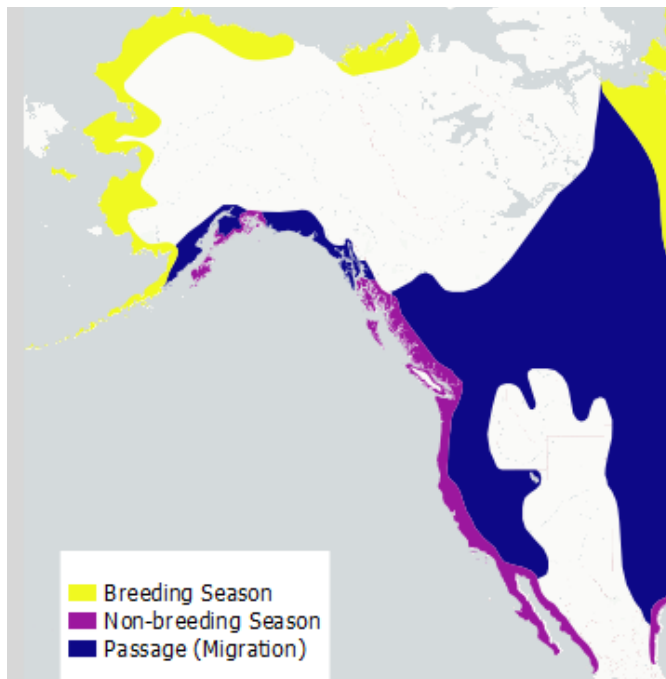


Figure 21: Dunlin range map created by the author using data from BirdLife International.

The established range for Dunlin (DUNL) within British Columbia covers ~165,000km<sup>2</sup>. Their population is ranked as globally secure (G5) and provincially not at risk (yellow). They are notorious for migrating in massive flocks through B.C. with numbers in the hundreds of thousands. Full niche modeling for the species can be viewed [here](#).

### Overall Findings:

- Under a low-emissions climate scenario (SSP1-2.6), DUNL gain habitat in the optimal habitat classes (4 and 5, 60-100% probability of occurrence in each grid cell), while the amount of habitat in the marginal category (0-19%) is reduced.
- Under the high-emissions scenario (SSP5-8.5) the amount of habitat in the marginal category increases from 91% to 97%, while optimal habitat decreases from 3% down to 1%.
- The Maxent model output indicates that the variables that individually contribute the most to the model (and

explain the most variation) are mean temperature of the warmest month (with 42.9%) and elevation (31%). These variables likely explain the most variation in where DUNL observations were recorded because observations were likely more common in warmer months and at low elevations. I attempted to account for this natural clustering in my data preprocessing, but it is still reflected in the results. I suppose it supports proof of concept!

Climate Scenario	Class	Mid-century (2050) – Coverage in Km <sup>2</sup> and % of Current Range		Late Century (2080) - Coverage in Km <sup>2</sup> and % of Current Range	
SSP1 – 2.6	0	159,333 (96%)	<b>96%</b> Marginal Habitat	153,722 (93%)	<b>93%</b> Marginal Habitat
	1	122.9 (0%)		161 (0%)	
	2	3778.9 (2%)	<b>3%</b> Moderate Habitat	6434.7 (4%)	<b>5%</b> Moderate Habitat
	3	1520.7 (1%)		1993.4 (1%)	
	4	392.4 (0%)	<b>0%</b> Optimal Habitat	1408.4 (1%)	<b>2%</b> Optimal Habitat
	5	21.7 (0%)		1550.1 (1%)	
SSP2 – 4.5	0	161,351 (98%)	<b>98%</b> Marginal Habitat	150,910 (91%)	<b>91%</b> Marginal Habitat
	1	11.4 (0%)		198.2 (0%)	
	2	2535.9 (2%)	<b>3%</b> Moderate Habitat	6930.7 (4%)	<b>6%</b> Moderate Habitat
	3	1260.7 (1%)		3005.4 (2%)	
	4	87.8 (0%)	<b>0%</b> Optimal Habitat	1565.9 (1%)	<b>3%</b> Optimal Habitat
	5	4.9 (0%)		2659.9 (2%)	
SSP3 – 7.0	0	152,003 (92%)	<b>92%</b> Marginal Habitat	149,217 (90%)	<b>90%</b> Marginal Habitat
	1	142.4 (0%)		276.2 (0%)	
	2	6796.6 (4%)	<b>6%</b> Moderate Habitat	6623.4 (4%)	<b>7%</b> Moderate Habitat
	3	2572.7 (2%)		4627.5 (3%)	
	4	1380.1 (1%)	<b>2%</b> Optimal Habitat	1910.8 (1%)	<b>3%</b> Optimal Habitat
	5	2336.5 (1%)		2615.5 (2%)	
SSP5 – 8.5	0	150,797 (91%)	<b>91%</b> Marginal Habitat	159,816 (97%)	<b>97%</b> Marginal Habitat
	1	206.6 (0%)		83.2 (0%)	
	2	7073.8 (4%)	<b>6%</b> Moderate Habitat	2792.3 (2%)	<b>3%</b> Moderate Habitat
	3	2902.2 (2%)		1588.3 (1%)	
	4	1569.5 (1%)	<b>3%</b> Optimal Habitat	937.7 (1%)	<b>1%</b> Optimal Habitat
	5	2682.2 (2%)		33.6 (0%)	

## Red Knot (*Calidris canutus*)



“Red Knot (*Calidris canutus* ssp. *roselaari*)” by the U.S. Fish and Wildlife Service is licensed under CC BY-ND 2.0.

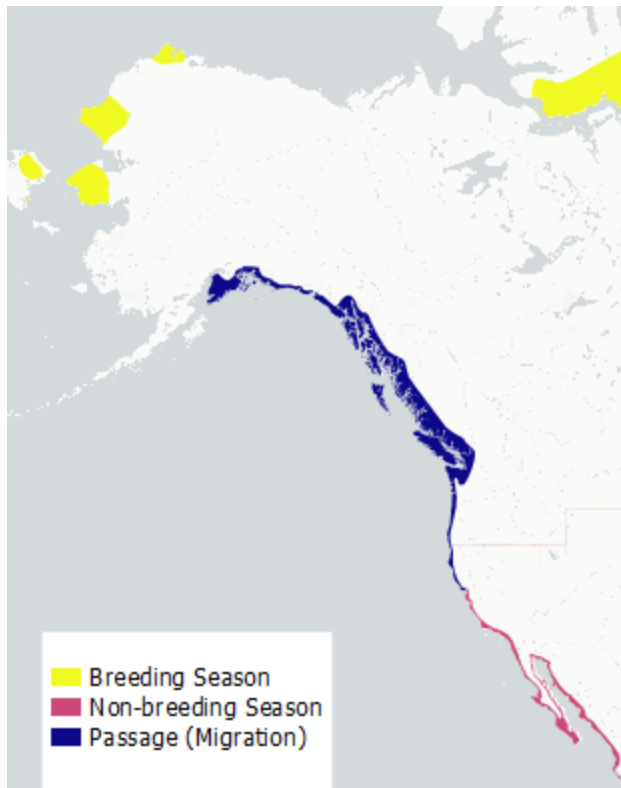


Figure 22: Red Knot range map created by the author using data from BirdLife International.

The established range for Red Knot (REKN) within British Columbia covers ~**146,800km<sup>2</sup>** and is migratory habitat. Three subspecies of Red Knot are found in Canada, but only *Calidris canutus roselaari* (hereafter *roselaari*) migrates through in B.C. Due to long-term declines, *rufa* is listed as Endangered, *roselaari* as Threatened, and *islandica* as a species of Special Concern on Schedule 1 of SARA. *Roselaari* breeds in Alaska and Russia and occurs in Canada in small numbers during migration. Full niche modeling for the species can be viewed [here](#).

### Overall Findings:

- Under a low-emissions climate scenario (SSP1-2.6), REKN migratory habitat in the optimal habitat classes (4 and 5, 60-100% probability of occurrence in each grid cell) does not change between mid and late century, remaining at 7%. The amount of habitat in the marginal category (0-19%) is reduced.
  - Under the high-emissions scenario (SSP5-8.5) optimal habitat decreases from 11% down to 0%. Marginal habitat increases from 74% up to 97%.
- The Maxent model output indicates that the variables that individually contribute the most to the model (and explain the most variation) are mean temperature of the warmest month (43.3%) and continentality (td, 37.8%).

Climate Scenario	Class	Mid-century (2050) – Coverage in Km <sup>2</sup> and % of Current Range		Late Century (2080) - Coverage in Km <sup>2</sup> and % of Current Range	
SSP1 – 2.6	0	1479.0 (1%)	<b>79%</b> Marginal Habitat	1455.4 (1%)	<b>78%</b> Marginal Habitat
	1	114289.0 (78%)		112929.0 (77%)	
	2	12729.5 (9%)	<b>15%</b> Moderate Habitat	12625.7 (9%)	<b>15%</b> Moderate Habitat
	3	8994.4 (6%)		9412.3 (6%)	
	4	5258.0 (4%)	<b>7%</b> Optimal Habitat	5559.1 (4%)	<b>7%</b> Optimal Habitat
	5	4470.5 (3%)		4902.3 (3%)	
SSP2 – 4.5	0	516.2 (0%)	<b>97%</b> Marginal Habitat	1344.8 (1%)	<b>74%</b> Marginal Habitat
	1	142471.0 (97%)		107427.0 (73%)	
	2	2437.7 (2%)	<b>3%</b> Moderate Habitat	11668.0 (8%)	<b>14%</b> Moderate Habitat
	3	1018.7 (1%)		9546.7 (6%)	
	4	415.7 (0%)	<b>0%</b> Optimal Habitat	8244.4 (6%)	<b>14%</b> Optimal Habitat
	5	0.0 (0%)		8653.1 (6%)	
SSP3 – 7.0	0	1401.4 (1%)	<b>76%</b> Marginal Habitat	1261.0 (1%)	<b>71%</b> Marginal Habitat
	1	110,752.0 (75%)		103,024.0 (70%)	
	2	12397.4 (8%)	<b>15%</b> Moderate Habitat	10815.7 (7%)	<b>14%</b> Moderate Habitat
	3	9987.3 (7%)		10269.7 (7%)	
	4	6265.8 (4%)	<b>8%</b> Optimal Habitat	11027.5 (8%)	<b>15%</b> Optimal Habitat
	5	6040.9 (4%)		10484.5 (7%)	
SSP5 – 8.5	0	1361.5 (1%)	<b>74%</b> Marginal Habitat	506.4 (0%)	<b>97%</b> Marginal Habitat
	1	107910.0 (73%)		143058.0 (97%)	
	2	11869.9 (8%)	<b>15%</b> Moderate Habitat	2030.8 (1%)	<b>2%</b> Moderate Habitat
	3	9780.4 (7%)		1072.2 (1%)	
	4	7677.3 (5%)	<b>11%</b> Optimal Habitat	197.5 (0%)	<b>0%</b> Optimal Habitat
	5	8245.5 (6%)		0.0 (0%)	

## Rock Sandpiper (*Calidris ptilocnemis*)



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Figure 23: Rock Sandpiper range map created by the author using data from BirdLife International.

The established range for Rock Sandpiper (ROSA) within British Columbia covers ~**189,000km<sup>2</sup>**. ROSA occur in B.C. only during the non-breeding season. Their population is ranked as globally secure (G5) and provincially not at risk (yellow). Full niche modeling for the species can be viewed [here](#).

### Overall Findings:

- Under a low-emissions climate scenario (SSP1-2.6), ROSA habitat in the optimal habitat classes (4 and 5, 60-100% probability of occurrence in each grid cell) increases from 12% in the mid-century model to 15% at the late century. The amount of habitat in the marginal category (0-19%) is reduced by 2%.
- Under the high-emissions scenario (SSP5-8.5) optimal habitat increases from 23% up to 48%. Marginal habitat is reported to decrease from 58% to 37%.

- The Maxent model output indicates that the variables that individually contribute the most to the model (and explain the most variation) are mean temperature of the coldest month (65%) and mean annual temperature (34.5%).

Climate Scenario	Class	Mid-century (2050) – Coverage in Km <sup>2</sup> and % of Current Range		Late Century (2080) - Coverage in Km <sup>2</sup> and % of Current Range	
SSP1 – 2.6	0	111,485.0 (2%)	<b>70%</b> Marginal Habitat	103,816 (2%)	<b>68%</b> Marginal Habitat
	1	65,783.5 (68%)		61,552.6 (66%)	
	2	15,950.0 (12%)	<b>20%</b> Moderate Habitat	14,150.2 (12%)	<b>19%</b> Moderate Habitat
	3	5,197.2 (6%)		9,551.1 (7%)	
	4	2,140.4 (4%)	<b>12%</b> Optimal Habitat	4,885.3 (5%)	<b>15%</b> Optimal Habitat
	5	0 (8%)		6,203.2 (10%)	
SSP2 – 4.5	0	104,565 (2%)	<b>66%</b> Marginal Habitat	102,398 (2%)	<b>56%</b> Marginal Habitat
	1	64,201.7 (64%)		59,056.1 (54%)	
	2	21,004.8 (12%)	<b>19%</b> Moderate Habitat	13,579.3 (11%)	<b>19%</b> Moderate Habitat
	3	6,017.5 (7%)		9,513.9 (8%)	
	4	3,931.3 (5%)	<b>15%</b> Optimal Habitat	7,190.8 (8%)	<b>25%</b> Optimal Habitat
	5	417.1 (10%)		8,420.8 (17%)	
SSP3 – 7.0	0	103,368 (2%)	<b>63%</b> Marginal Habitat	101,141 (2%)	<b>45%</b> Marginal Habitat
	1	59,977.5 (61%)		56,403.9 (43%)	
	2	13,840.6 (12%)	<b>19%</b> Moderate Habitat	13,318.4 (10%)	<b>18%</b> Moderate Habitat
	3	9,631.9 (8%)		9,491.1 (8%)	
	4	5,924.1 (6%)	<b>17%</b> Optimal Habitat	8,617.5 (10%)	<b>38%</b> Optimal Habitat
	5	7,373.2 (11%)		11,187.3 (28%)	
SSP5 – 8.5	0	102482 (2%)	<b>58%</b> Marginal Habitat	97937.8 (2%)	<b>37%</b> Marginal Habitat
	1	59082.5 (56%)		63164.3 (35%)	
	2	13608.2 (12%)	<b>20%</b> Moderate Habitat	21502.6 (9%)	<b>16%</b> Moderate Habitat
	3	9575.5 (8%)		11030.0 (7%)	
	4	6911.5 (8%)	<b>23%</b> Optimal Habitat	4141.1 (9%)	<b>48%</b> Optimal Habitat
	5	8455.7 (15%)		2362.6 (39%)	

## *Semipalmated Plover (Charadrius semipalmatus)*



The established range for the Semipalmated Plover (SEPL) within British Columbia covers ~200,100km<sup>2</sup>. SEPL are reported to breed along the northern B.C. coast and Haida Gwaii. Their population is ranked as globally secure (G5) and provincially not at risk (yellow). Full niche modeling for the species can be viewed [here](#).

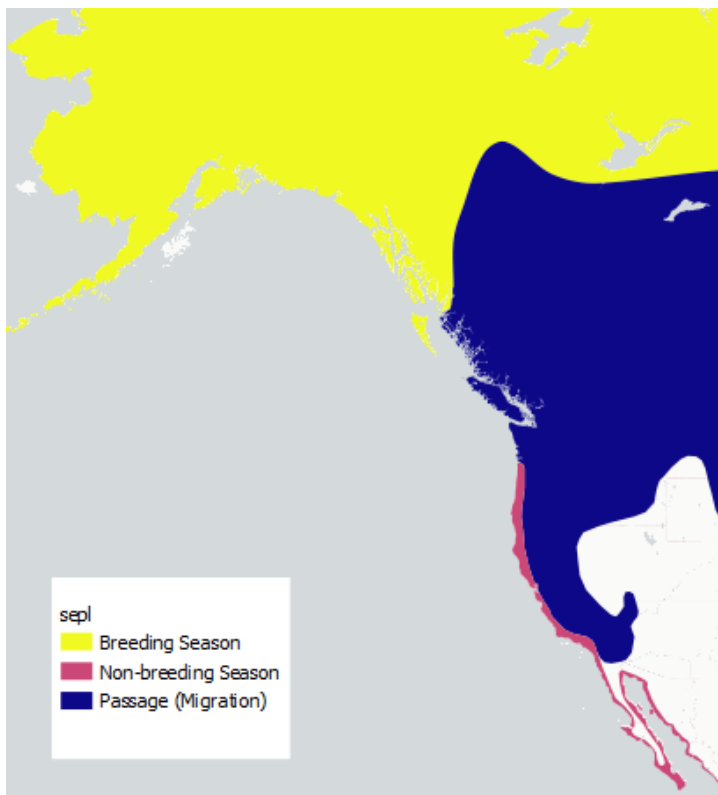


Figure 24: Semipalmated Plover range map created by the author using data from BirdLife International.

### Overall Findings:

- Under a low-emissions climate scenario (SSP1-2.6), SEPL habitat in the optimal habitat classes (4 and 5, 60-100% probability of occurrence in each grid cell) increases from 1% in the mid-century model to 5% at the late century. The amount of habitat in the marginal category (0-19%) is reduced from 89% to 85%.
- Under the high-emissions scenario (SSP5-8.5) optimal habitat decreases from 11% down to 0%. Marginal habitat is reported to increase from 74% to 97%. The Maxent model output indicates that the variables that

individually contribute the most to the model (and explain the most variation) are elevation (81.2%) and mean temperature of the warmest month (9.2%).

Climate Scenario	Class	Mid-century (2050) – Coverage in Km <sup>2</sup> and % of Current Range		Late Century (2080) - Coverage in Km <sup>2</sup> and % of Current Range	
SSP1 – 2.6	0	111,485.0 (56%)	<b>89%</b> Marginal Habitat	103,816 (52%)	<b>83%</b> Marginal Habitat
	1	65,783.5 (33%)		61,552.6 (31%)	
	2	15,950.0 (8%)	<b>11%</b> Moderate Habitat	14,150.2 (7%)	<b>12%</b> Moderate Habitat
	3	5,197.2 (3%)		9,551.1 (5%)	
	4	2,140.4 (1%)	<b>1%</b> Optimal Habitat	4,885.3 (2%)	<b>5%</b> Optimal Habitat
	5	0 (0%)		6,203.2 (3%)	
SSP2 – 4.5	0	104,565 (52%)	<b>98%</b> Marginal Habitat	102,398 (51%)	<b>91%</b> Marginal Habitat
	1	64,201.7 (32%)		59,056.1 (30%)	
	2	21,004.8 (10%)	<b>3%</b> Moderate Habitat	13,579.3 (7%)	<b>6%</b> Moderate Habitat
	3	6,017.5 (3%)		9,513.9 (5%)	
	4	3,931.3 (2%)	<b>0%</b> Optimal Habitat	7,190.8 (4%)	<b>3%</b> Optimal Habitat
	5	417.1 (0%)		8,420.8 (4%)	
SSP3 – 7.0	0	103,368 (52%)	<b>76%</b> Marginal Habitat	101,141 (51%)	<b>71%</b> Marginal Habitat
	1	59,977.5 (30%)		56,403.9 (28%)	
	2	13,840.6 (7%)	<b>15%</b> Moderate Habitat	13,318.4 (7%)	<b>14%</b> Moderate Habitat
	3	9,631.9 (5%)		9,491.1 (5%)	
	4	5,924.1 (3%)	<b>8%</b> Optimal Habitat	8,617.5 (4%)	<b>15%</b> Optimal Habitat
	5	7,373.2 (4%)		11,187.3 (6%)	
SSP5 – 8.5	0	102482 (51%)	<b>74%</b> Marginal Habitat	97937.8 (49%)	<b>97%</b> Marginal Habitat
	1	59082.5 (30%)		63164.3 (32%)	
	2	13608.2 (7%)	<b>15%</b> Moderate Habitat	21502.6 (11%)	<b>2%</b> Moderate Habitat
	3	9575.5 (5%)		11030.0 (6%)	
	4	6911.5 (3%)	<b>11%</b> Optimal Habitat	4141.1 (2%)	<b>0%</b> Optimal Habitat
	5	8455.7 (4%)		2362.6 (1%)	

## Short-billed Dowitcher (*Limnodromus griseus*)



“*Limnodromus griseus*” by Mike Baird is licensed under CC BY-ND 2.0.

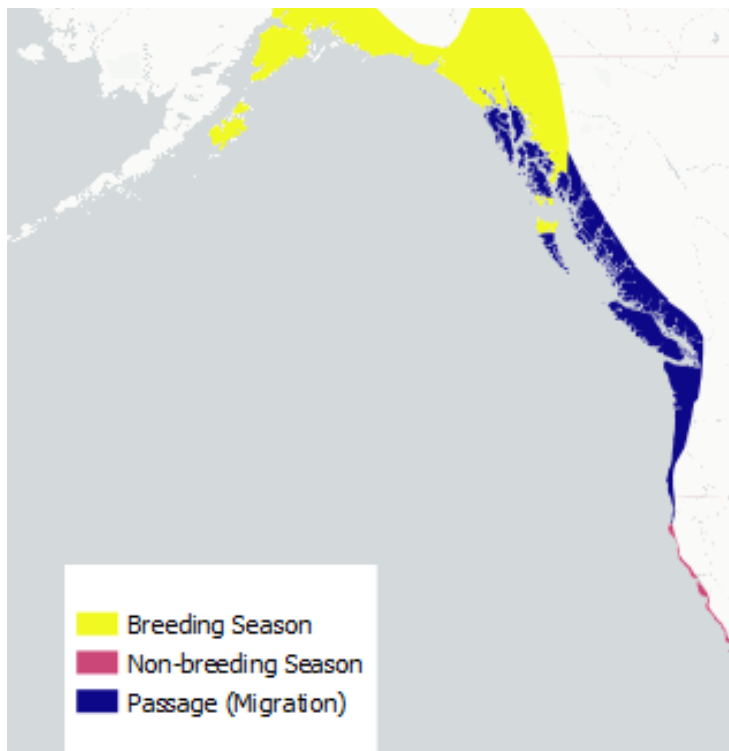


Figure 25: Short-billed Dowitcher range map created by the author using data from BirdLife International.

The established range for the Short-billed Dowitcher (SBDO) within British Columbia covers ~**147,400km<sup>2</sup>**. Their population is ranked as globally secure (G5) but is listed as special concern provincially (blue) due to population decline (Partners in Flight, 2017). Full niche modeling for the species can be viewed [here](#).

### Overall Findings:

- Under a low-emissions climate scenario (SSP1-2.6), SBDO habitat in the optimal habitat classes (4 and 5, 60-100% probability of occurrence in each grid cell) decreases from 87% in the mid-century model to 80% for the late century. The amount of habitat in the marginal category (0-19%) increases from 12% to 14%. These numbers seem unrealistic and indicate the model may be performing poorly due to too few observations.
- Under the high-emissions scenario (SSP5-8.5) optimal habitat decreases from 78% down to 52%. Marginal

habitat is reported to increase from 22% to 48%. The Maxent model output indicates that the variables that individually contribute the most to the model (and explain the most variation) are elevation (46.9%) and mean temperature of the warmest month (27.6%).

Climate Scenario	Class	Mid-century (2050) – Coverage in Km <sup>2</sup> and % of Current Range		Late Century (2080) - Coverage in Km <sup>2</sup> and % of Current Range	
SSP1 – 2.6	0	0 (0%)	12% Marginal Habitat	0 (0%)	14% Marginal Habitat
	1	40712.6 (12%)		30093.3 (14%)	
	2	0 (0%)	0% Moderate Habitat	0 (0%)	0% Moderate Habitat
	3	776.8 (0%)		127.3 (0%)	
	4	34112.9 (29%)	87% Optimal Habitat	26227.4 (18%)	80% Optimal Habitat
	5	71826.8 (58%)		90998.0 (62%)	
SSP2 – 4.5	0	0 (0%)	28% Marginal Habitat	0 (0%)	20% Marginal Habitat
	1	64,201.7 (28%)		59,056.1 (20%)	
	2	0 (0%)	1% Moderate Habitat	0 (0%)	0% Moderate Habitat
	3	6,017.5 (1%)		9,513.9 (0%)	
	4	3,931.3 (23%)	72% Optimal Habitat	7,190.8 (18%)	80% Optimal Habitat
	5	417.1 (49%)		8,420.8 (62%)	
SSP3 – 7.0	0	0 (0%)	21% Marginal Habitat	0 (0%)	37% Marginal Habitat
	1	59,977.5 (21%)		56,403.9 (37%)	
	2	0 (0%)	0% Moderate Habitat	0 (0%)	0% Moderate Habitat
	3	9,631.9 (0%)		9,491.1 (0%)	
	4	5,924.1 (21%)	79% Optimal Habitat	8,617.5 (10%)	62% Optimal Habitat
	5	7,373.2 (58%)		11,187.3 (52%)	
SSP5 – 8.5	0	0 (0%)	22% Marginal Habitat	0 (0%)	48% Marginal Habitat
	1	59082.5 (22%)		63164.3 (48%)	
	2	0 (0%)	0% Moderate Habitat	0 (0%)	1% Moderate Habitat
	3	9575.5 (0%)		11030.0 (1%)	
	4	6911.5 (18%)	78% Optimal Habitat	4141.1 (18%)	52% Optimal Habitat
	5	8455.7 (60%)		2362.6 (34%)	

## Surfbird (*Aphriza virgata*)



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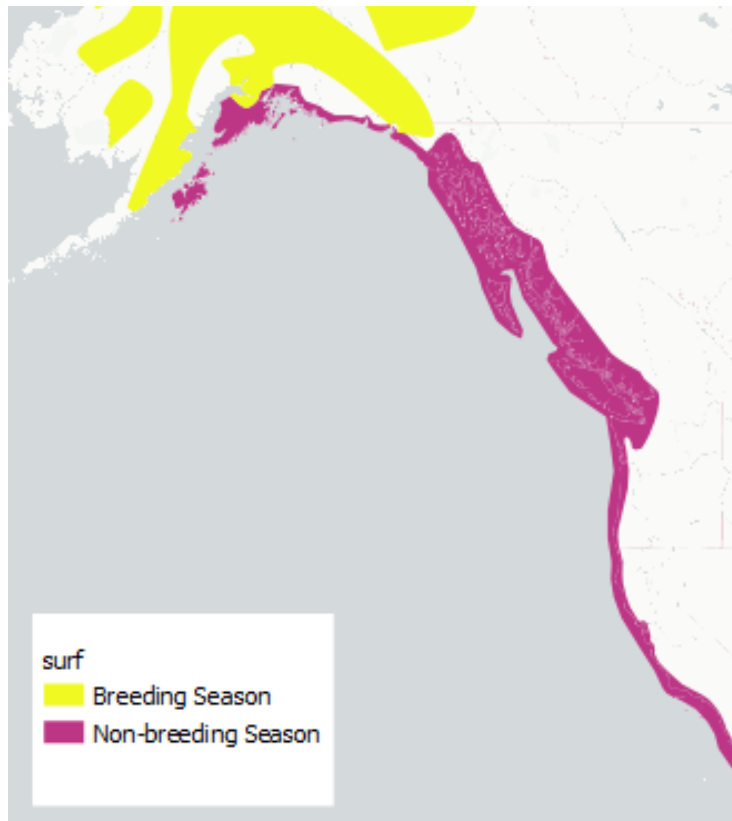


Figure 26: Surfbird range map created by the author using data from BirdLife International.

The established range for the Surfbird (SURF) within British Columbia covers ~**147,400km<sup>2</sup>**. Their population is ranked as globally secure (G5) and not at risk provincially (yellow). Full niche modeling for the species can be viewed [here](#).

### Overall Findings:

- Under a low-emissions climate scenario (SSP1-2.6), SURF habitat in the optimal habitat class (60-100% probability of occurrence in each grid cell) increases from 3% in the mid-century model to 6% at the late century. The amount of habitat in the marginal category (0-19%) decreases from 87% to 85%.
- Under the high-emissions scenario (SSP5-8.5) optimal habitat increases from 7% to 11%. Marginal habitat is reported to decrease from 80% to 71%. The Maxent model output indicates that the variables that individually contribute the most to the model (and explain the most variation) are mean annual temperature (68.4%) and mean temperature of the coldest month (12.5%).

Climate Scenario	Class	Mid-century (2050) – Coverage in Km <sup>2</sup> and % of Current Range		Late Century (2080) - Coverage in Km <sup>2</sup> and % of Current Range	
SSP1 – 2.6	0	1041.554 (1%)	<b>87%</b> Marginal Habitat	1091.534 (1%)	<b>85%</b> Marginal Habitat
	1	127831 (86%)		124823 (84%)	
	2	8986.272 (6%)	<b>10%</b> Moderate Habitat	9352.134 (6%)	<b>10%</b> Moderate Habitat
	3	5257.423 (4%)		5289.169 (4%)	
	4	3654.193 (2%)	<b>3%</b> Optimal Habitat	4245.659 (3%)	<b>6%</b> Optimal Habitat
	5	2161.186 (1%)		3732.395 (3%)	
SSP2 – 4.5	0	1185.8 (1%)	<b>83%</b> Marginal Habitat	1546.6 (1%)	<b>79%</b> Marginal Habitat
	1	121976.0 (82%)		115706.0 (78%)	
	2	10315.3 (7%)	<b>11%</b> Moderate Habitat	12443.6 (8%)	<b>13%</b> Moderate Habitat
	3	5913.6 (4%)		7366.5 (5%)	
	4	4925.9 (3%)	<b>6%</b> Optimal Habitat	6691.5 (5%)	<b>8%</b> Optimal Habitat
	5	4195.4 (3%)		4777.5 (3%)	
SSP3 – 7.0	0	1265.8 (1%)	<b>83%</b> Marginal Habitat	2113.4 (1%)	<b>75%</b> Marginal Habitat
	1	121571.0 (82%)		109168.0 (74%)	
	2	10228.5 (7%)	<b>11%</b> Moderate Habitat	14414.0 (10%)	<b>16%</b> Moderate Habitat
	3	5975.9 (4%)		8460.2 (6%)	
	4	5176.4 (3%)	<b>6%</b> Optimal Habitat	8831.6 (6%)	<b>10%</b> Optimal Habitat
	5	4272.8 (3%)		5339.8 (4%)	
SSP5 – 8.5	0	1470.1 (1%)	<b>80%</b> Marginal Habitat	2315.6 (2%)	<b>71%</b> Marginal Habitat
	1	117328.0 (79%)		102716.0 (69%)	
	2	11705.3 (8%)	<b>13%</b> Moderate Habitat	16872.7 (11%)	<b>18%</b> Moderate Habitat
	3	6925.1 (5%)		9901.9 (7%)	
	4	6183.0 (4%)	<b>7%</b> Optimal Habitat	10296.0 (7%)	<b>11%</b> Optimal Habitat
	5	4876.6 (3%)		6195.0 (4%)	

## Western Grebe (*Aechmophorus occidentalis*)



"Western Grebe" by Ron Knight is licensed under CC BY-ND 2.0.

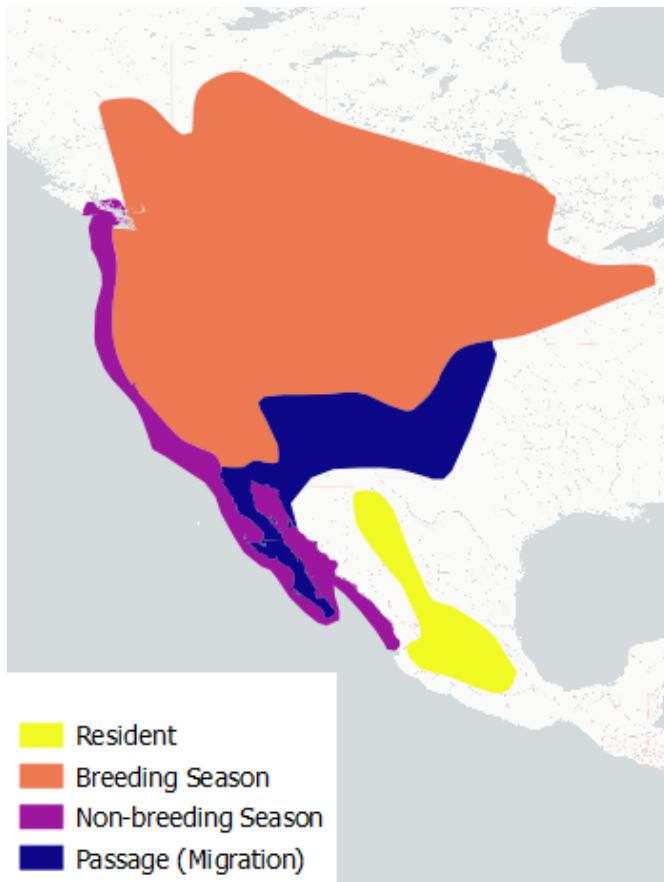


Figure 27: Western Grebe range map created by the author using data from BirdLife International.

Though it is not a shorebird like many of the birds studied here, I was curious to investigate climate change vulnerability for the Western Grebe (WEGR) due to its federal listing as a species of special concern. It is a red-listed (threatened) species provincially because there are only three regularly used breeding sites in British Columbia (B.C. Conservation

Data Centre, 1998). The established range for the Surfbird (SURF) within British Columbia covers only ~**34,600km<sup>2</sup>** and is limited to the southern portion of the province. Full niche modeling for the species can be viewed [here](#).

- Under a low-emissions climate scenario (SSP1-2.6), WEGR habitat in the optimal habitat classes (4 and 5, 60-100% probability of occurrence in each grid cell) increases from 11% in the mid-century model to 21% in the late century. The amount of habitat in the marginal category (0-19%) decreases from 70% to 63%.
- Under the high-emissions scenario (SSP5-8.5) optimal habitat decreases from 28% down to 10%. Marginal habitat is

reported to increase from 58% to 70%. The Maxent model output indicates that the variables that individually contribute the most to the model (and explain the most variation) are mean temperature of the warmest month (61.8%) and elevation (26%).

Climate Scenario	Class	Mid-century (2050) – Coverage in Km <sup>2</sup> and % of Current Range		Late Century (2080) - Coverage in Km <sup>2</sup> and % of Current Range	
SSP1 – 2.6	0	395.4 (1%)	<b>70%</b> Marginal Habitat	352.0 (1%)	<b>63%</b> Marginal Habitat
	1	23796.5 (69%)		21371.0 (62%)	
	2	3713.4 (11%)	<b>20%</b> Moderate Habitat	3078.1 (9%)	<b>16%</b> Moderate Habitat
	3	3132.6 (9%)		2264.2 (7%)	
	4	2257.5 (7%)	<b>11%</b> Optimal Habitat	1831.5 (5%)	<b>21%</b> Optimal Habitat
	5	1327.7 (4%)		5691.6 (16%)	
SSP2 – 4.5	0	451.4 (1%)	<b>80%</b> Marginal Habitat	305.1 (1%)	<b>58%</b> Marginal Habitat
	1	27422.2 (79%)		19845.0 (57%)	
	2	4124.0 (12%)	<b>18%</b> Moderate Habitat	2697.8 (8%)	<b>13%</b> Moderate Habitat
	3	2007.5 (6%)		1892.8 (5%)	
	4	565.2 (2%)	<b>2%</b> Optimal Habitat	1929.3 (6%)	<b>29%</b> Optimal Habitat
	5	18.3 (0%)		7917.8 (23%)	
SSP3 – 7.0	0	339.8 (1%)	<b>60%</b> Marginal Habitat	310.1 (1%)	<b>59%</b> Marginal Habitat
	1	20417.9 (59%)		17843.9 (52%)	
	2	2869.7 (8%)	<b>14%</b> Moderate Habitat	2800.3 (8%)	<b>14%</b> Moderate Habitat
	3	2065.0 (6%)		2003.4 (6%)	
	4	1769.9 (5%)	<b>26%</b> Optimal Habitat	2193.3 (6%)	<b>33%</b> Optimal Habitat
	5	7129.9 (21%)		9436.8 (27%)	
SSP5 – 8.5	0	310.0 (1%)	<b>58%</b> Marginal Habitat	391.5 (1%)	<b>70%</b> Marginal Habitat
	1	19812.6 (57%)		23985.0 (69%)	
	2	2733.7 (8%)	<b>14%</b> Moderate Habitat	3705.4 (11%)	<b>19%</b> Moderate Habitat
	3	1908.4 (6%)		2790.8 (8%)	
	4	1900.8 (5%)	<b>28%</b> Optimal Habitat	2224.9 (6%)	<b>10%</b> Optimal Habitat
	5	7926.9 (23%)		1491.0 (4%)	

## Western Sandpiper (*Calidris mauri*)



"Western Sandpiper" by Alan D. Wilson is licensed under CC BY-ND 3.0.

The Western Sandpiper (WESA) is an iconic species during its migration along the coasts of British Columbia. Its range map in the Birdlife International database did not show the entire range of the species, only indicating its presence in the southern portion of the province. For that reason, I elected to use the entire BCR5 polygon for analysis, covering

~203,000km<sup>2</sup>. Their population is ranked as globally secure (G5) and not at risk provincially (yellow). Full niche modeling for the species can be viewed [here](#).

### Overall Findings:

- Under a low-emissions climate scenario (SSP1-2.6), WESA habitat in the optimal habitat classes (4 and 5, 60-100% probability of occurrence in each grid cell) increases from 11% in the mid-century model to 21% in the late century. The amount of habitat in the marginal category (0-19%) decreases from 70% to 63%.
- Under the high-emissions scenario (SSP5-8.5) optimal habitat decreases from 28% down to 10%. Marginal habitat is reported to increase from 58% to 70%. The Maxent model output indicates that the variables that individually contribute the most to the model (and explain the most variation)

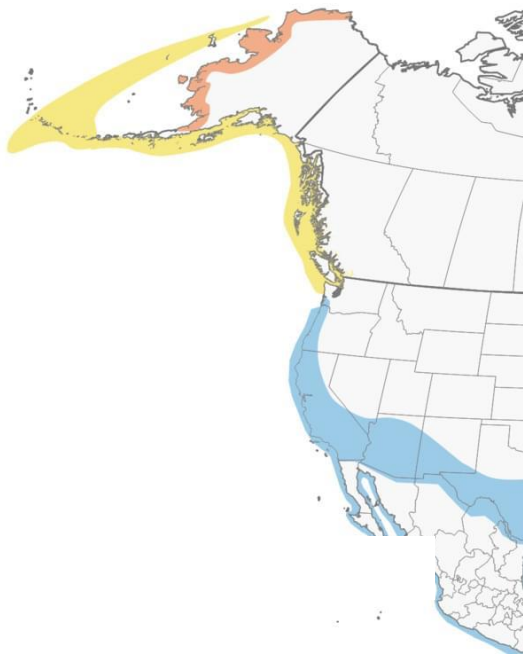


Figure 28: Range map for Western Sandpiper. Yellow indicates migratory habitat. Accessed from the Cornell "All About Birds" database: [5https://www.allaboutbirds.org/guide/Western\\_Sandpiper/maps-range](https://www.allaboutbirds.org/guide/Western_Sandpiper/maps-range)

are mean annual temperature (69.6%) and elevation (22.1%).

Climate Scenario	Class	Mid-century (2050) – Coverage in Km <sup>2</sup> and % of Current Range		Late Century (2080) - Coverage in Km <sup>2</sup> and % of Current Range	
SSP1 – 2.6	0	122879 (61%)	<b>93%</b> Marginal Habitat	114930 (57%)	<b>86%</b> Marginal Habitat
	1	63836.54 (32%)		58701.35 (29%)	
	2	11572.17 (6%)	<b>7%</b> Moderate Habitat	13664.47 (7%)	<b>11%</b> Moderate Habitat
	3	1680.023 (1%)		7640.067 (4%)	
	4	232.6785 (0%)	<b>0%</b> Optimal Habitat	4182.719 (2%)	<b>3%</b> Optimal Habitat
	5	3.843957 (0%)		1633.801 (1%)	
SSP2 – 4.5	0	117622 (59%)	<b>89%</b> Marginal Habitat	106680.0 (53%)	<b>84%</b> Marginal Habitat
	1	60439.3 (30%)		61654.2 (31%)	
	2	11637.1 (6%)	<b>8%</b> Moderate Habitat	14905.5 (7%)	<b>12%</b> Moderate Habitat
	3	4479.4 (2%)		9387.6 (5%)	
	4	3255.8 (2%)	<b>3%</b> Optimal Habitat	5607.2 (3%)	<b>4%</b> Optimal Habitat
	5	2729.9 (1%)		1969.7 (1%)	
SSP3 – 7.0	0	110570.0 (55%)	<b>85%</b> Marginal Habitat	99638.9 (50%)	<b>82%</b> Marginal Habitat
	1	60190.6 (30%)		64118.7 (32%)	
	2	13954.5 (7%)	<b>11%</b> Moderate Habitat	16599.5 (8%)	<b>13%</b> Moderate Habitat
	3	8521.2 (4%)		10254.1 (5%)	
	4	4811.9 (2%)	<b>3%</b> Optimal Habitat	6341.7 (3%)	<b>5%</b> Optimal Habitat
	5	1956.7 (1%)		3251.2 (2%)	
SSP5 – 8.5	0	104894 (52%)	<b>85%</b> Marginal Habitat	91640.6 (46%)	<b>81%</b> Marginal Habitat
	1	65965.3 (33%)		70593.4 (35%)	
	2	14704.7 (7%)	<b>11%</b> Moderate Habitat	17232.4 (9%)	<b>14%</b> Moderate Habitat
	3	8411.1 (4%)		10124.3 (5%)	
	4	4607.4 (2%)	<b>3%</b> Optimal Habitat	5353.6 (3%)	<b>6%</b> Optimal Habitat
	5	1734.0 (1%)		5749.6 (3%)	

### *Whimbrel (Numenius phaeopus)*



"Whimbrel (*Numenius phaeopus*)" by Noel Reynolds is licensed under CC BY-ND 2.0.

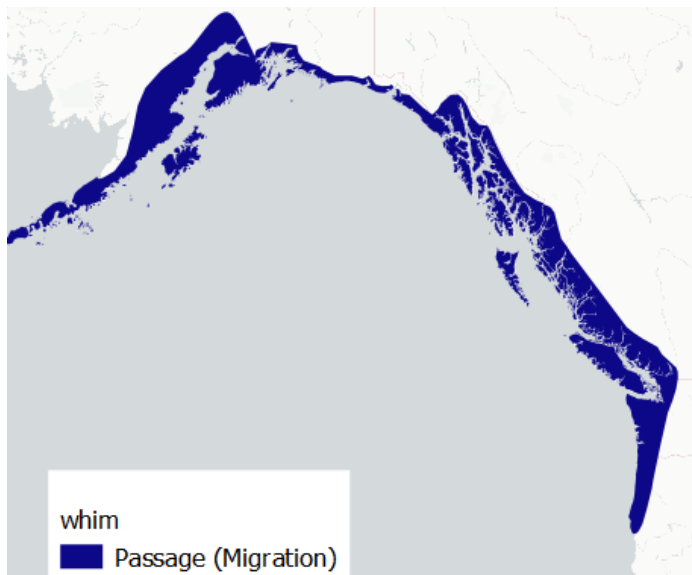


Figure 29: Whimbrel range map created by the author using data from BirdLife International.

The established range for the Whimbrel (WHIM) within British Columbia covers ~145,800km<sup>2</sup> and is fully migratory habitat. It is a red-listed (threatened) species provincially because its breeding habitat is limited to one very small area in northern B.C. and its non-breeding numbers appear to be declining (B.C. Conservation Data Centre, 1990). Full niche modeling for the species can be viewed [here](#).

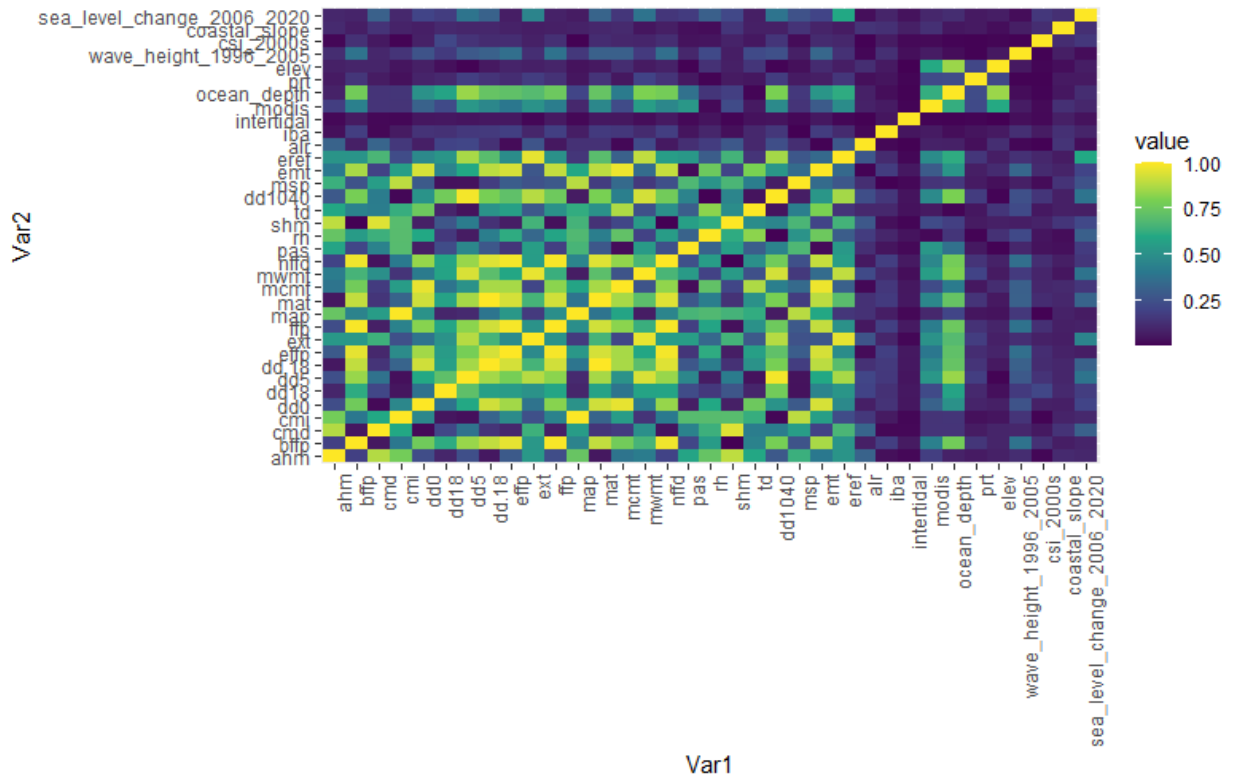
#### **Overall Findings:**

- Under a low-emissions climate scenario (SSP1-2.6), WHIM habitat in the optimal habitat classes (4 and 5, 60-100% probability of occurrence in each grid cell) increases from 7% in the mid-century model to 8% in the late century. The amount of habitat in the marginal category (0-19%) decreases by 1%.
- Under the high-emissions scenario (SSP5-8.5) optimal habitat increases from 11% up to 19%. Marginal habitat is

reported to decrease from 78% to 67%. The Maxent model output indicates that the variables that individually contribute the most to the model (and explain the most variation) are mean annual temperature (72%) and mean temperature of the coldest month (10.5%).

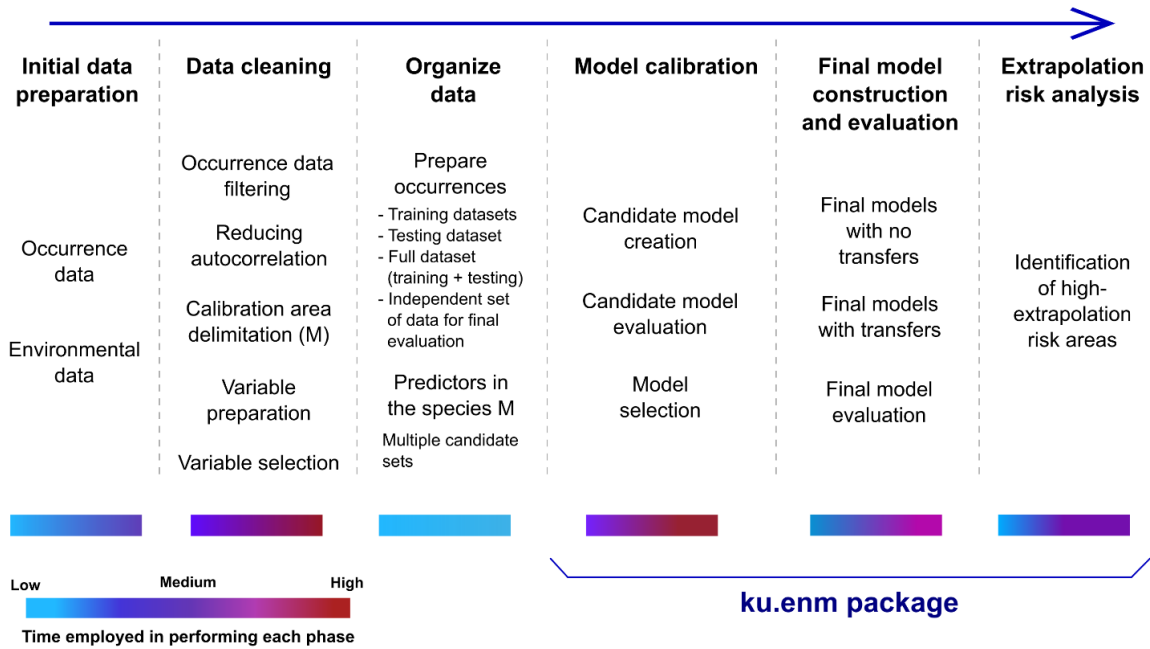
Climate Scenario	Class	Mid-century (2050) – Coverage in Km <sup>2</sup> and % of Current Range		Late Century (2080) - Coverage in Km <sup>2</sup> and % of Current Range	
SSP1 – 2.6	0	90057.8 (62%)	<b>84%</b> Marginal Habitat	88608.8 (61%)	<b>83%</b> Marginal Habitat
	1	32330.1 (22%)		31819.5 (22%)	
	2	8790.9 (6%)	<b>9%</b> Moderate Habitat	9515.9 (7%)	<b>10%</b> Moderate Habitat
	3	4527.6 (3%)		4725.9 (3%)	
	4	3895.1 (3%)	<b>7%</b> Optimal Habitat	4483.2 (3%)	<b>8%</b> Optimal Habitat
	5	6051.5 (4%)		6730.7 (5%)	
SSP2 – 4.5	0	85553.6 (59%)	<b>81%</b> Marginal Habitat	81557.1 (56%)	<b>77%</b> Marginal Habitat
	1	31621.7 (22%)		30327.8 (21%)	
	2	10586.9 (7%)	<b>11%</b> Moderate Habitat	9369.3 (5%)	<b>10%</b> Moderate Habitat
	3	5389.8 (4%)		7843.1 (5%)	
	4	4960.3 (3%)	<b>8%</b> Optimal Habitat	7292.4 (5%)	<b>12%</b> Optimal Habitat
	5	7800.9 (5%)		9486.1 (7%)	
SSP3 – 7.0	0	86096.3 (59%)	<b>80%</b> Marginal Habitat	75580.0 (52%)	<b>73%</b> Marginal Habitat
	1	30848.6 (21%)		30205.9 (21%)	
	2	9778.7 (7%)	<b>11%</b> Moderate Habitat	10057.7 (7%)	<b>12%</b> Moderate Habitat
	3	5657.6 (4%)		7881.6 (5%)	
	4	5302.4 (4%)	<b>10%</b> Optimal Habitat	10083.7 (7%)	<b>15%</b> Optimal Habitat
	5	8061.0 (6%)		12063.8 (8%)	
SSP5 – 8.5	0	82694.7 (57%)	<b>78%</b> Marginal Habitat	66691.3 (46%)	<b>67%</b> Marginal Habitat
	1	30288.0 (21%)		30434.0 (21%)	
	2	9429.0 (6%)	<b>11%</b> Moderate Habitat	11156.5 (8%)	<b>15%</b> Moderate Habitat
	3	7629.7 (5%)		9635.2 (7%)	
	4	6195.3 (4%)	<b>11%</b> Optimal Habitat	12212.4 (8%)	<b>19%</b> Optimal Habitat
	5	9507.4 (7%)		15765.8 (11%)	

## Appendix B: Supplemental Material



Appendix Figure 1: Collinearity heatmap for the full suite of environmental predictor variables before correlated variables were removed. Variables that are more similar (based on Pearson correlation coefficients) are yellow or light green in colour (closer to 1), while variables that are dissimilar are purple. Many of the climate variables were highly correlated, as were ocean depth and elevation. Please see Table 3 for a list of variable codes.

## Ecological niche modeling process



*Appendix Figure 2: Ecological niche modeling process. Reprinted from "ku.enm: an R package for detailed development of ecological niche models using Maxent" by Cobos ME, Peterson AT, Barve N, Osorio-Olvera L., 2019, PeerJ 7:e6281 <https://doi.org/10.7717/peerj.62>*

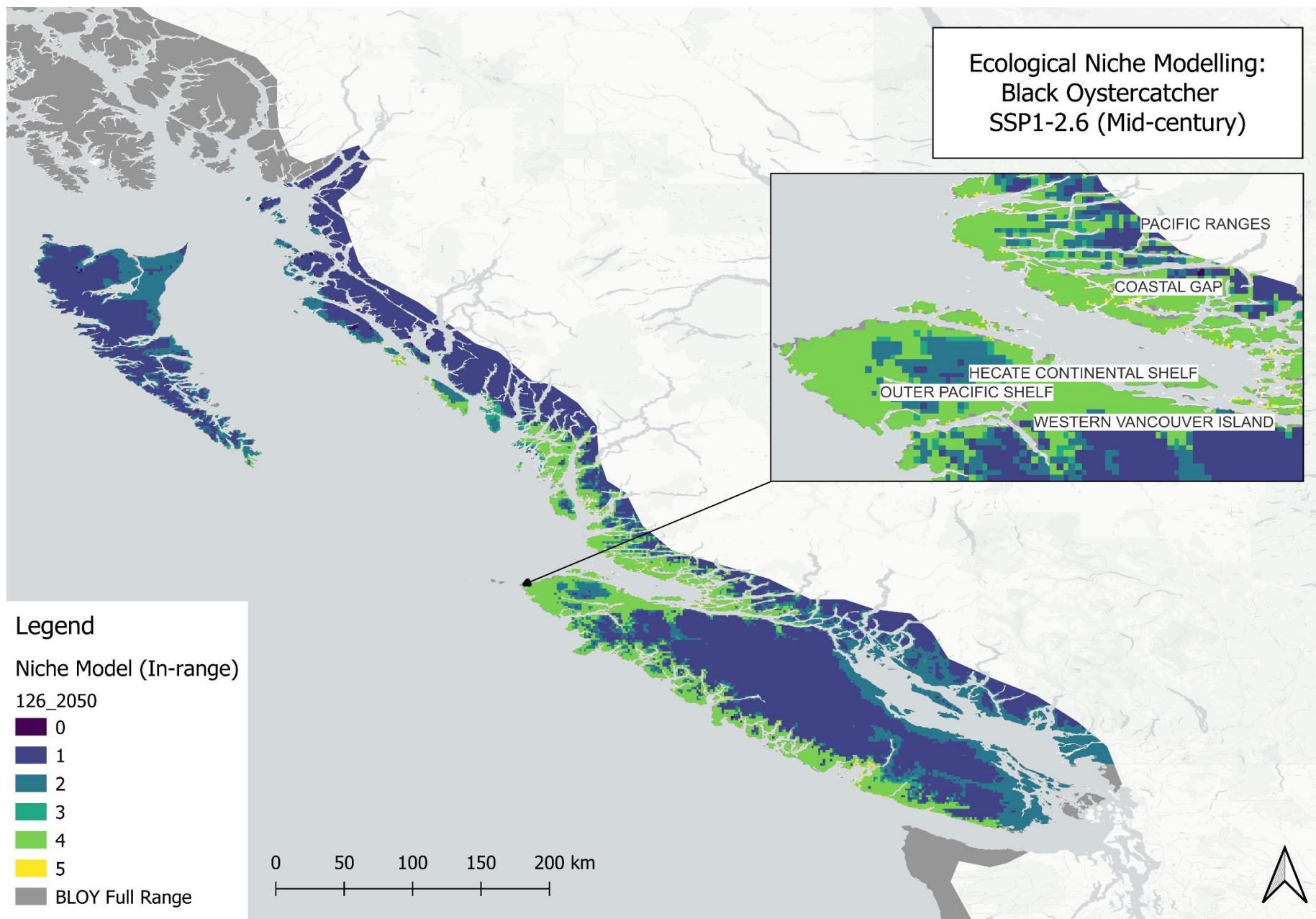
### Appendix C: Full Ecological Niche Modelling

Model Value	Category	Habitat Class	Explanation
0 – 0	Marginal	0	0% probability of occurrence
0.01 – 0.19		1	<19% probability of occurrence
0.20 – 0.39	Moderate	2	20-39% probability of occurrence
0.40 – 0.59		3	40-59% probability of occurrence
0.60 – 0.79	Optimal	4	60-79% probability of occurrence
0.80 – 1.0		5	80-100% probability of occurrence

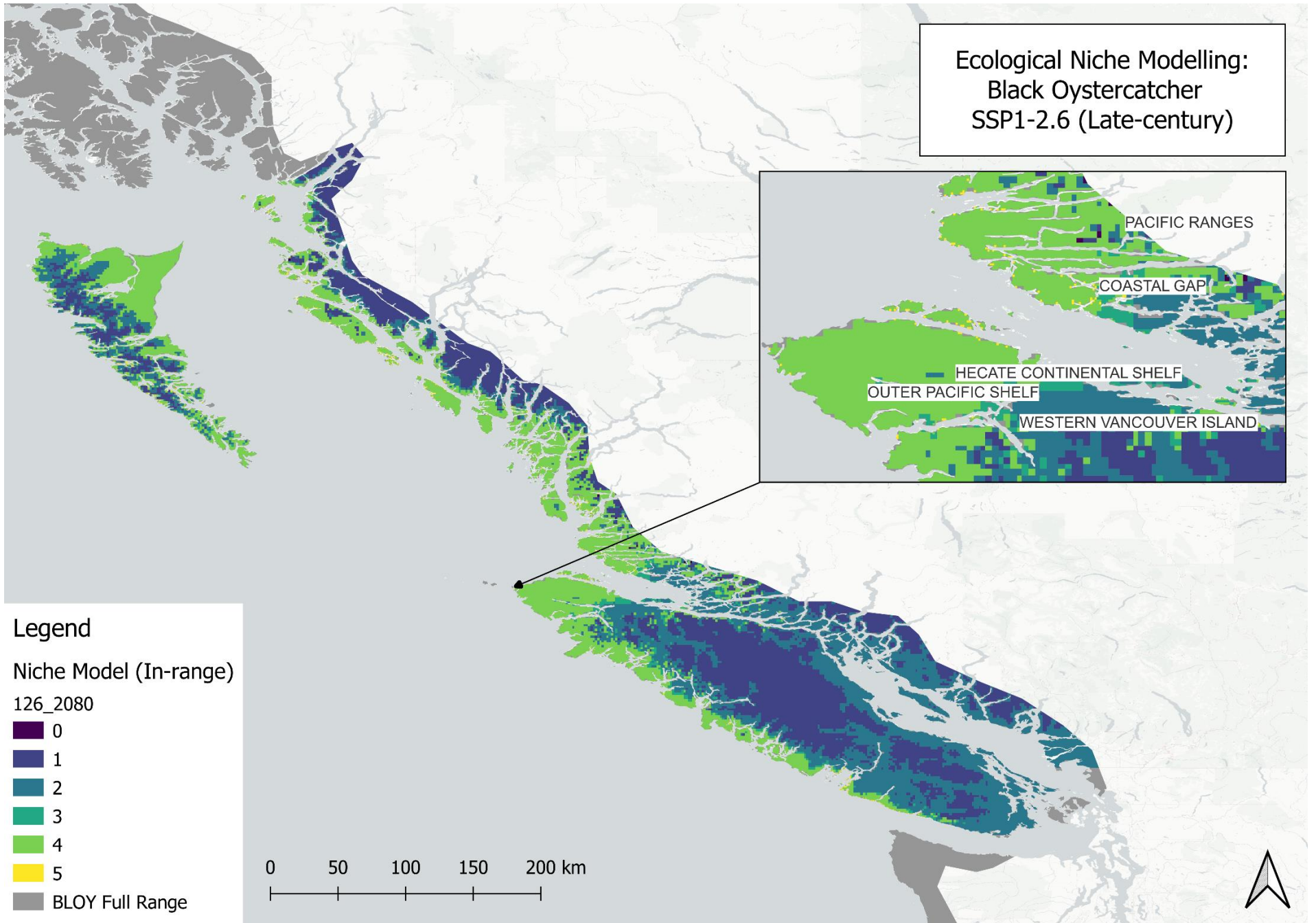
The table above indicates which colour corresponds with which Habitat Class. Before binning, probability of occurrence scores ranged from 0-1. By binning the rasters into habitat classes (0-5) and then aggregating these scores into broader, descriptive categories, this facilitates easier comparison of the model outputs over time and between climate scenarios. Here, I also aimed to simplify the data visualization process, because it is easier to visually depict changes in an area over time (and between climate scenarios) if the values are binned into a smaller, but still meaningful number of categories. This also facilitates easier identification of climate refugia. Since the spatial data that fed into the models was coarse-scale, with all layers resampled to a 1x1km grid, I deemed it appropriate to aggregate the final scores into broad descriptive categories (e.g. Marginal, Moderate and Optimal). Therefore, in the maps below, 60-100% probability of bird occurrence in each grid cell would be a good indicator of suitable habitat.

The grey polygons in each map (overlaid by the Ecological Niche Model) indicate each species' range as determined by Birdlife International. I indicate whether this is migratory or breeding range in the legends.

Ecological Niche Modelling: Black Oystercatcher (*Haematopus bachmani*)



Ecological Niche Modelling:  
Black Oystercatcher  
SSP1-2.6 (Late-century)



Legend

Niche Model (In-range)

126\_2080

0

1

2

3

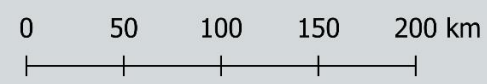
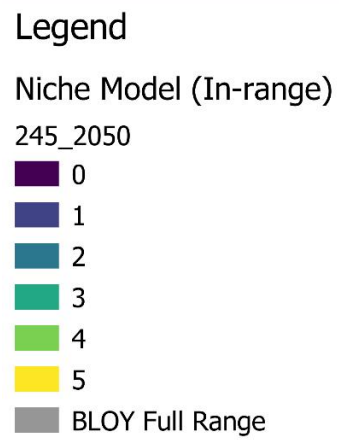
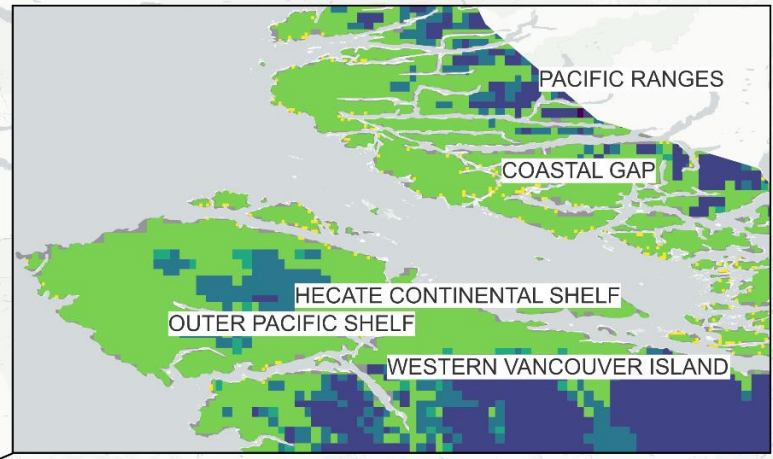
4

5

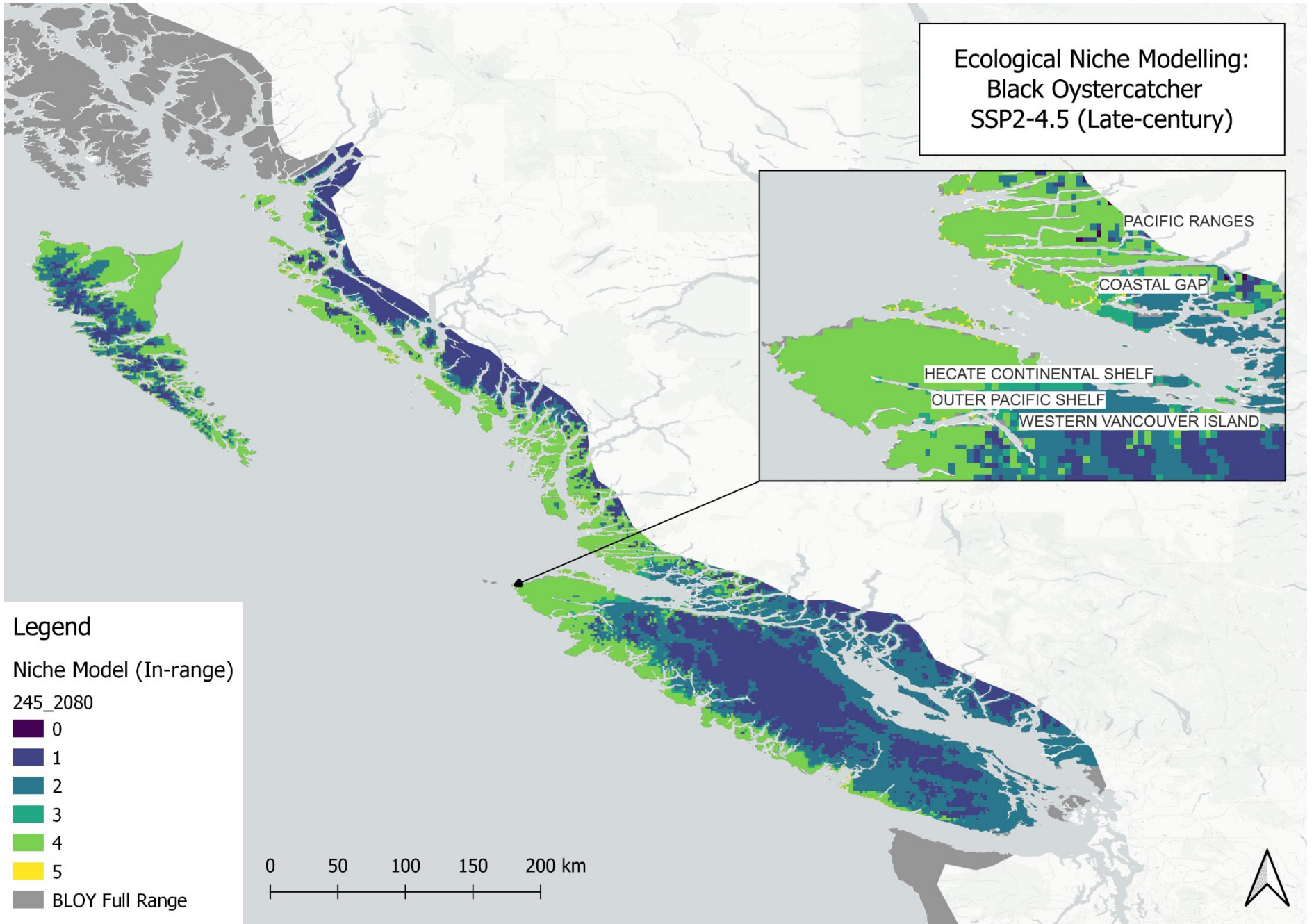
BLOY Full Range

0 50 100 150 200 km

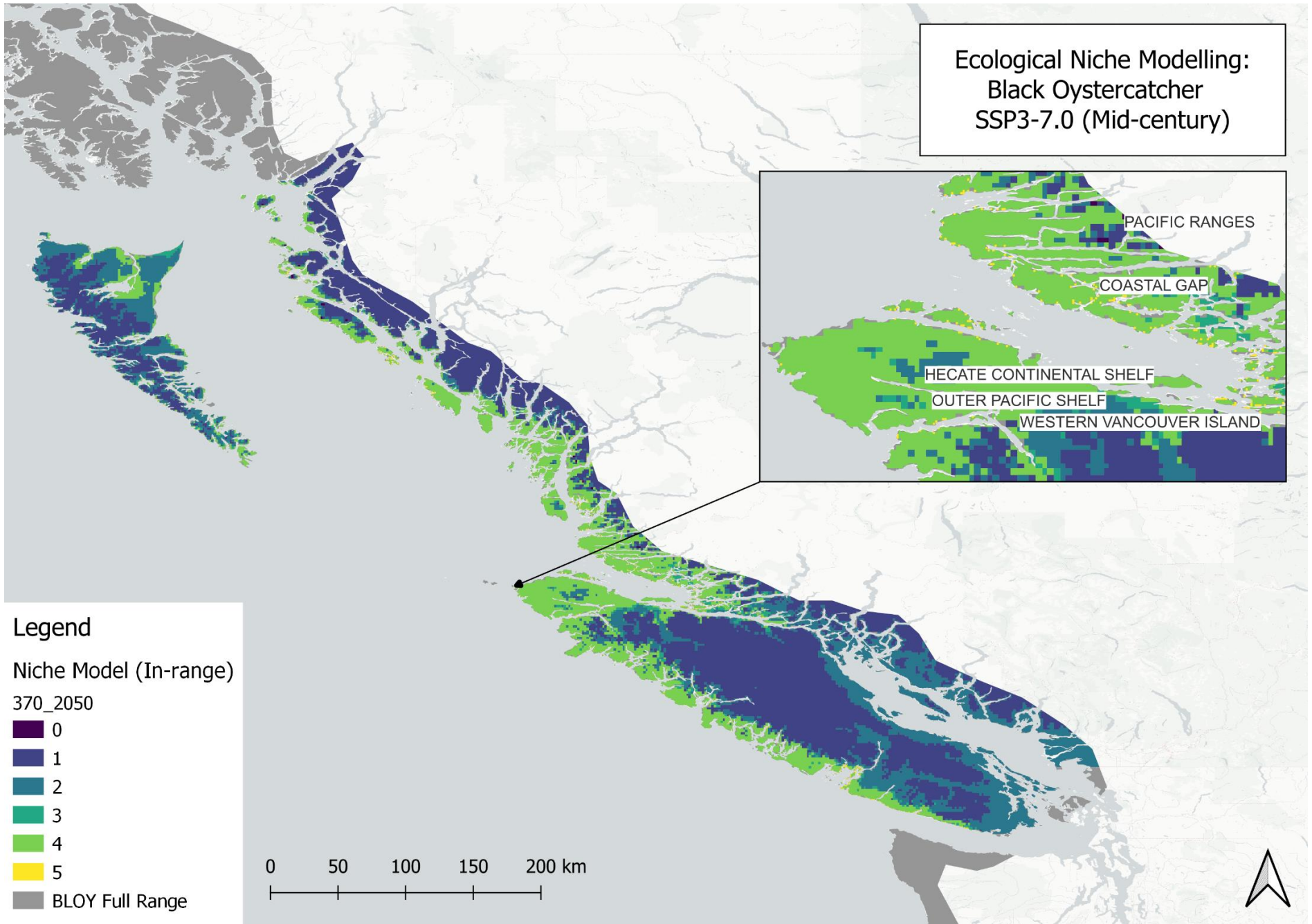
Ecological Niche Modelling:  
Black Oystercatcher  
SSP2-4.5 (Mid-century)

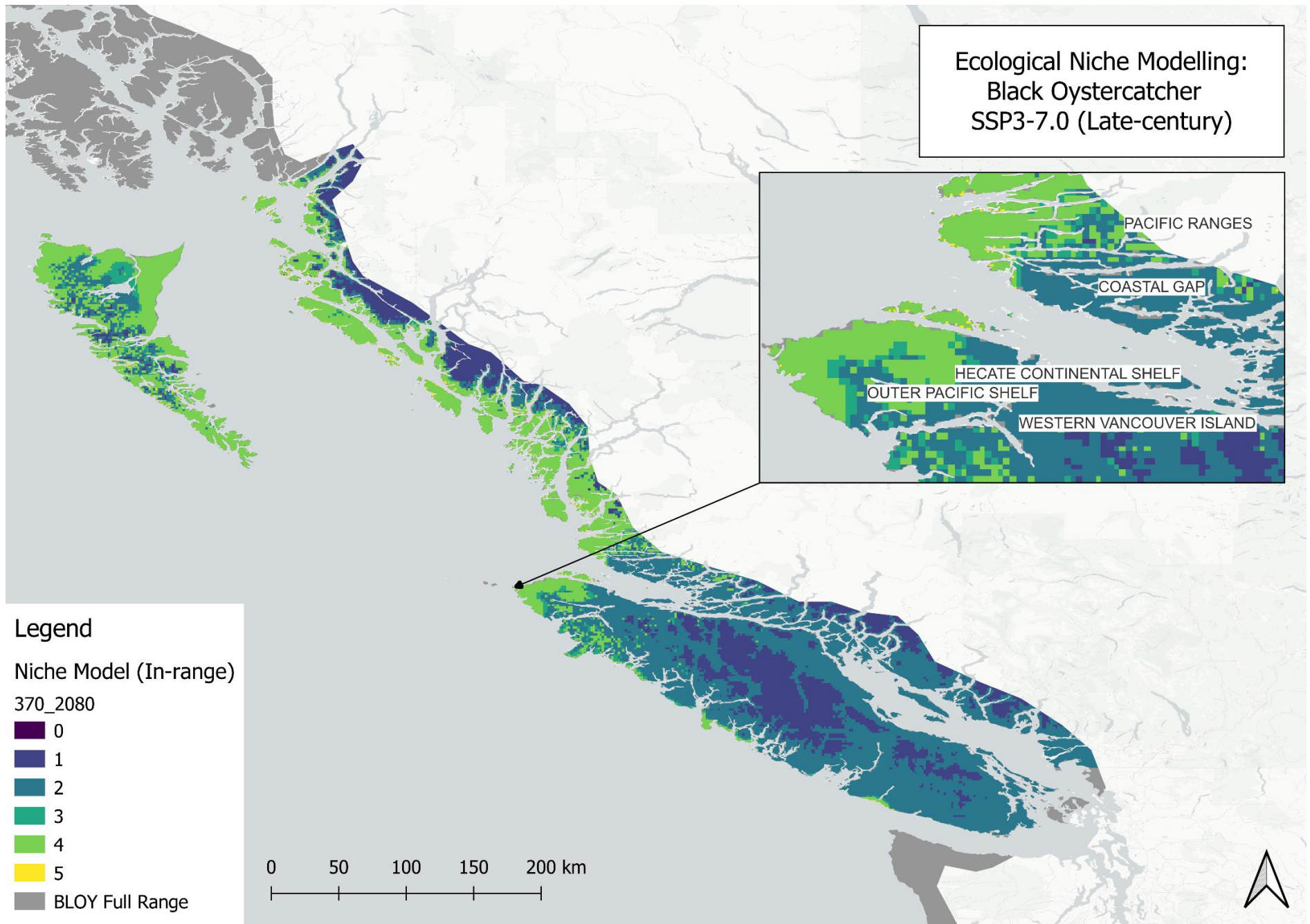


Ecological Niche Modelling:  
Black Oystercatcher  
SSP2-4.5 (Late-century)

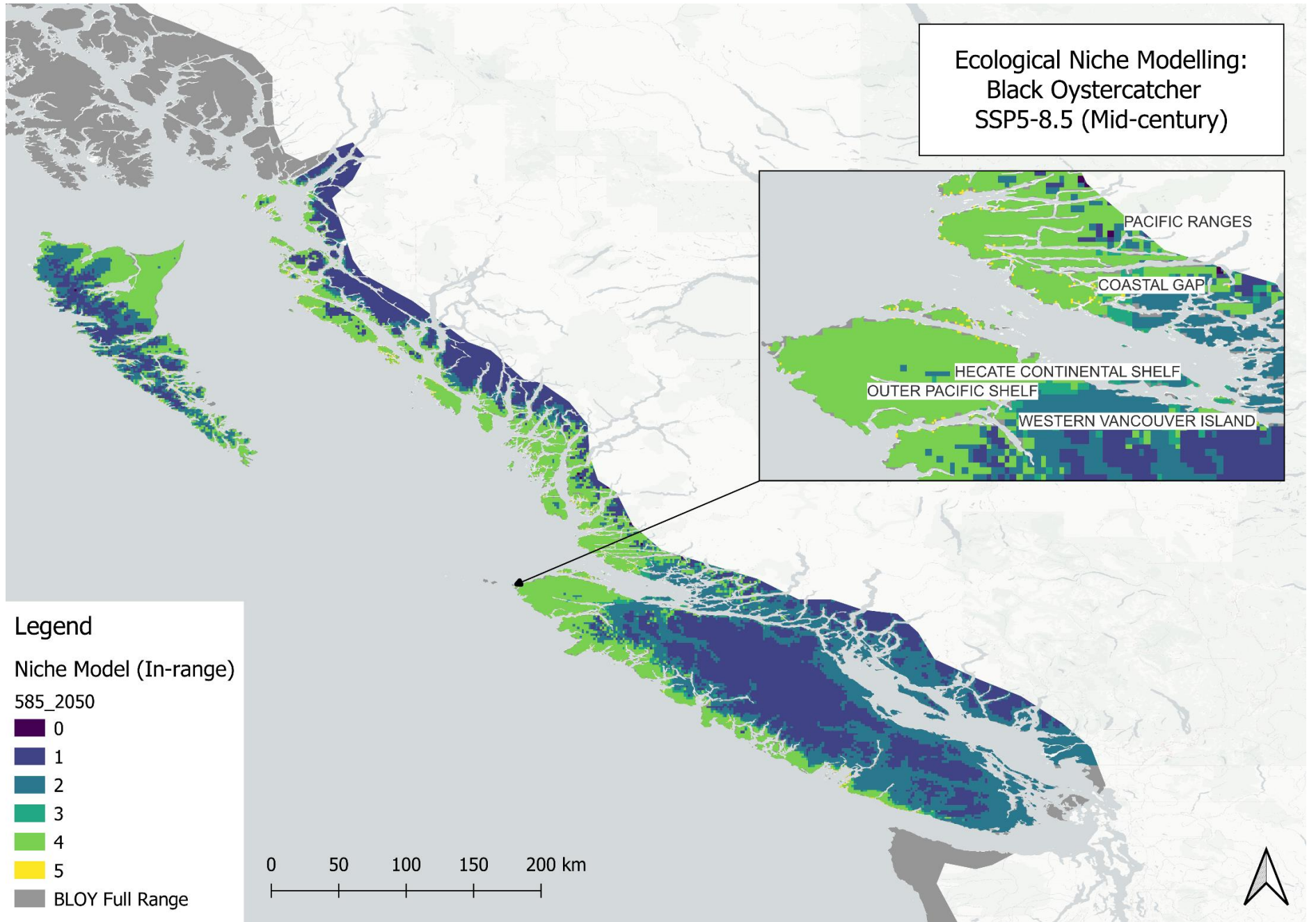


Ecological Niche Modelling:  
Black Oystercatcher  
SSP3-7.0 (Mid-century)

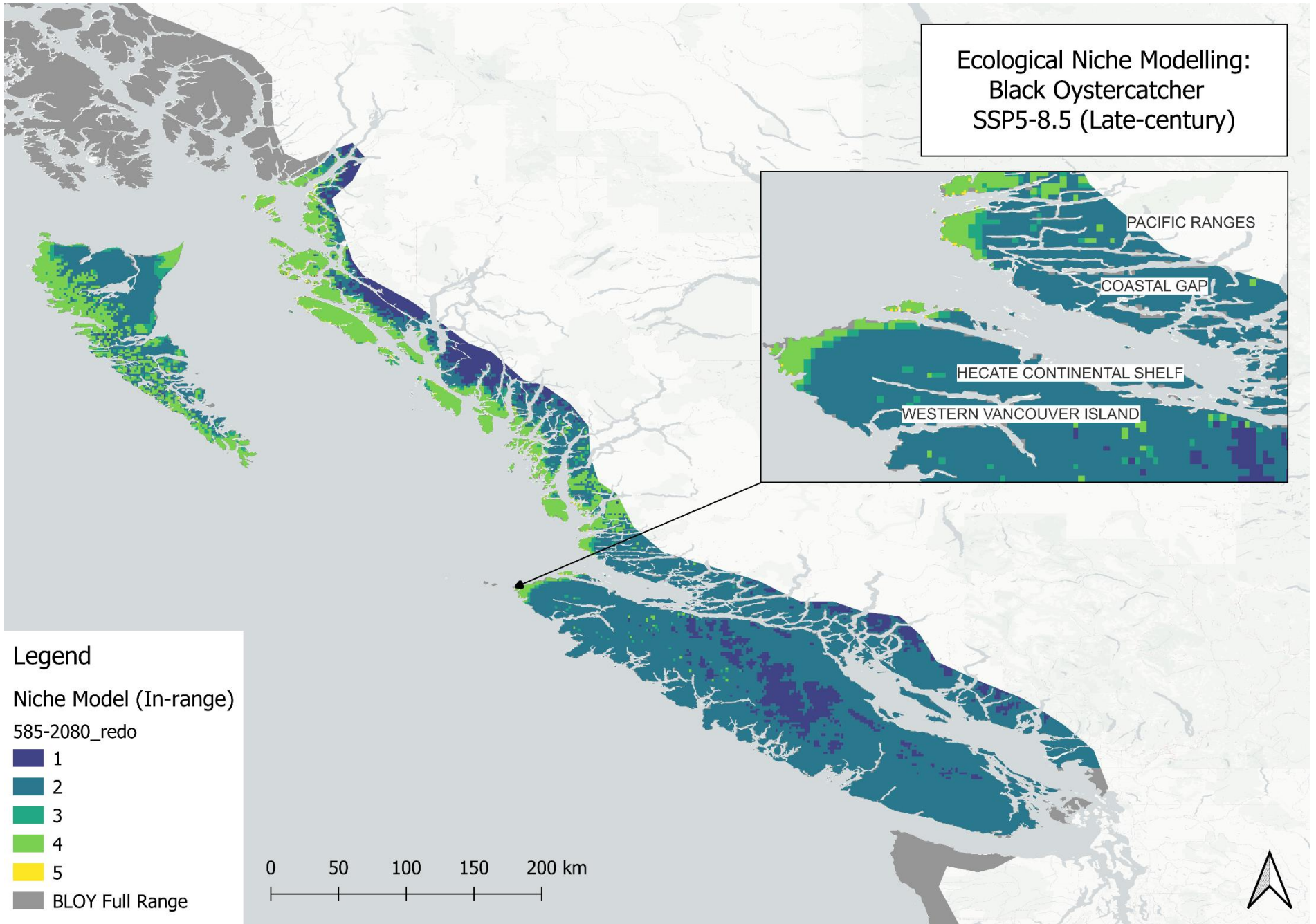




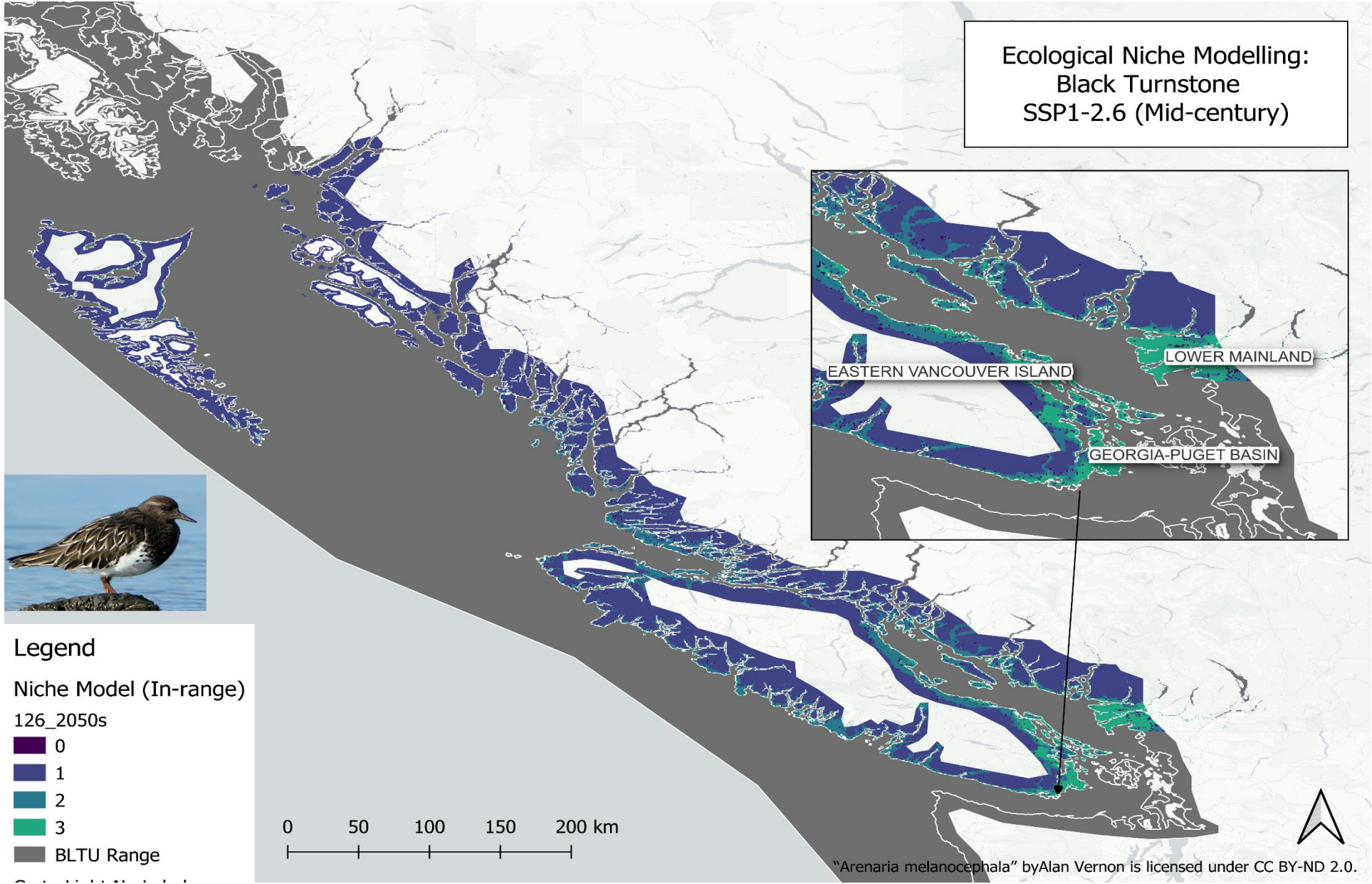
Ecological Niche Modelling:  
Black Oystercatcher  
SSP5-8.5 (Mid-century)



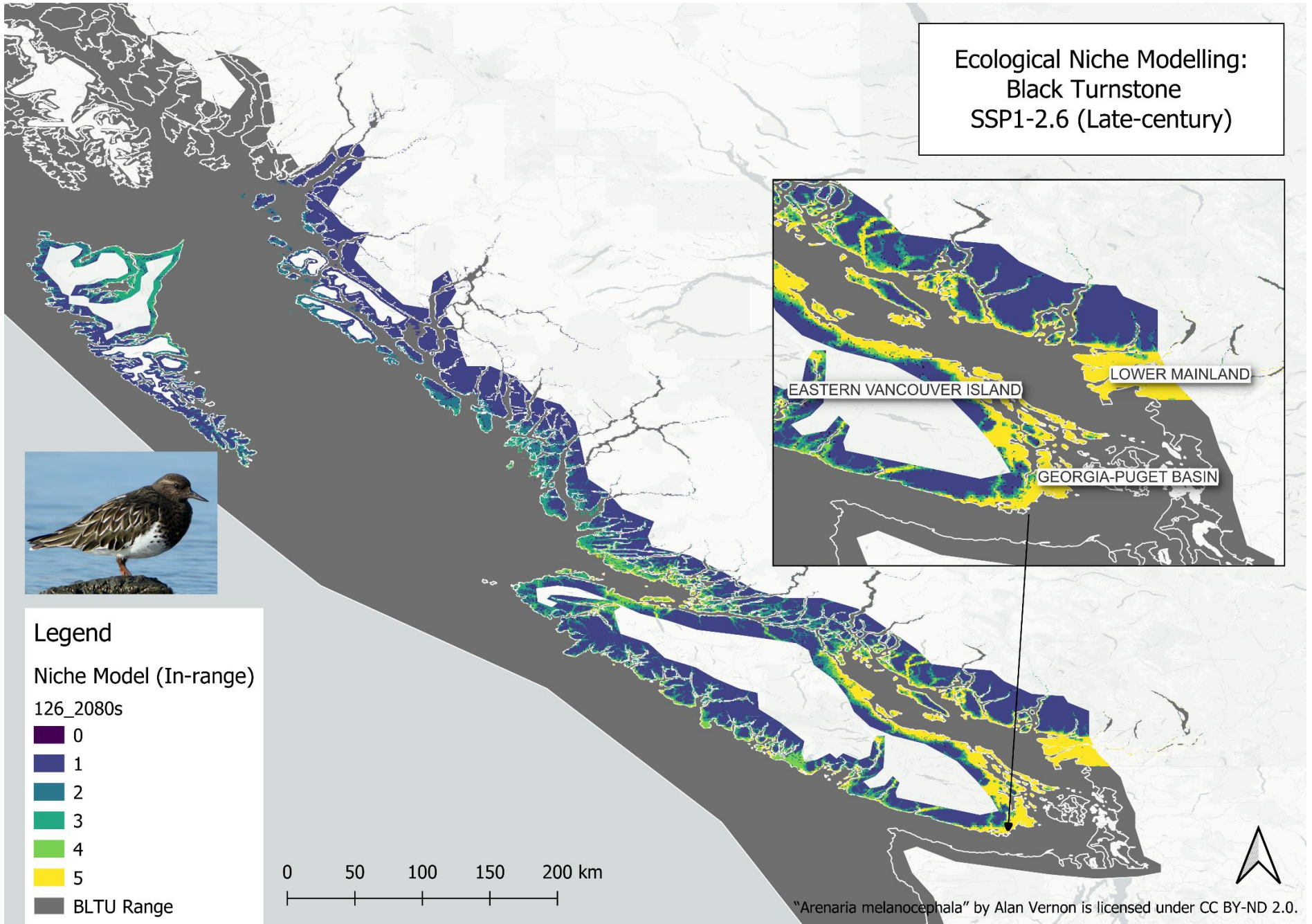
Ecological Niche Modelling:  
Black Oystercatcher  
SSP5-8.5 (Late-century)



# Ecological Niche Modelling: Black Turnstone (*Arenaria melanocephala*)



Ecological Niche Modelling:  
Black Turnstone  
SSP1-2.6 (Late-century)



Ecological Niche Modelling:  
Black Turnstone  
SSP2-4.5 (Mid-century)



Legend

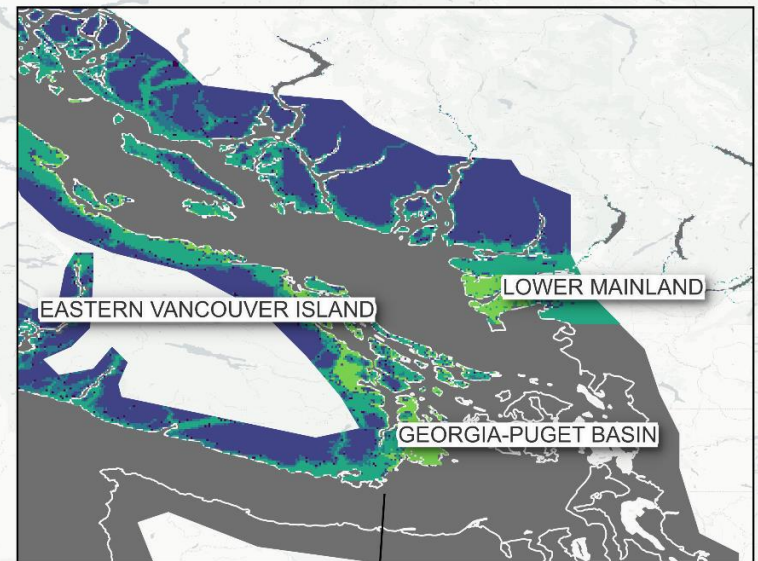
Niche Model (In-range)

245\_2050s

- 0
- 1
- 2
- 3
- 4

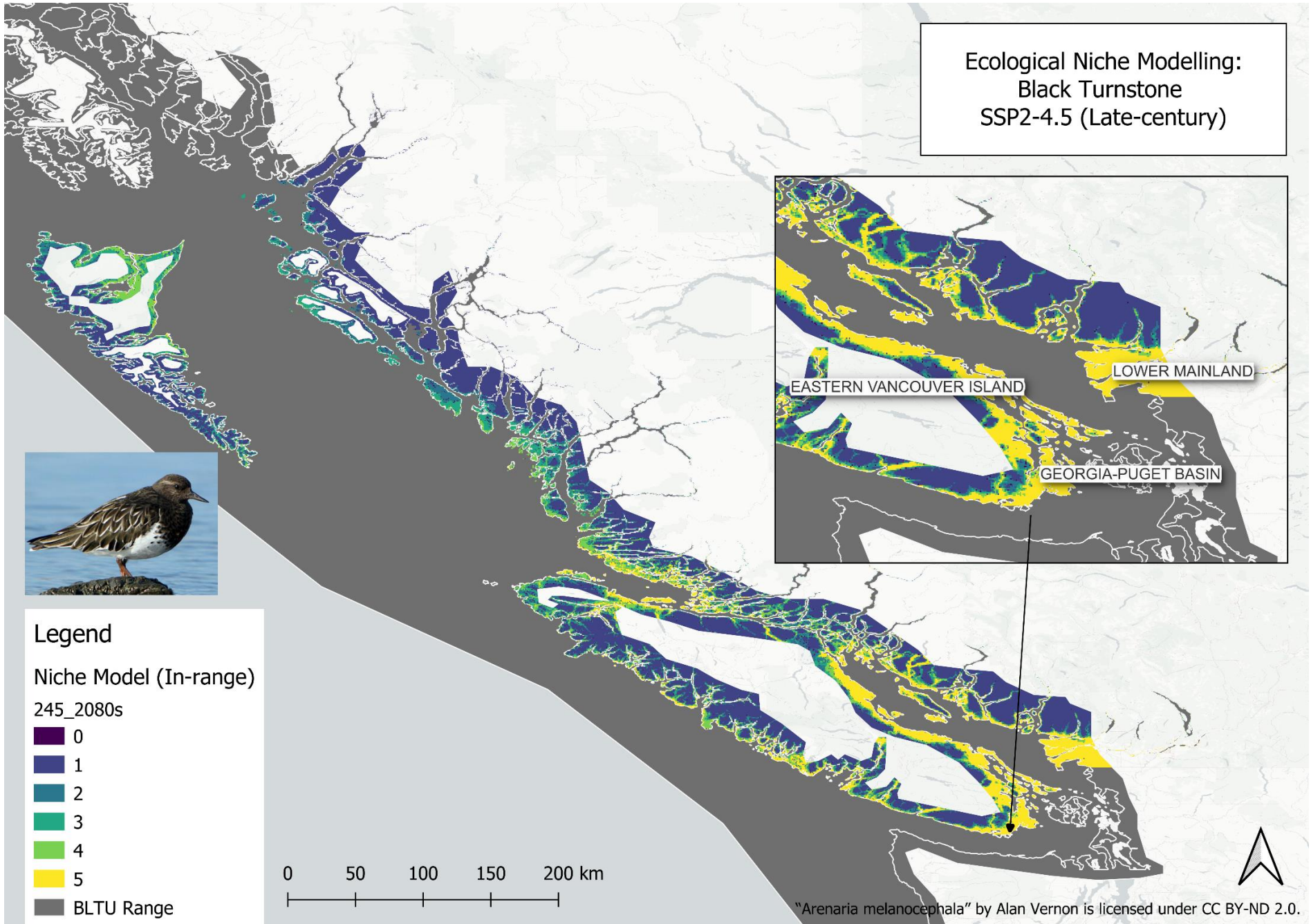
BLTU Range

Carto Light No Labels

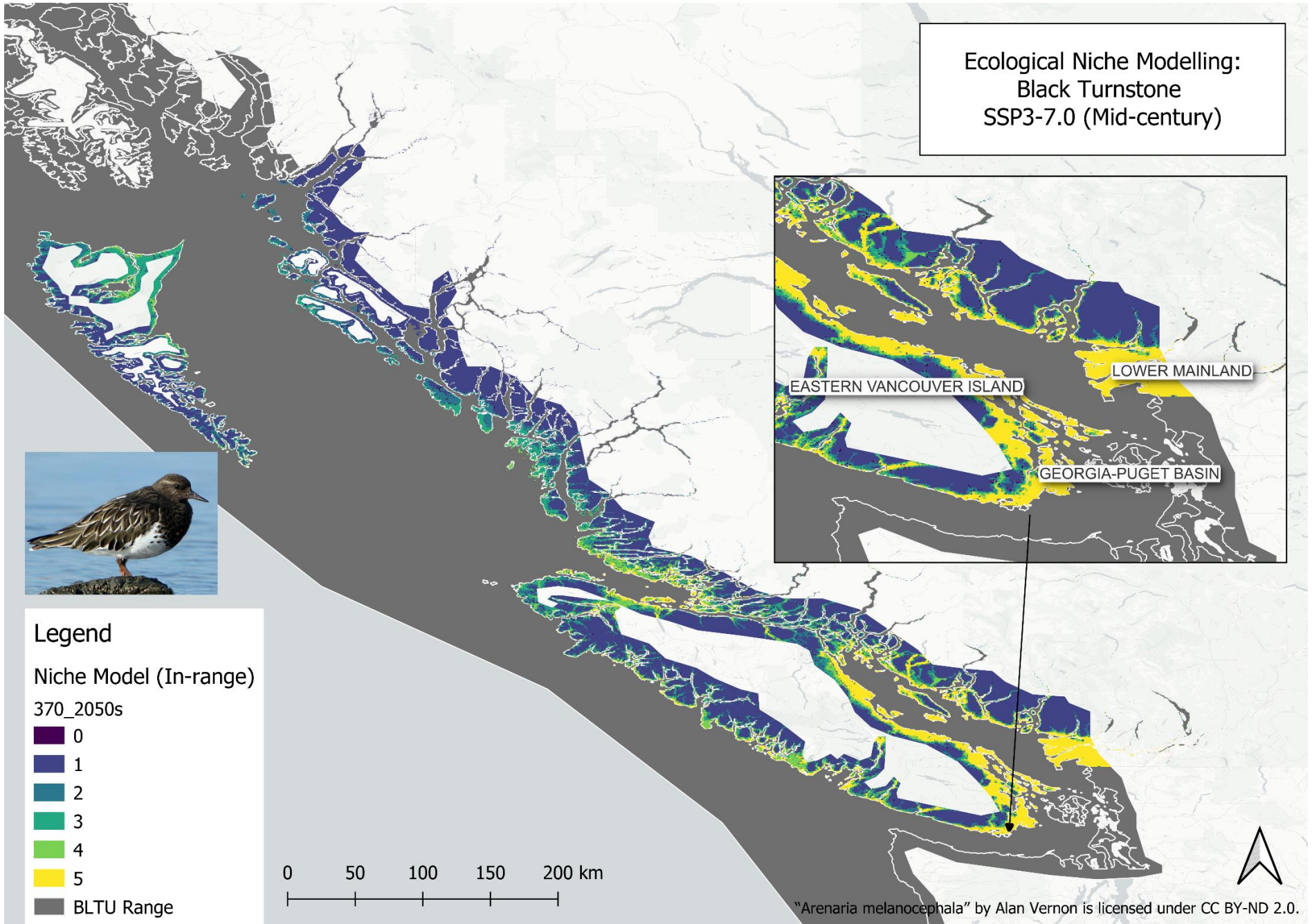


"Arenaria melanocephala" by Alan Vernon is licensed under CC BY-ND 2.0.

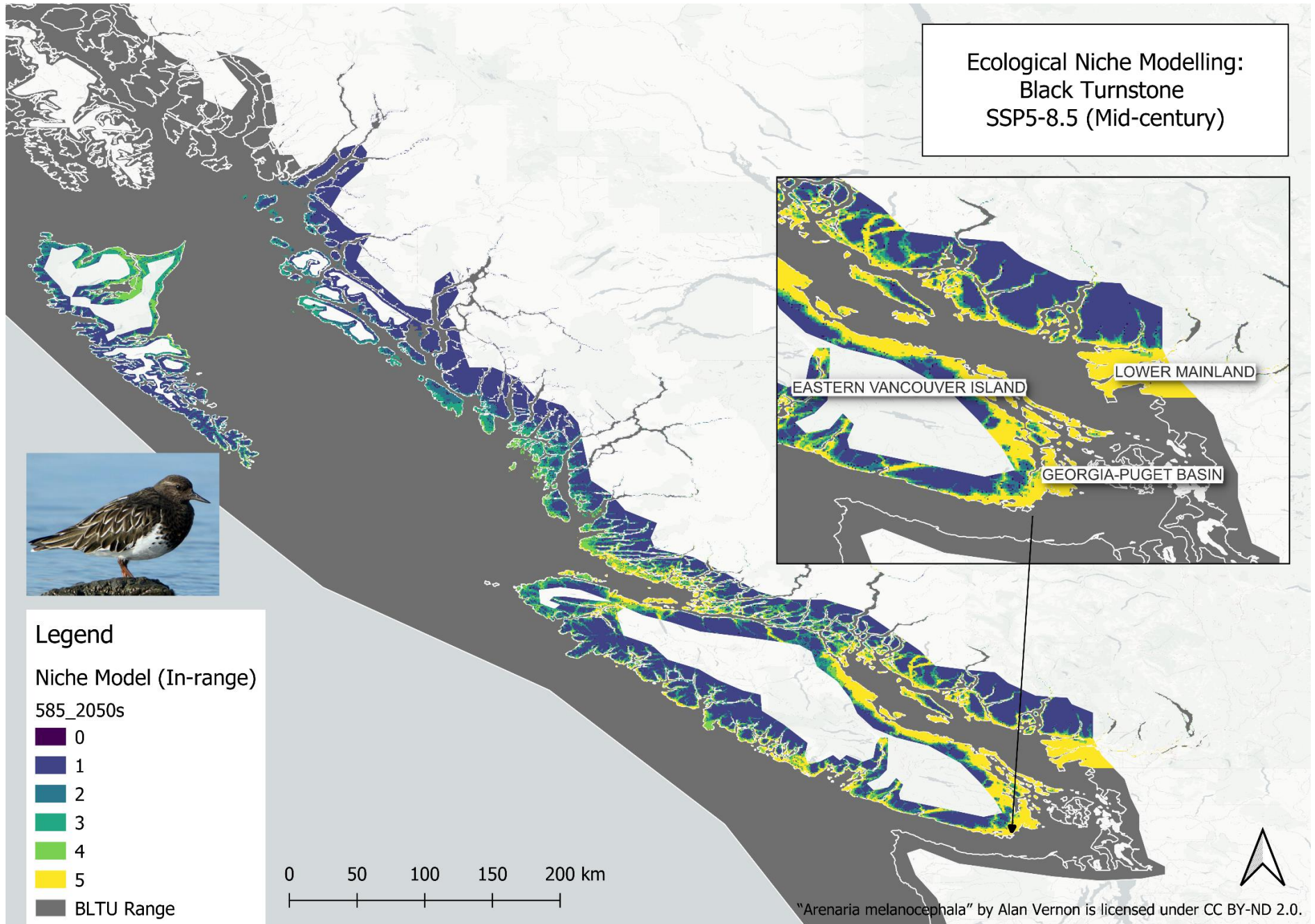
Ecological Niche Modelling:  
Black Turnstone  
SSP2-4.5 (Late-century)



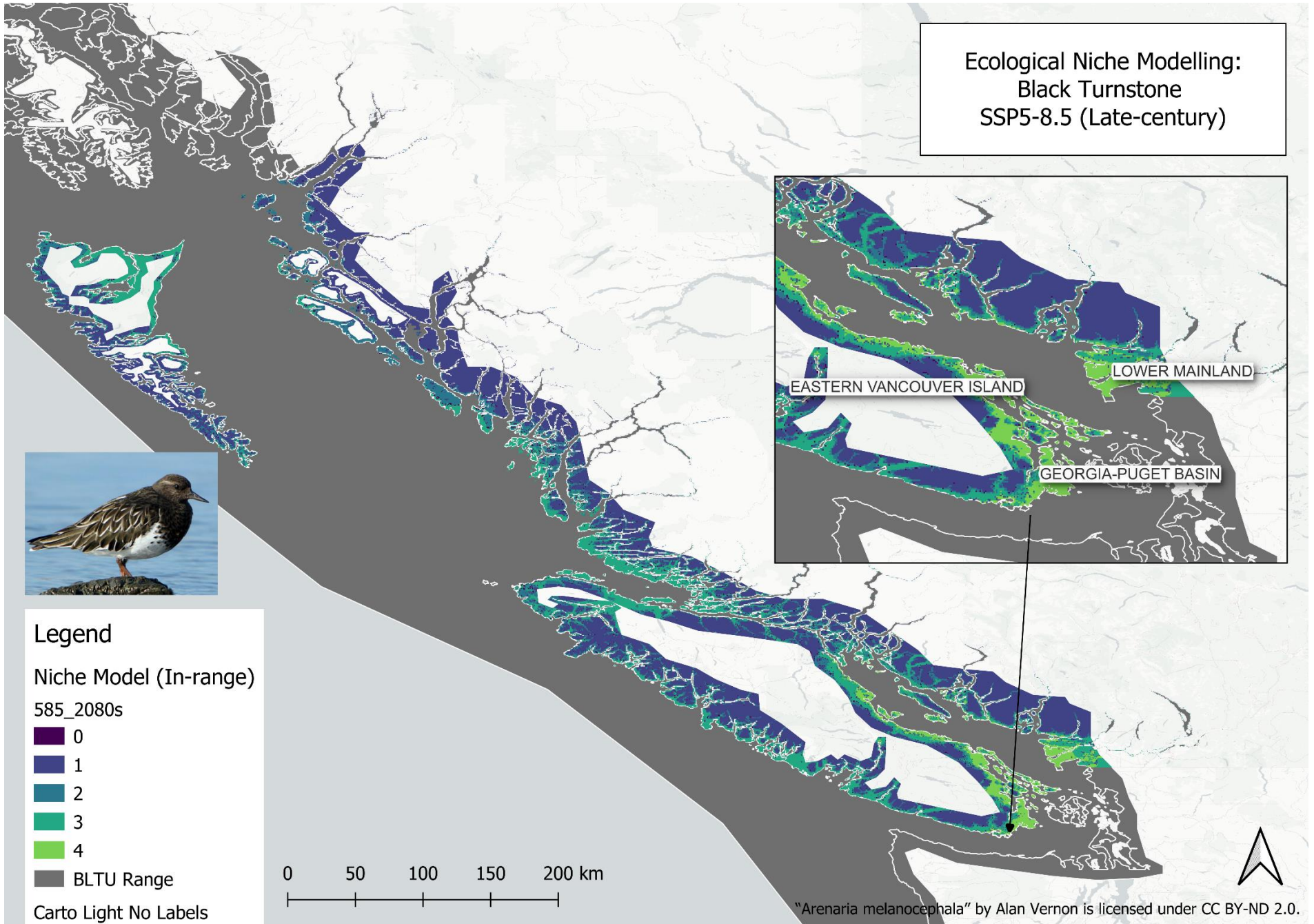
Ecological Niche Modelling:  
Black Turnstone  
SSP3-7.0 (Mid-century)



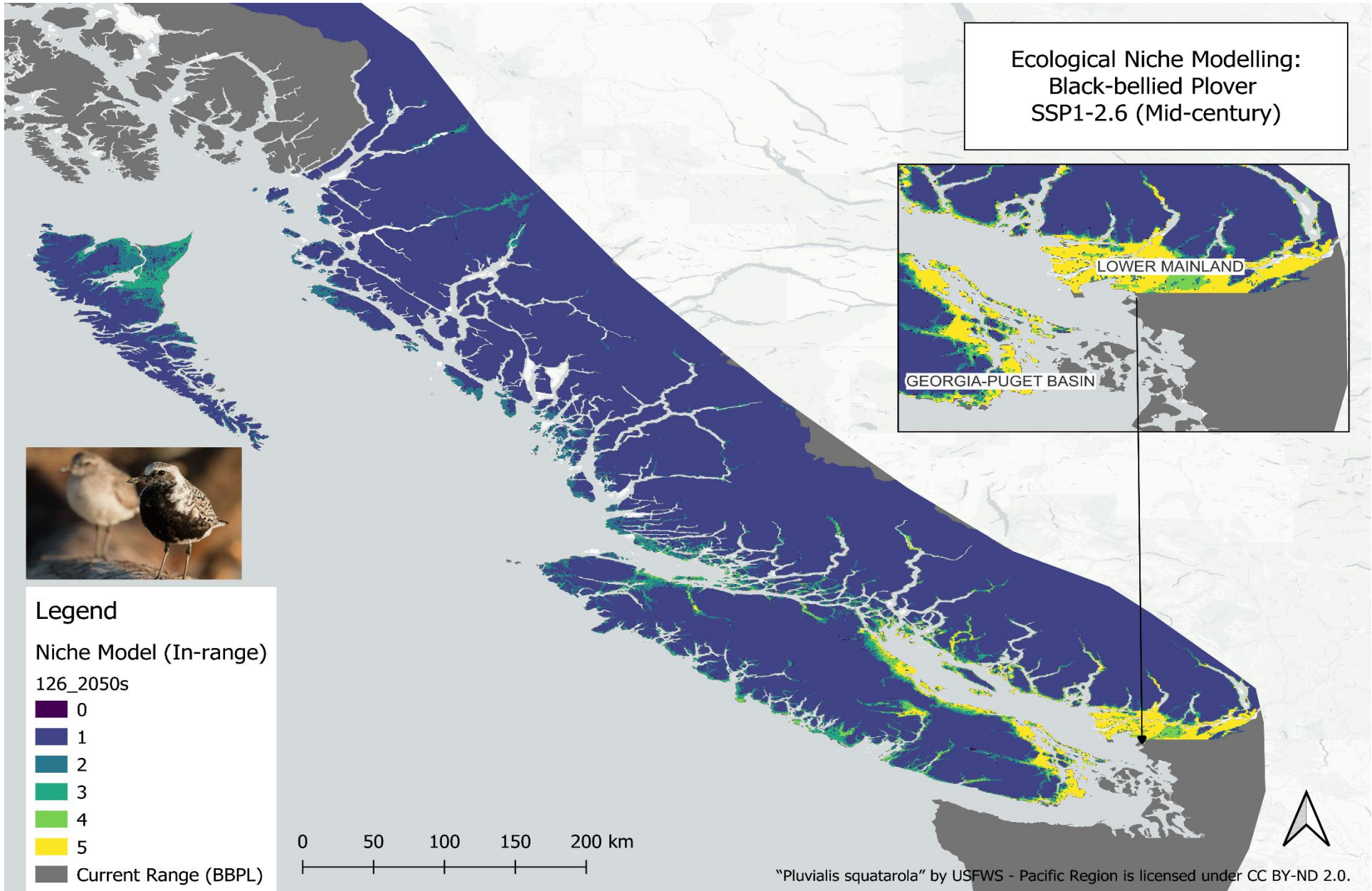
Ecological Niche Modelling:  
Black Turnstone  
SSP5-8.5 (Mid-century)



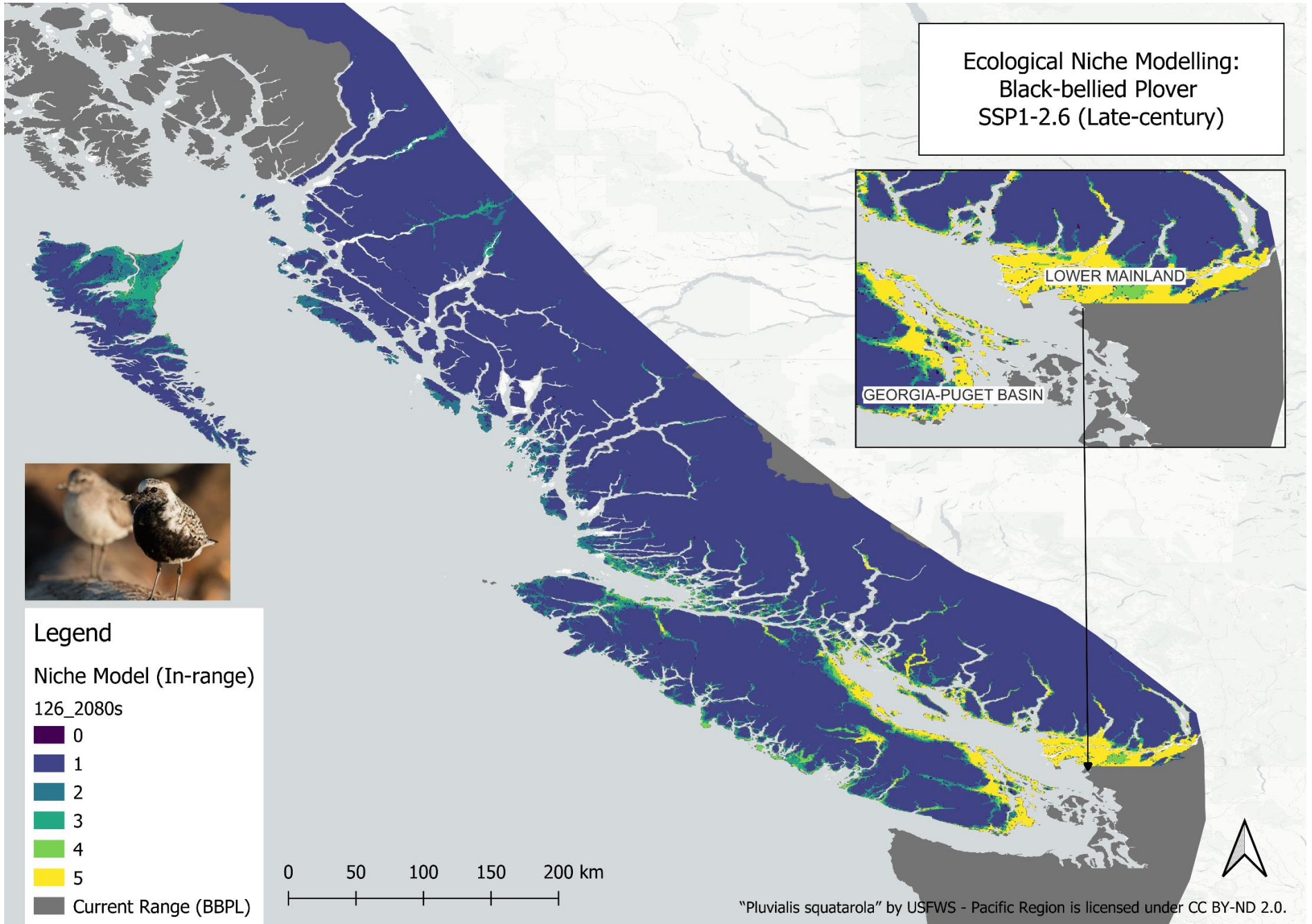
Ecological Niche Modelling:  
Black Turnstone  
SSP5-8.5 (Late-century)



# Ecological Niche Modelling: Black-bellied Plover (*Pluvialis squatarola*)



Ecological Niche Modelling:  
Black-bellied Plover  
SSP1-2.6 (Late-century)



Legend

Niche Model (In-range)

126\_2080s

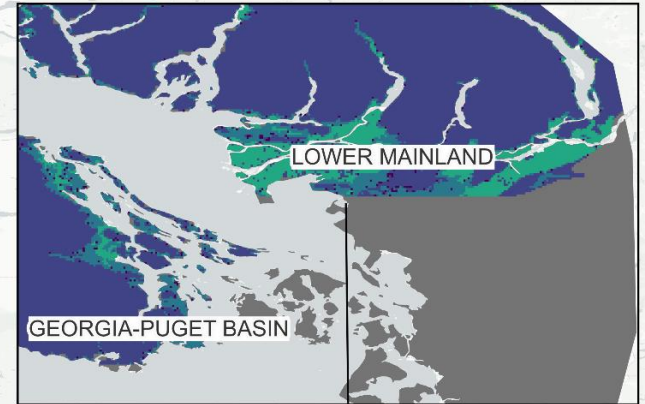
- 0
- 1
- 2
- 3
- 4
- 5

Current Range (BBPL)

0 50 100 150 200 km

"Pluvialis squatarola" by USFWS - Pacific Region is licensed under CC BY-ND 2.0.

Ecological Niche Modelling:  
Black-bellied Plover  
SSP2-4.5 (Mid-century)

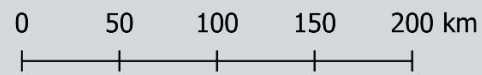


Legend

Niche Model (In-range)

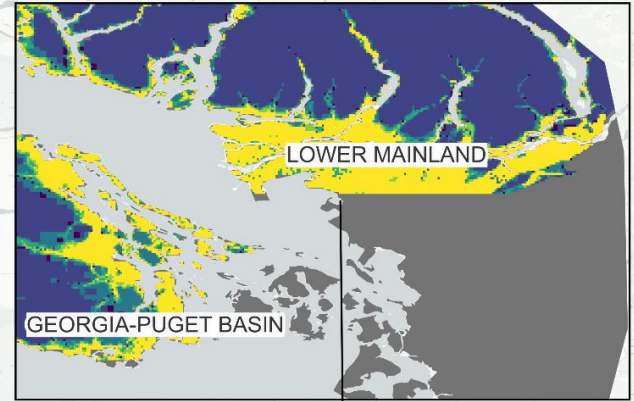
245\_2050s

- 0
- 1
- 2
- 3
- 4
- 5
- Current Range (BBPL)



"Pluvialis squatarola" by USFWS - Pacific Region is licensed under CC BY-ND 2.0.

Ecological Niche Modelling:  
Black-bellied Plover  
SSP2-4.5 (Late-century)



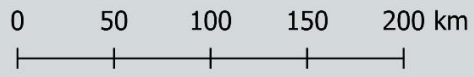
Legend

Niche Model (In-range)

245\_2080s

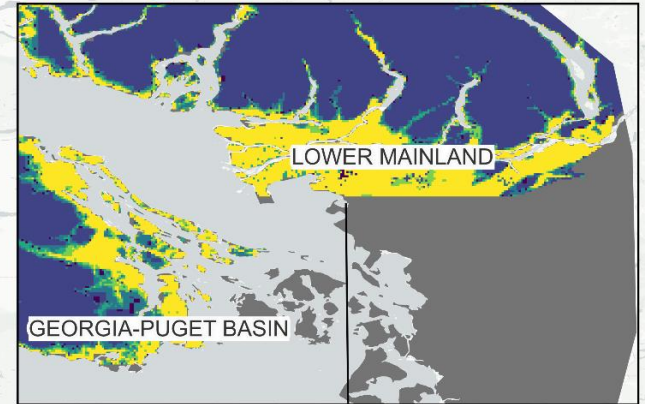


Current Range (BBPL)



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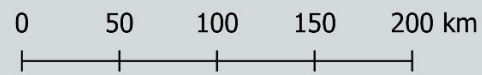
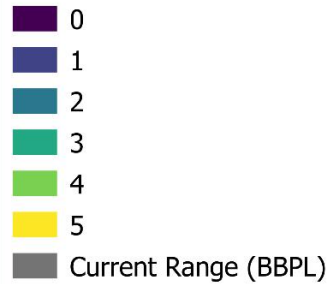
Ecological Niche Modelling:  
Black-bellied Plover  
SSP3-7.0 (Mid-century)



Legend

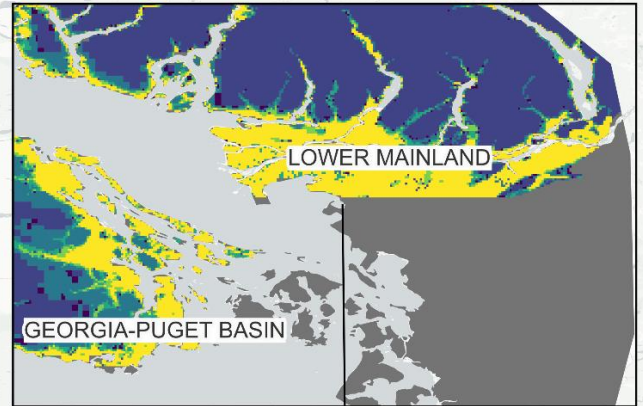
Niche Model (In-range)

370\_2050s



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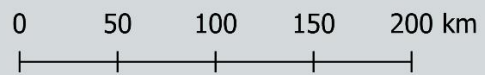
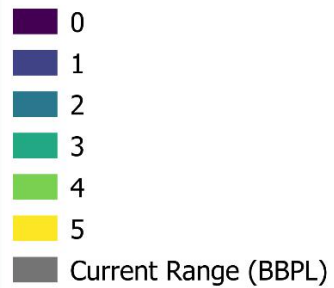
Ecological Niche Modelling:  
Black-bellied Plover  
SSP3-7.0 (Late-century)



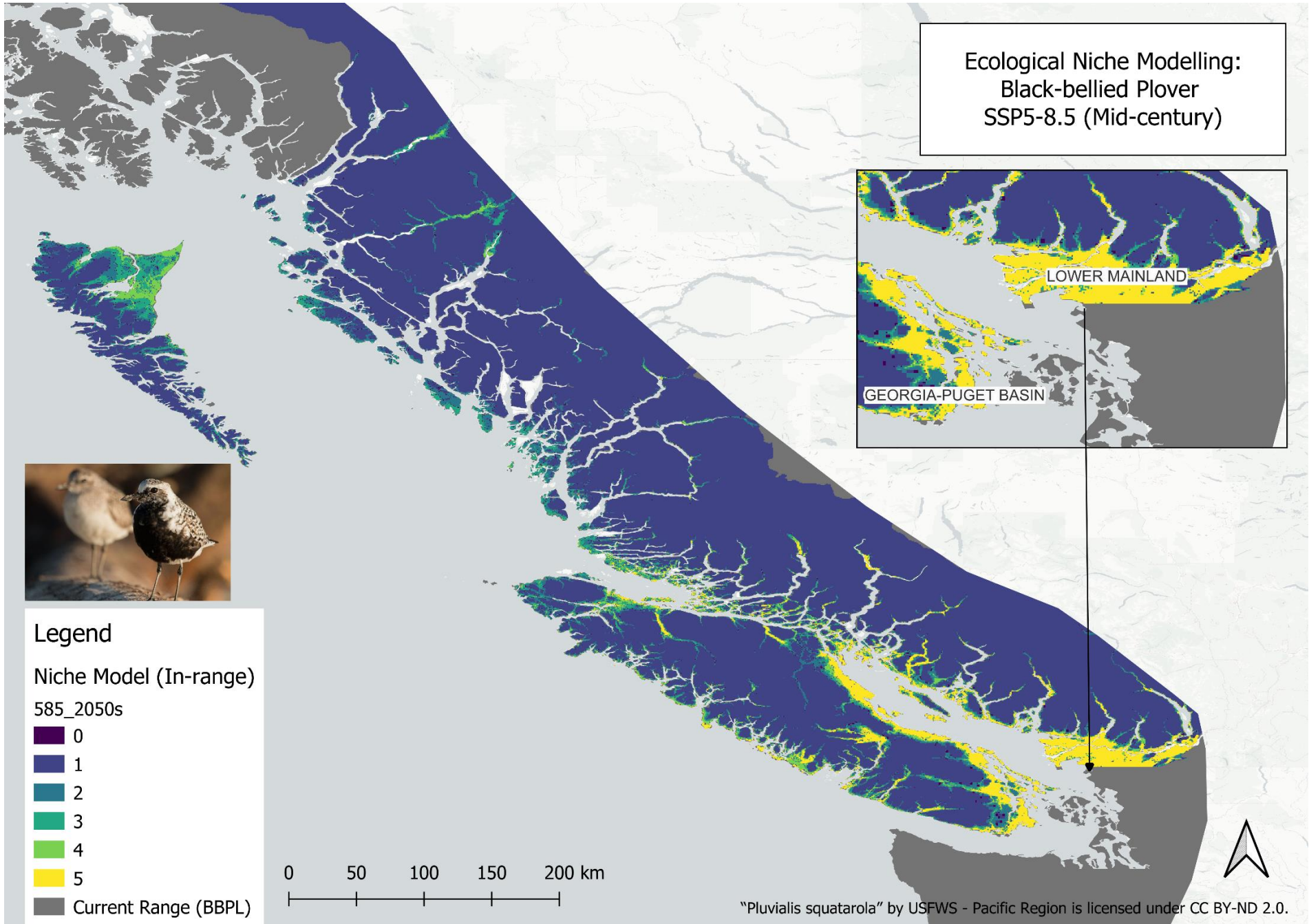
Legend

Niche Model (In-range)

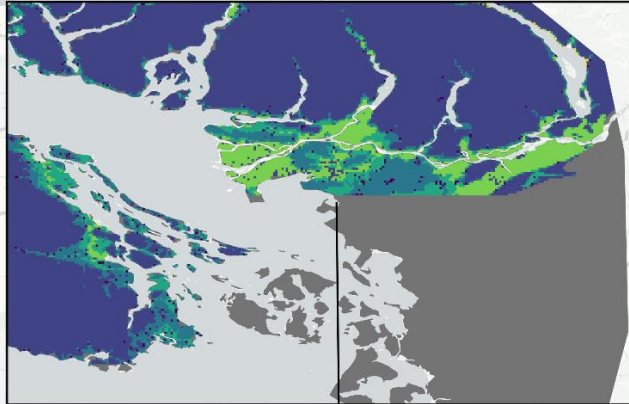
370\_2080s



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Ecological Niche Modelling:  
Black-bellied Plover  
SSP5-8.5 (Late-century)

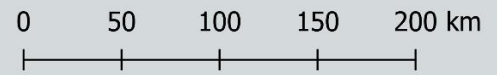


**Legend**

Niche Model (In-range)  
585\_2080s

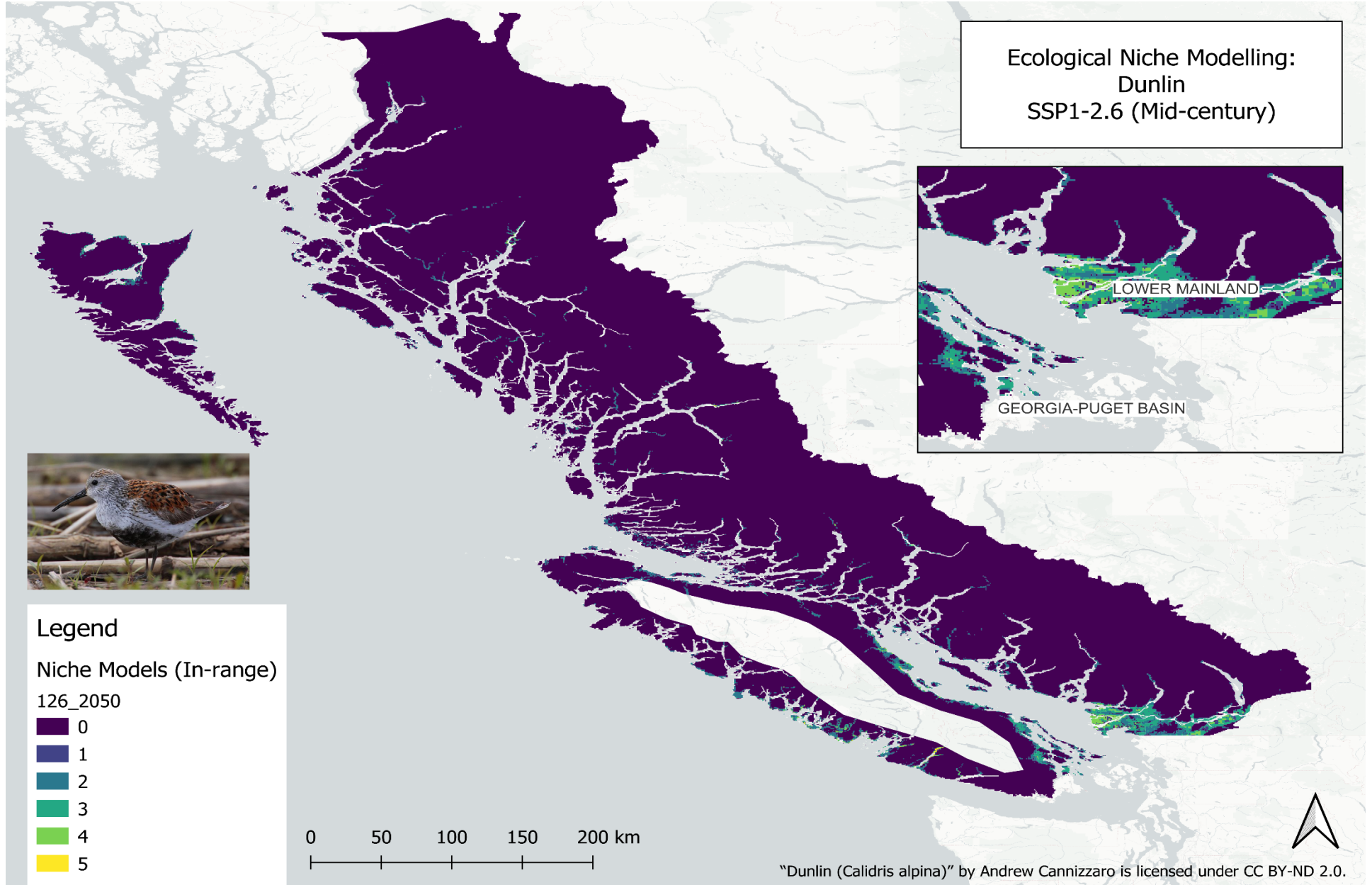
- 0
- 1
- 2
- 3
- 4
- 5

Current Range (BBPL)

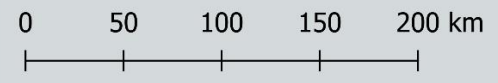
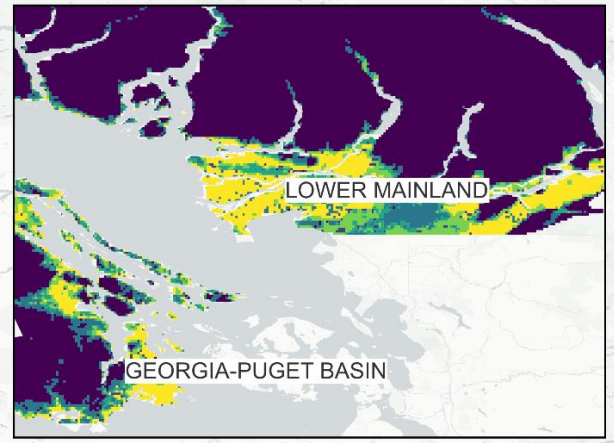


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# Ecological Niche Modelling: Dunlin (*Calidris alpina*)



Ecological Niche Modelling:  
Dunlin  
SSP1-2.6 (Late-century)



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Ecological Niche Modelling:  
Dunlin  
SSP2-4.5 (Mid-century)



Legend

Niche Models (In-range)

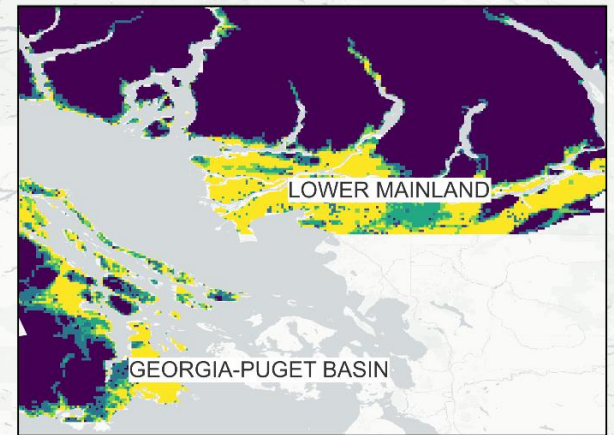
245\_2050

- 0
- 1
- 2
- 3
- 4
- 5



"Dunlin (Calidris alpina)" by Andrew Cannizzaro is licensed under CC BY-ND 2.0.

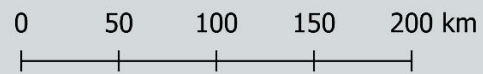
Ecological Niche Modelling:  
Dunlin  
SSP2-4.5 (Late-century)



Legend

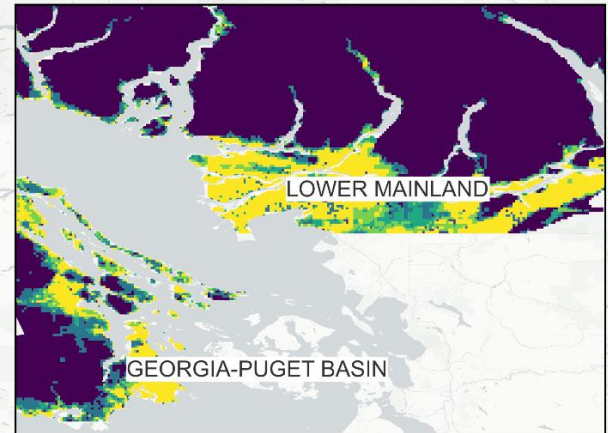
Niche Models (In-range)

245\_2080



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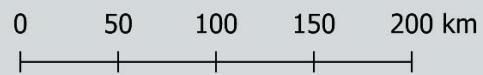
Ecological Niche Modelling:  
Dunlin  
SSP3-7.0 (Mid-century)



Legend

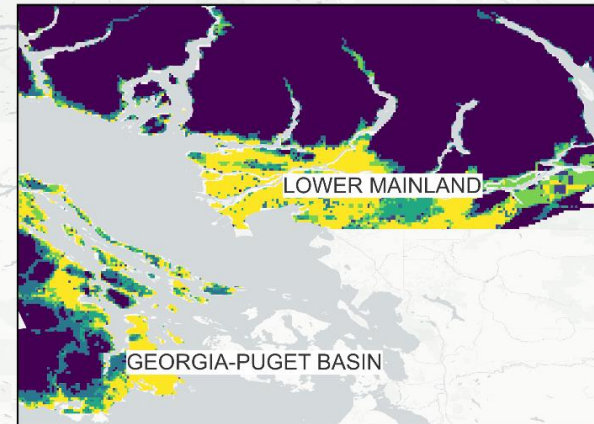
Niche Models (In-range)

370\_2050



"Dunlin (Calidris alpina)" by Andrew Cannizzaro is licensed under CC BY-ND 2.0.

Ecological Niche Modelling:  
Dunlin  
SSP3-7.0 (Late-century)



Legend

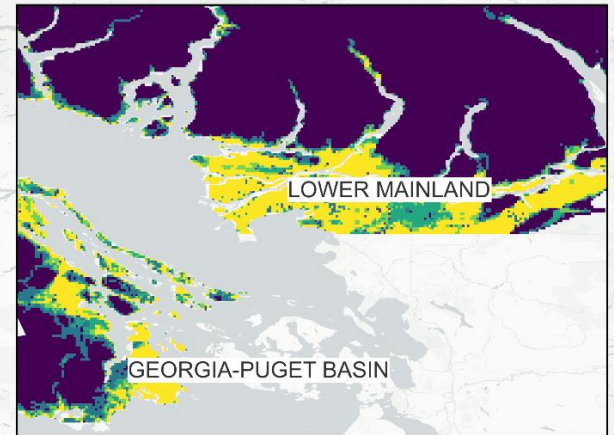
Niche Models (In-range)

370\_2080



"Dunlin (*Calidris alpina*)" by Andrew Cannizzaro is licensed under CC BY-ND 2.0.

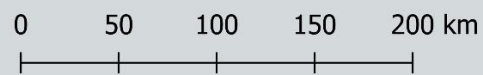
Ecological Niche Modelling:  
Dunlin  
SSP5-8.05 (Mid-century)



Legend

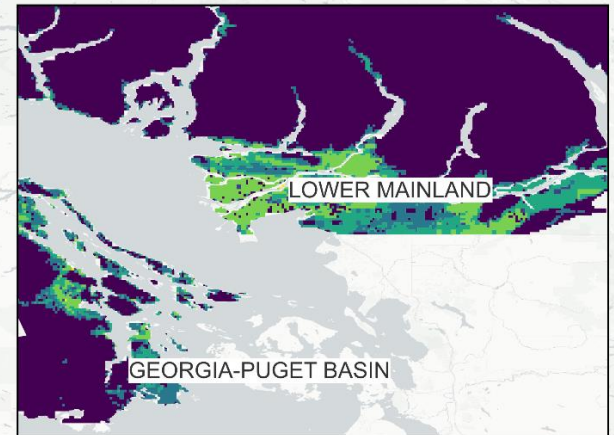
Niche Models (In-range)

585\_2050



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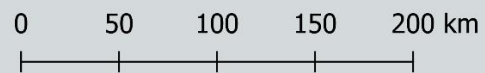
Ecological Niche Modelling:  
Dunlin  
SSP5-8.5 (Late-century)



Legend

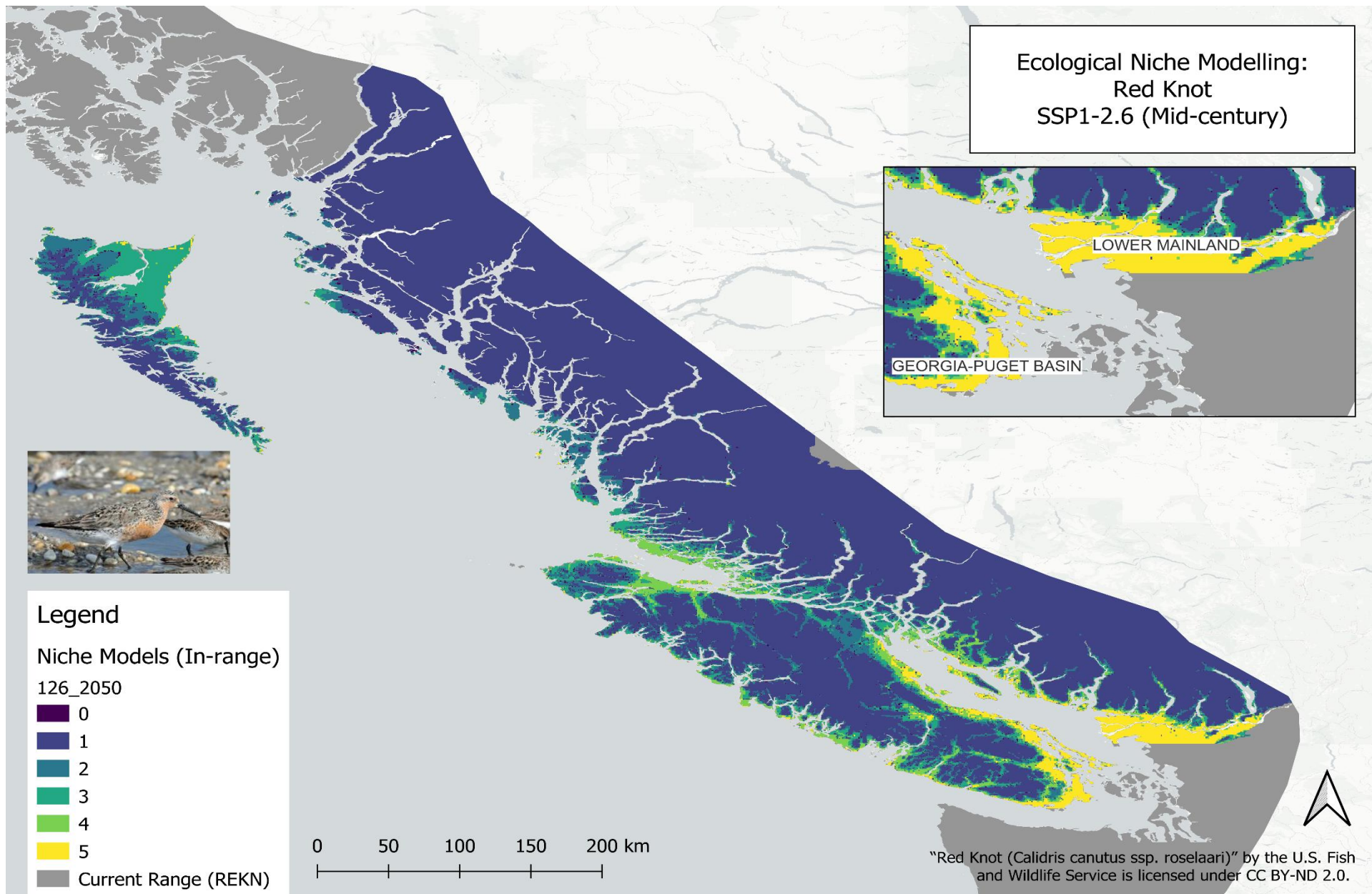
Niche Models (In-range)

585\_2080

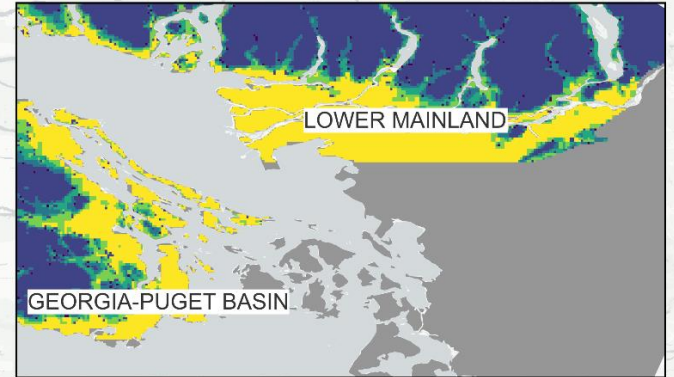


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# Ecological Niche Modelling: Red Knot (*Calidris canutus*)



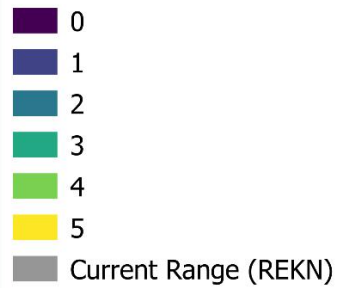
Ecological Niche Modelling:  
Red Knot  
SSP1-2.6 (Late-century)



Legend

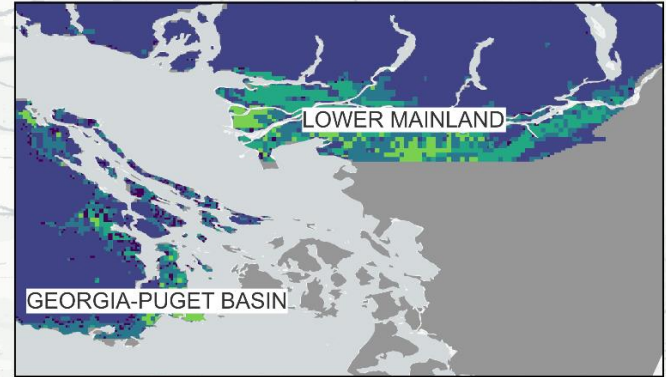
Niche Models (In-range)

126\_2050



"Red Knot (*Calidris canutus* ssp. *roselaari*)" by the U.S. Fish and Wildlife Service is licensed under CC BY-ND 2.0.

Ecological Niche Modelling:  
Red Knot  
SSP2-4.5 (Mid-century)



Legend

Niche Models (In-range)

245\_2050

0

1

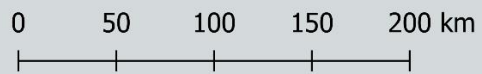
2

3

4

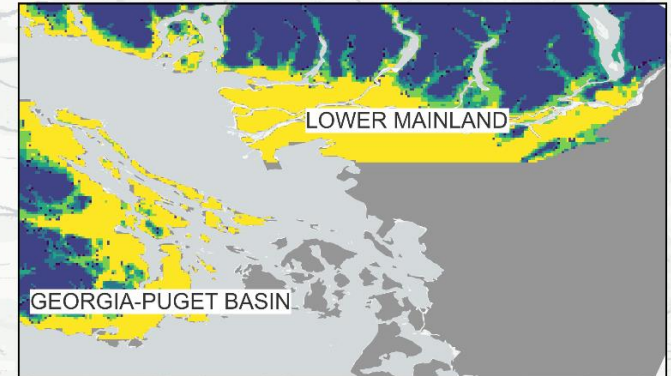
Current Range (REKN)

Carto Light No Labels



"Red Knot (*Calidris canutus* ssp. *roselaari*)" by the U.S. Fish and Wildlife Service is licensed under CC BY-ND 2.0.

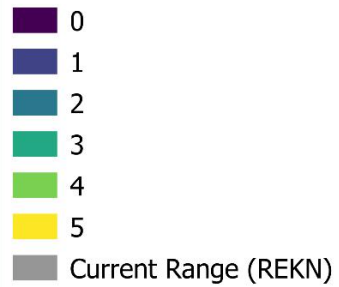
Ecological Niche Modelling:  
Red Knot  
SSP2-4.5 (Late-century)



Legend

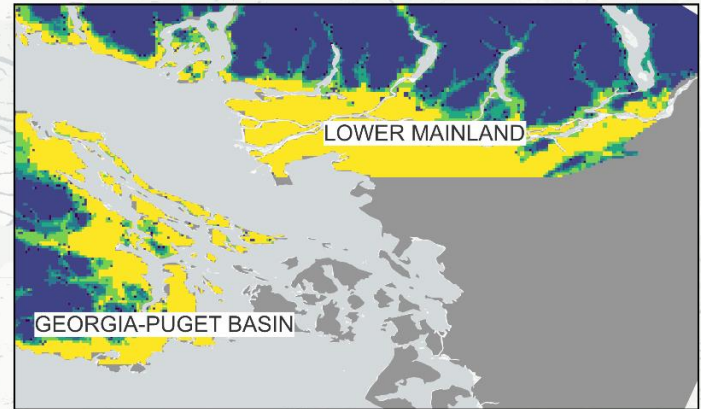
Niche Models (In-range)

245\_2080



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Ecological Niche Modelling:  
Red Knot  
SSP3-7.0 (Mid-century)



Legend

Niche Models (In-range)

370\_2050

0

1

2

3

4

5

Current Range (REKN)

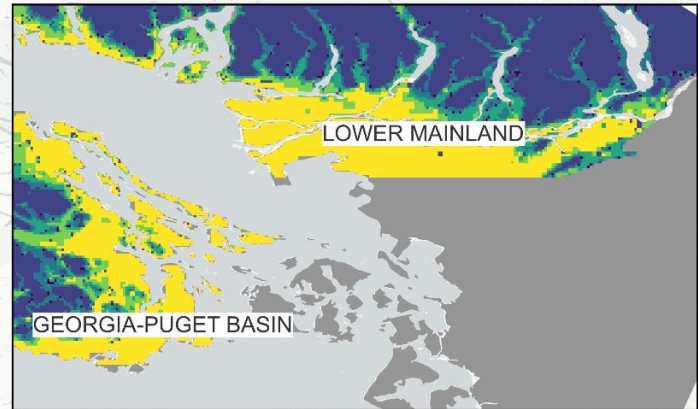
0 50 100 150 200 km



"Red Knot (*Calidris canutus* ssp. *roselaari*)" by the U.S. Fish and Wildlife Service is licensed under CC BY-ND 2.0.



Ecological Niche Modelling:  
Red Knot  
SSP3-7.0 (Late-century)



Legend

Niche Models (In-range)

370\_2080

0

1

2

3

4

5

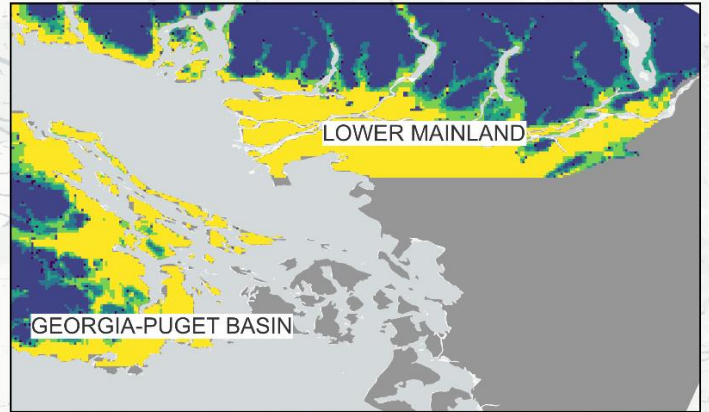
Current Range (REKN)

0 50 100 150 200 km



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Ecological Niche Modelling:  
Red Knot  
SSP5-8.5 (Mid-century)



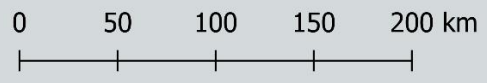
Legend

Niche Models (In-range)

585\_2050

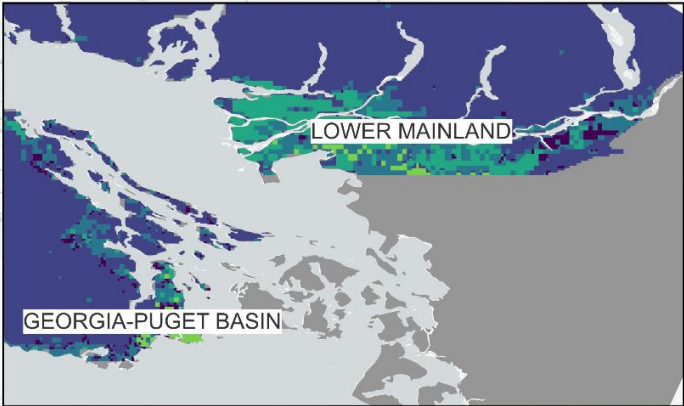
- 0
- 1
- 2
- 3
- 4
- 5

Current Range (REKN)



"Red Knot (*Calidris canutus ssp. roselaari*)" by the U.S. Fish and Wildlife Service is licensed under CC BY-ND 2.0.

Ecological Niche Modelling:  
Red Knot  
SSP5-8.5 (Late-century)



Legend

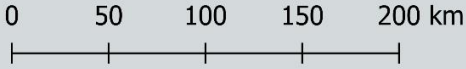
Niche Models (In-range)

585\_2080

- 0
- 1
- 2
- 3
- 4

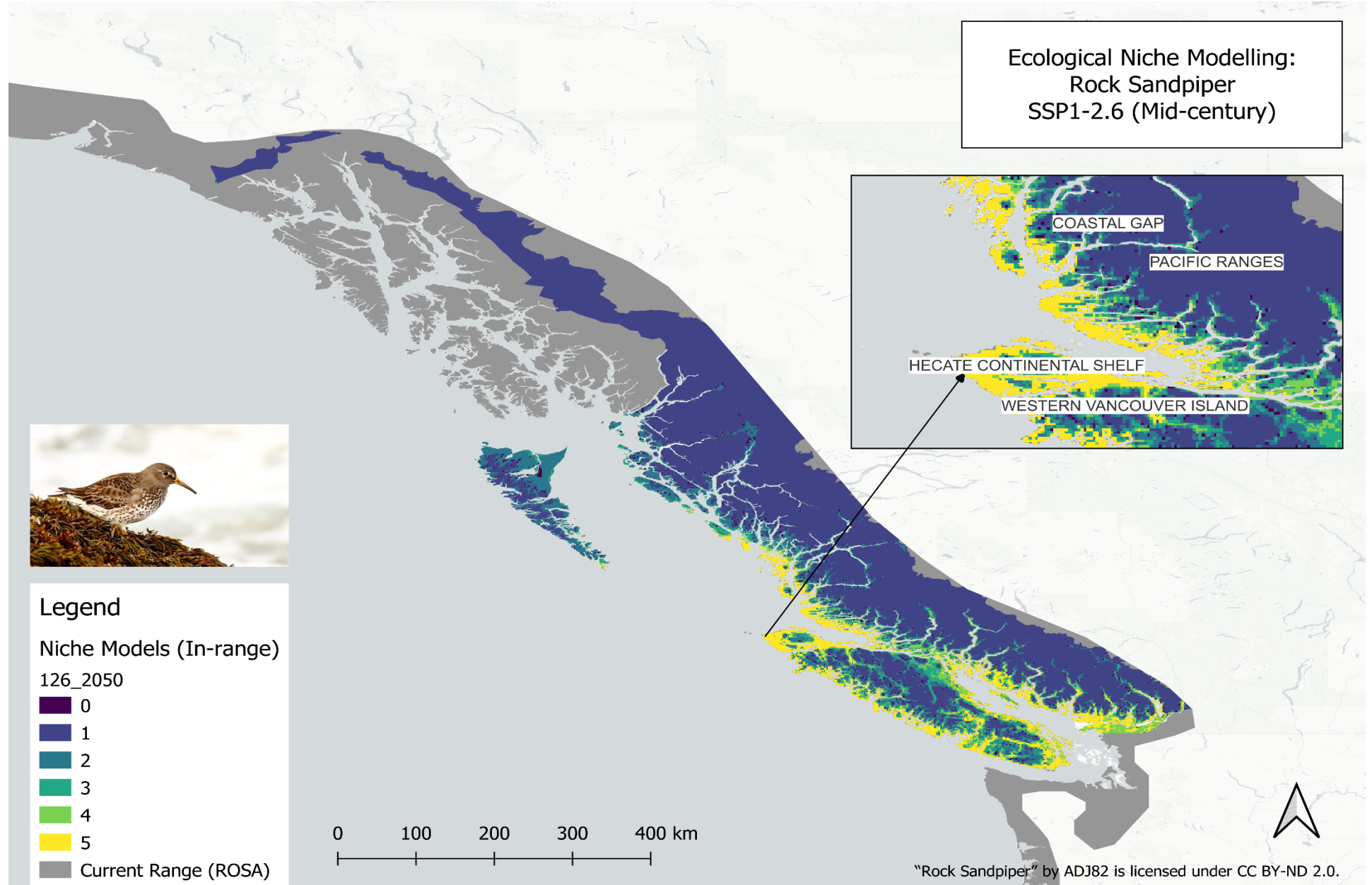
Current Range (REKN)

Carto Light No Labels

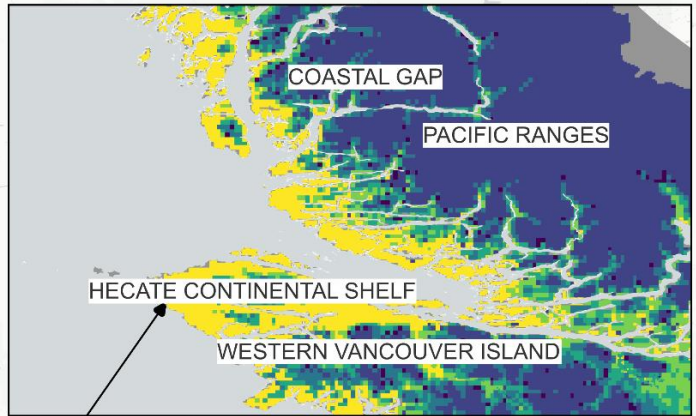


"Red Knot (*Calidris canutus* ssp. *roselaari*)" by the U.S. Fish and Wildlife Service is licensed under CC BY-ND 2.0.

# Ecological Niche Modelling: Rock Sandpiper (*Calidris ptilocnemis*)



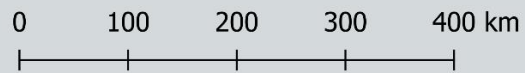
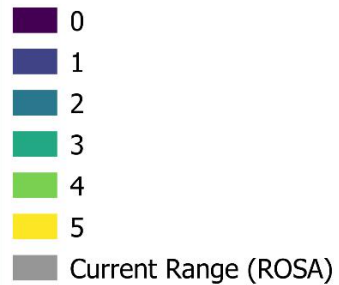
Ecological Niche Modelling:  
Rock Sandpiper  
SSP1-2.6 (Late-century)



Legend

Niche Models (In-range)

126\_2080



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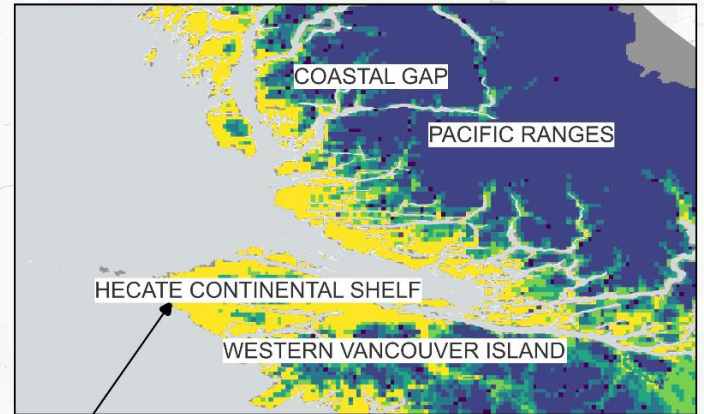
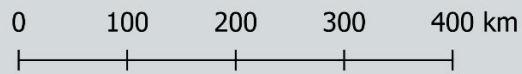
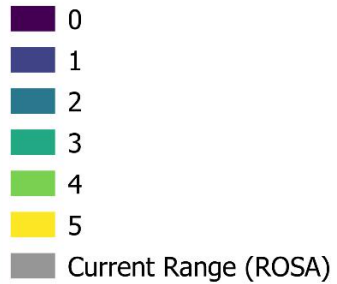
Ecological Niche Modelling:  
Rock Sandpiper  
SSP2-4.5 (Mid-century)



Legend

Niche Models (In-range)

245\_2050



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Ecological Niche Modelling:  
Rock Sandpiper  
SSP2-4.5 (Late-century)



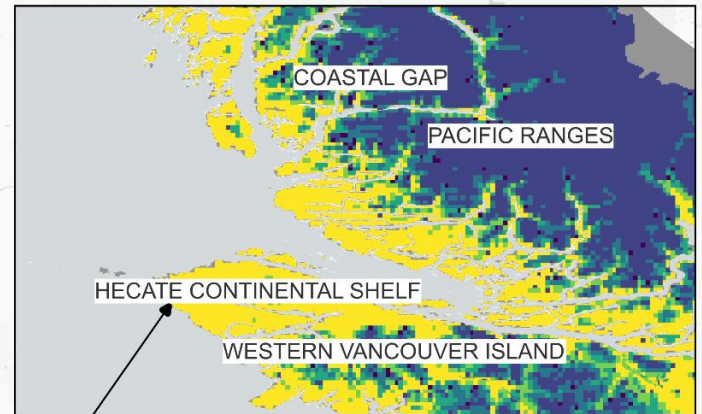
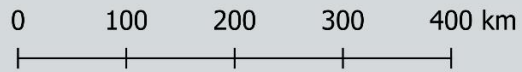
Legend

Niche Models (In-range)

245\_2080

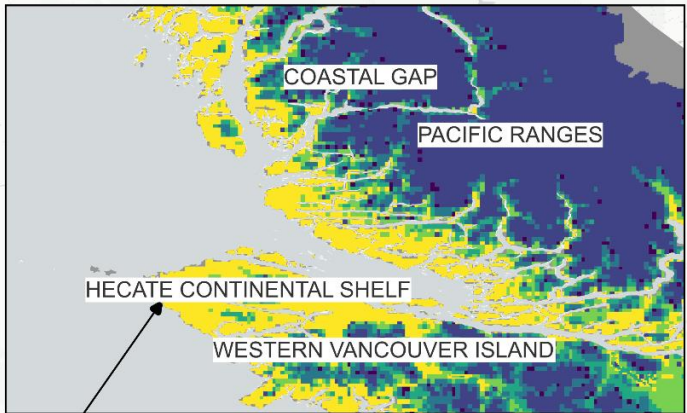


Current Range (ROSA)



"Rock Sandpiper" by ADJ82 is licensed under CC BY-ND 2.0.

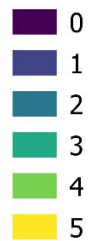
Ecological Niche Modelling:  
Rock Sandpiper  
SSP3-7.0 (Mid-century)



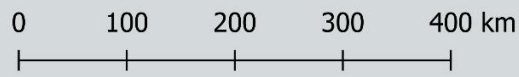
Legend

Niche Models (In-range)

370\_2050



Current Range (ROSA)



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Ecological Niche Modelling:  
Rock Sandpiper  
SSP3-7.0 (Late-century)



Legend

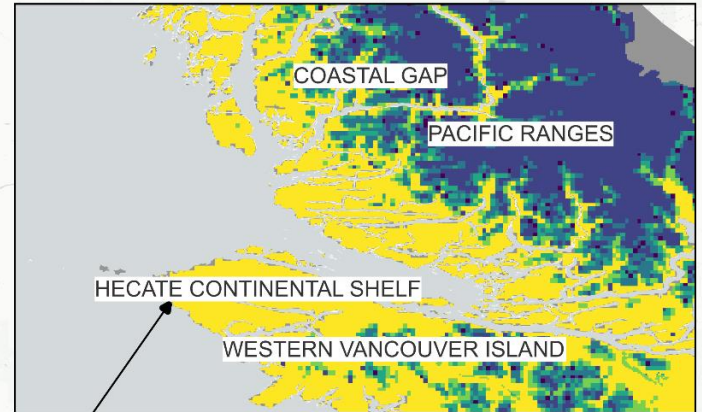
Niche Models (In-range)

370\_2080

- 0
- 1
- 2
- 3
- 4
- 5

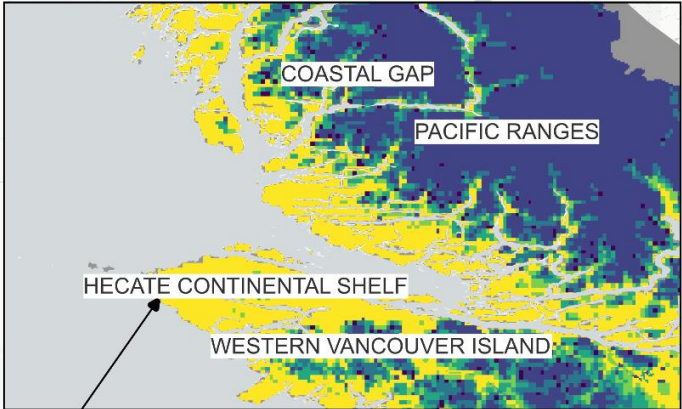
Current Range (ROSA)

0 100 200 300 400 km



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Ecological Niche Modelling:  
Rock Sandpiper  
SSP5-8.5 (Mid-century)



Legend

Niche Models (In-range)

585\_2050

- 0
- 1
- 2
- 3
- 4
- 5

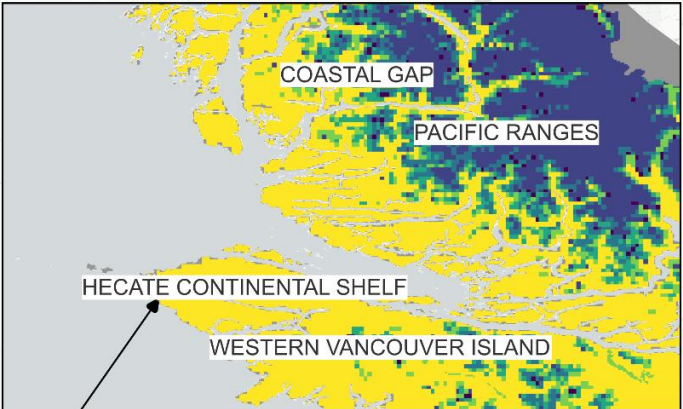
Current Range (ROSA)

0 100 200 300 400 km



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Ecological Niche Modelling:  
Rock Sandpiper  
SSP5-8.5 (Late-century)



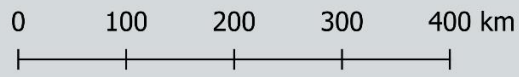
Legend

Niche Models (In-range)

585\_2080

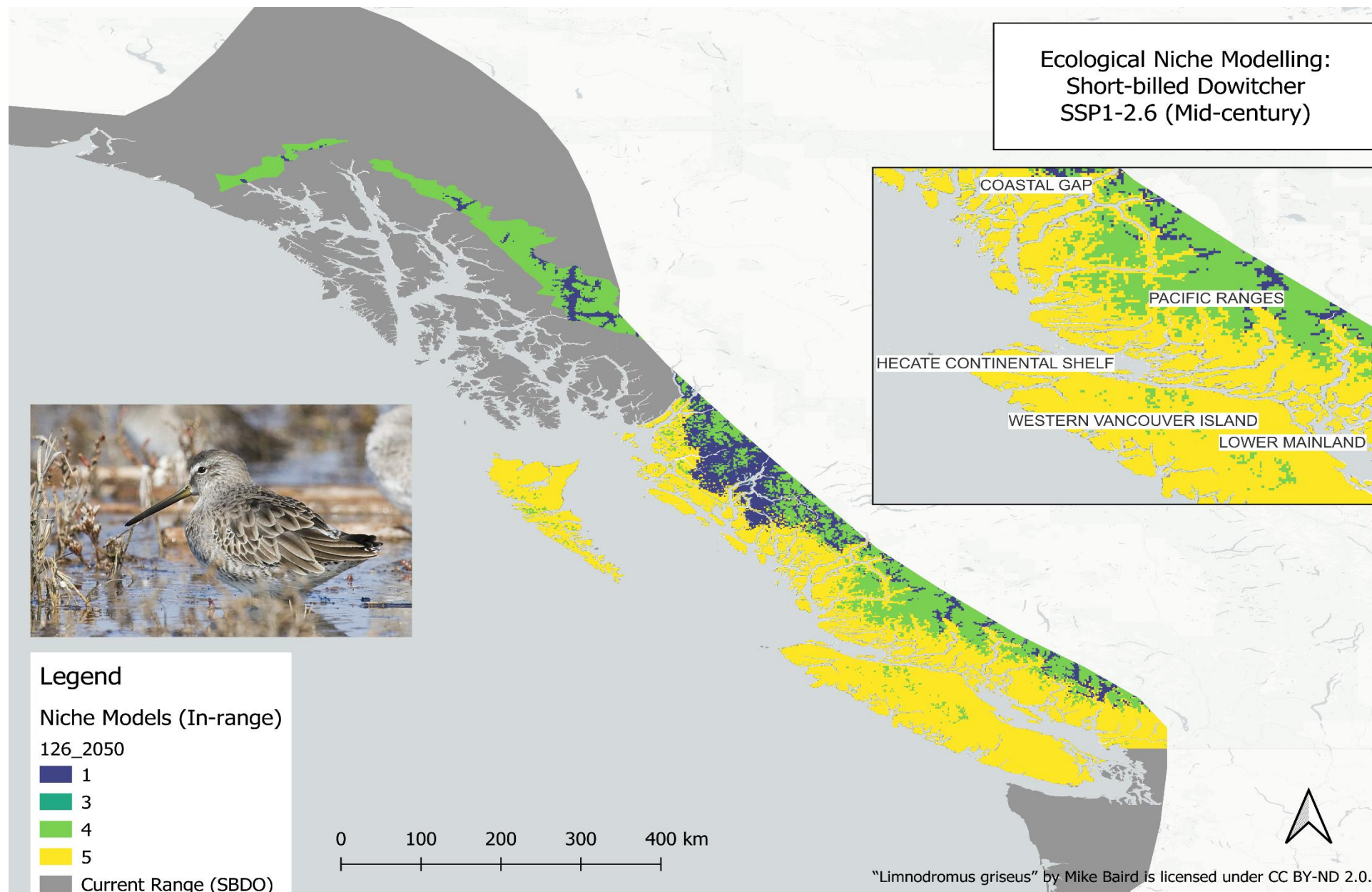
- 0
- 1
- 2
- 3
- 4
- 5

Current Range (ROSA)

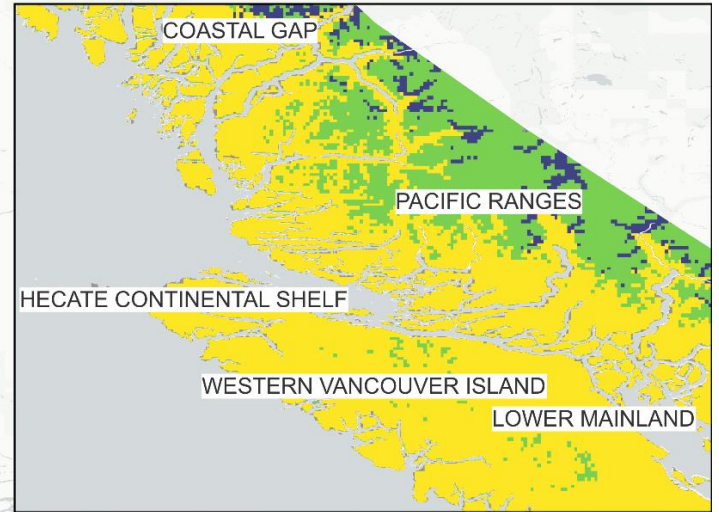


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# Ecological Niche Modelling: Short-billed Dowitcher (*Limnodromus griseus*)



Ecological Niche Modelling:  
Short-billed Dowitcher  
SSP1-2.6 (Late-century)



Legend

Niche Models (In-range)

126\_2080

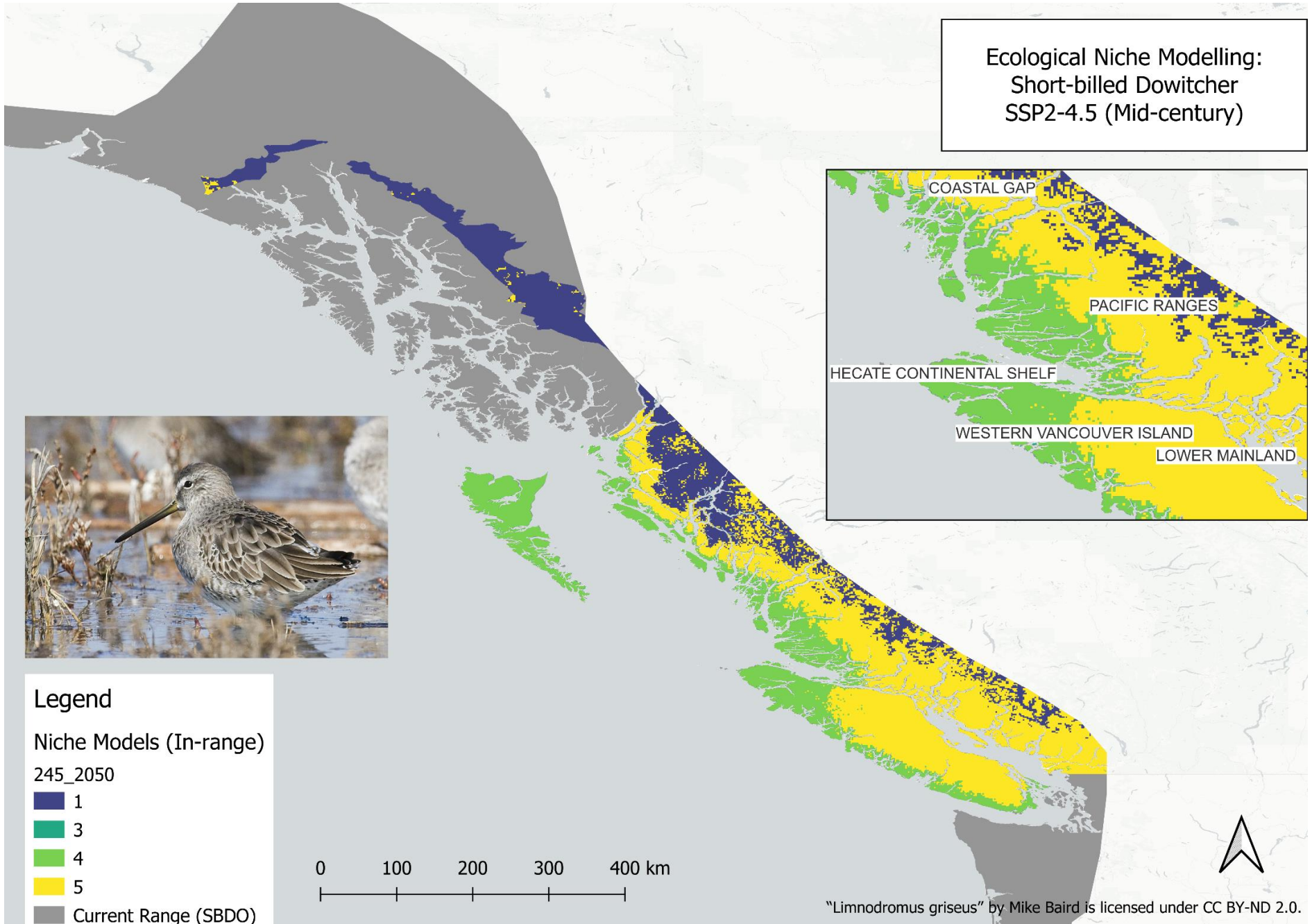
- 1
- 3
- 4
- 5

Current Range (SBDO)

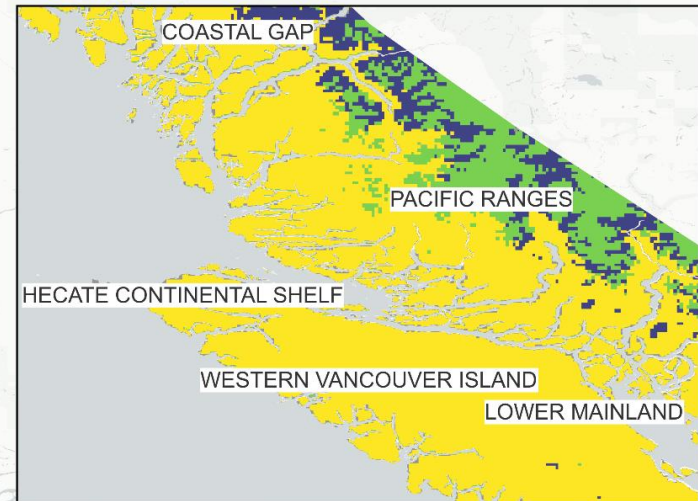


"Limnodromus griseus" by Mike Baird is licensed under CC BY-ND 2.0.

Ecological Niche Modelling:  
Short-billed Dowitcher  
SSP2-4.5 (Mid-century)



Ecological Niche Modelling:  
Short-billed Dowitcher  
SSP2-4.5 (Late-century)



Legend

Niche Models (In-range)

245\_2080

- 1
- 3
- 4
- 5

Current Range (SBDO)



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Ecological Niche Modelling:  
Short-billed Dowitcher  
SSP3-7.0 (Mid-century)



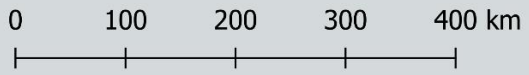
Legend

Niche Models (In-range)

370\_2050

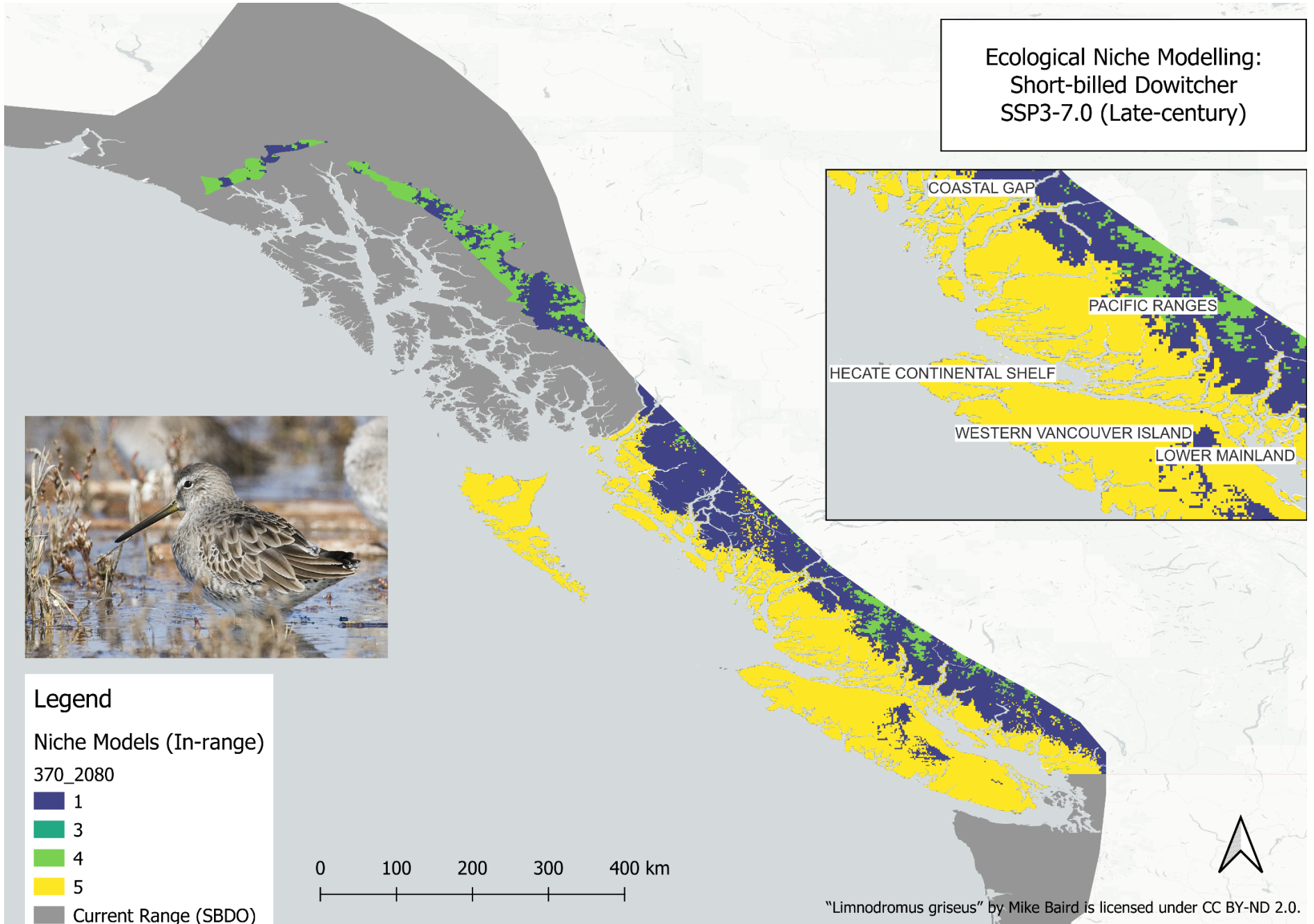
- 1
- 3
- 4
- 5

Current Range (SBDO)



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Ecological Niche Modelling:  
Short-billed Dowitcher  
SSP3-7.0 (Late-century)



Ecological Niche Modelling:  
Short-billed Dowitcher  
SSP5-8.5 (Mid-century)



Legend

Niche Models (In-range)

585\_2050

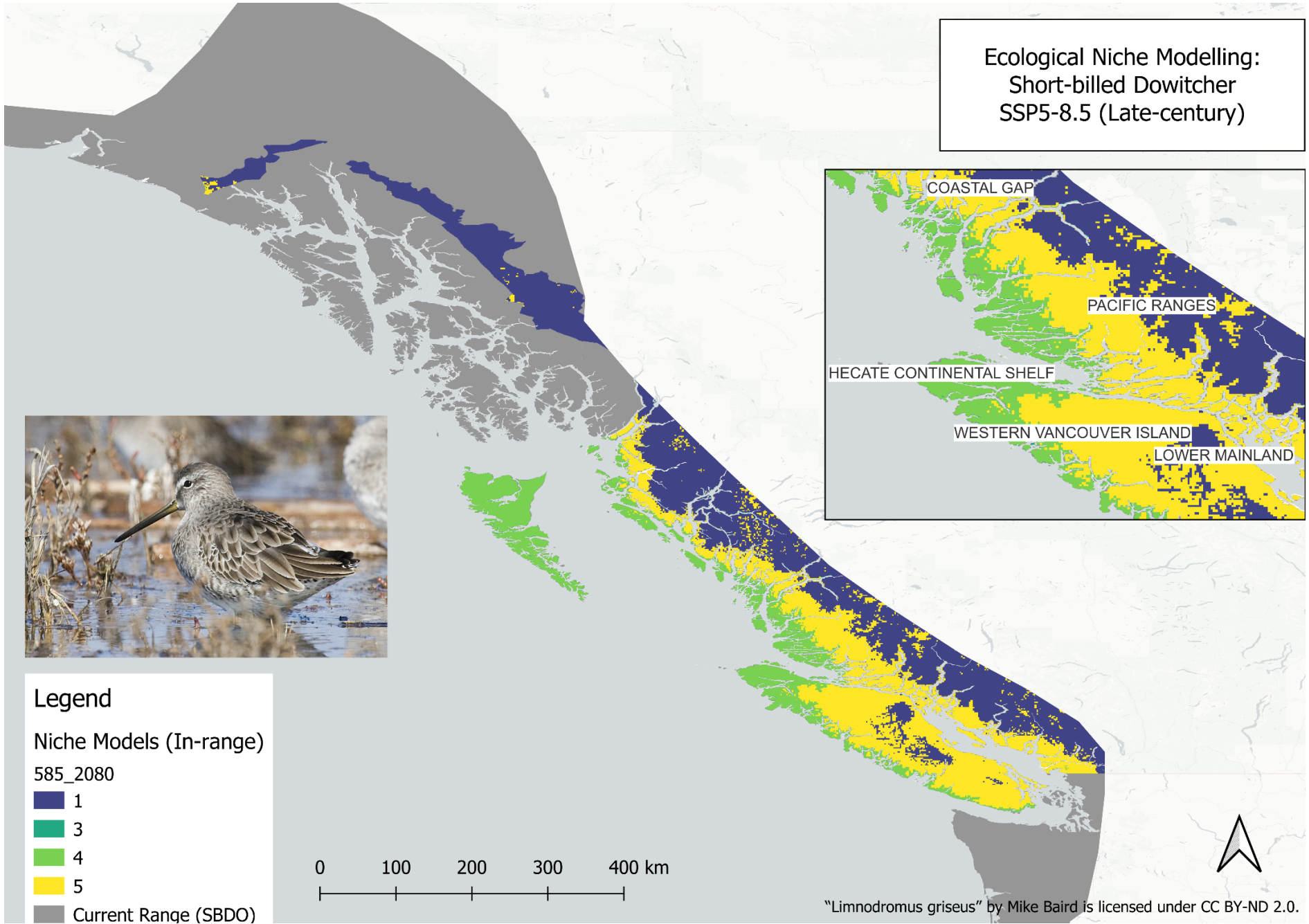
- 1
- 3
- 4
- 5

Current Range (SBDO)

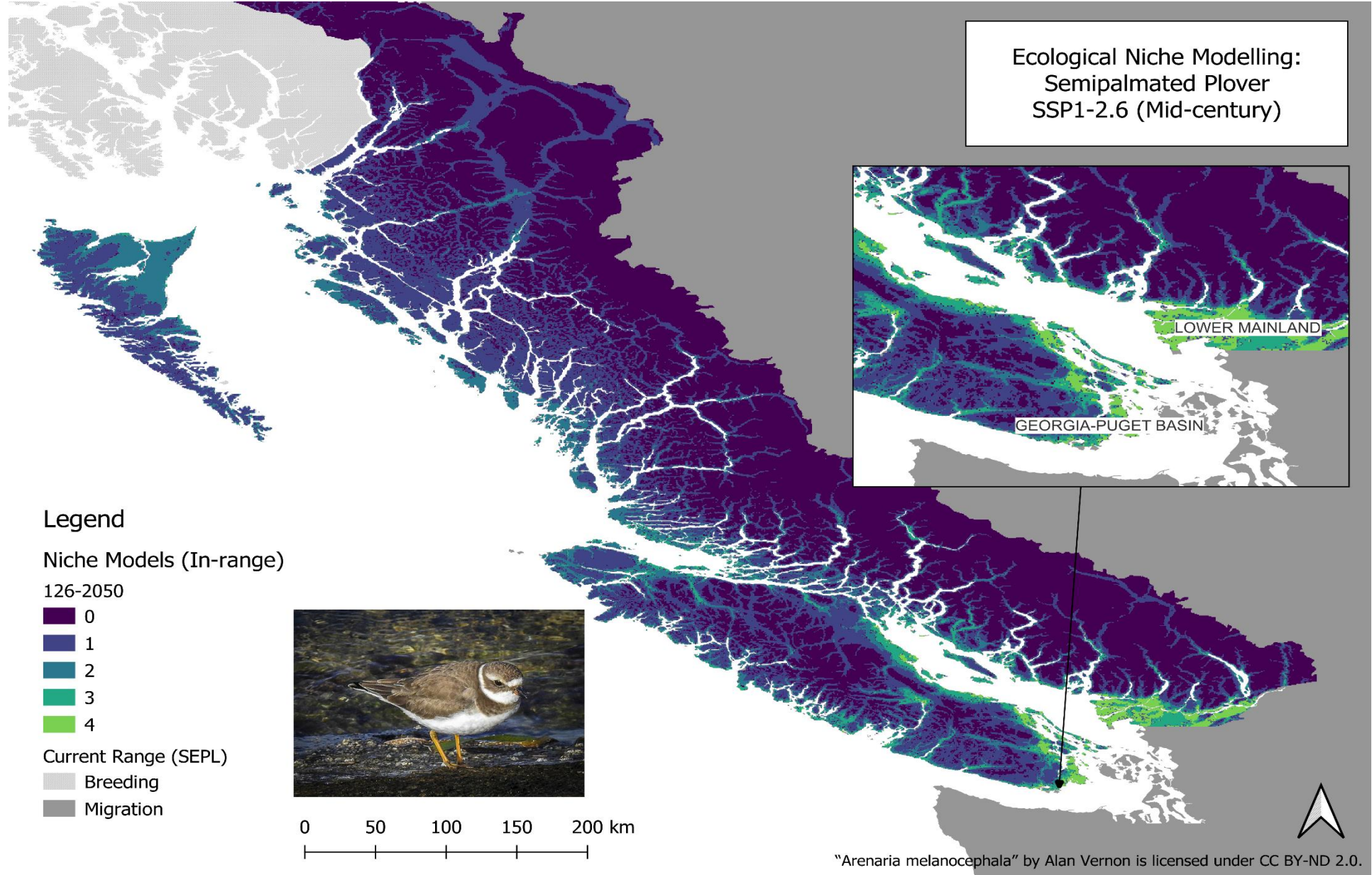


"Limnodromus griseus" by Mike Baird is licensed under CC BY-ND 2.0.

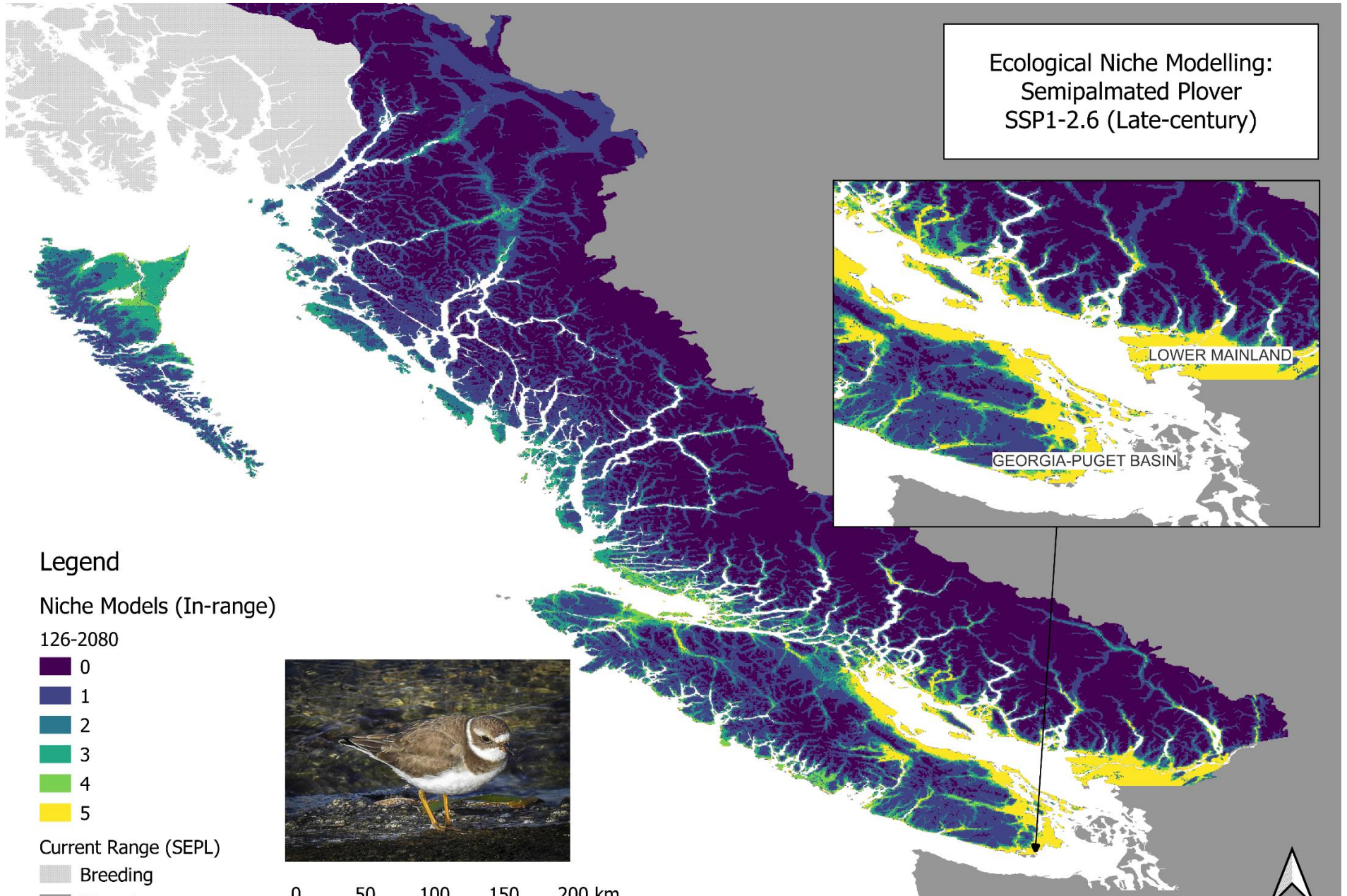
Ecological Niche Modelling:  
Short-billed Dowitcher  
SSP5-8.5 (Late-century)



# Ecological Niche Modelling: Semipalmated Plover (*Charadrius semipalmatus*)



Ecological Niche Modelling:  
Semipalmated Plover  
SSP1-2.6 (Late-century)



Legend

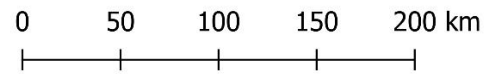
Niche Models (In-range)

126-2080

- 0
- 1
- 2
- 3
- 4
- 5

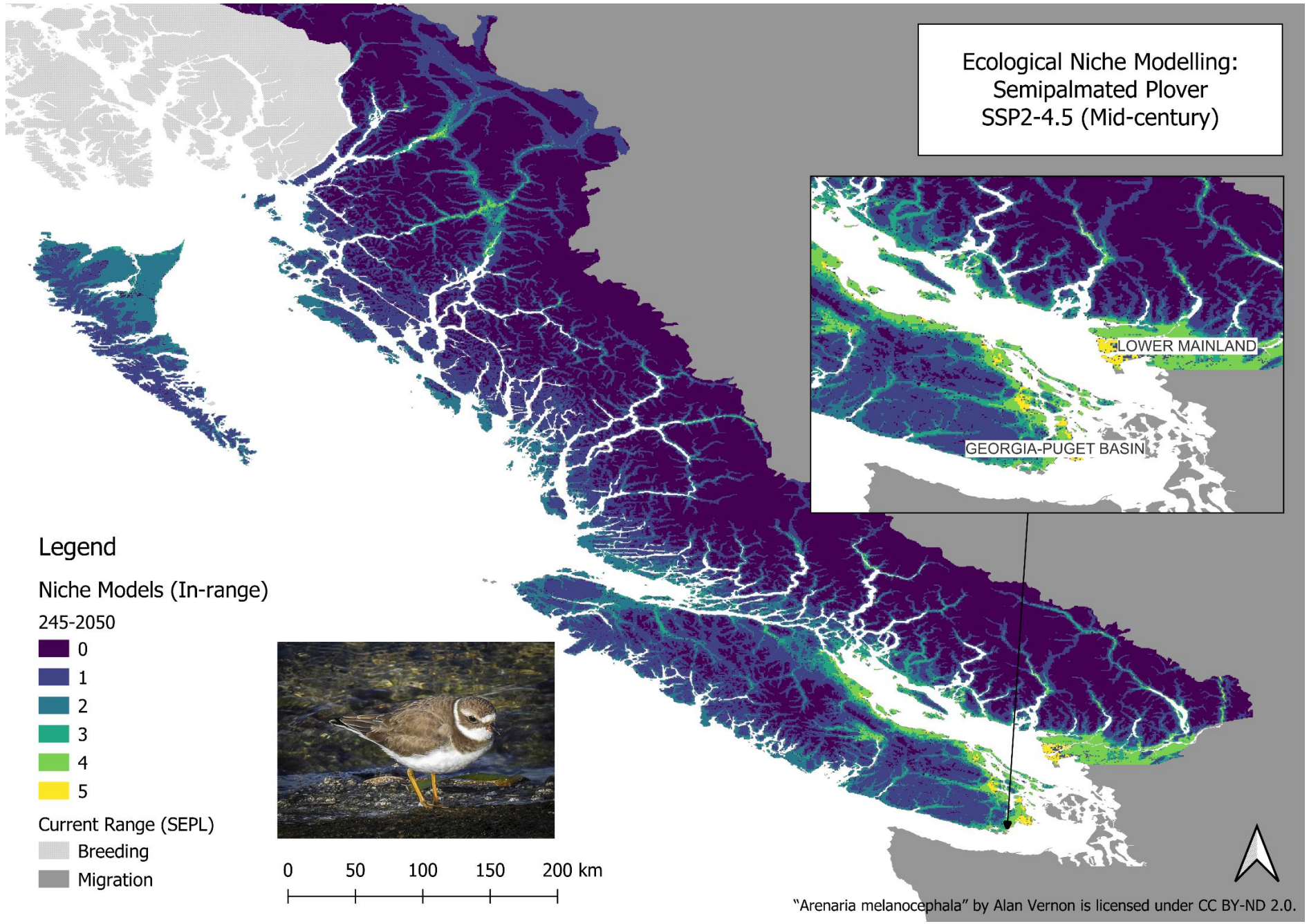
Current Range (SEPL)

- Breeding
- Migration

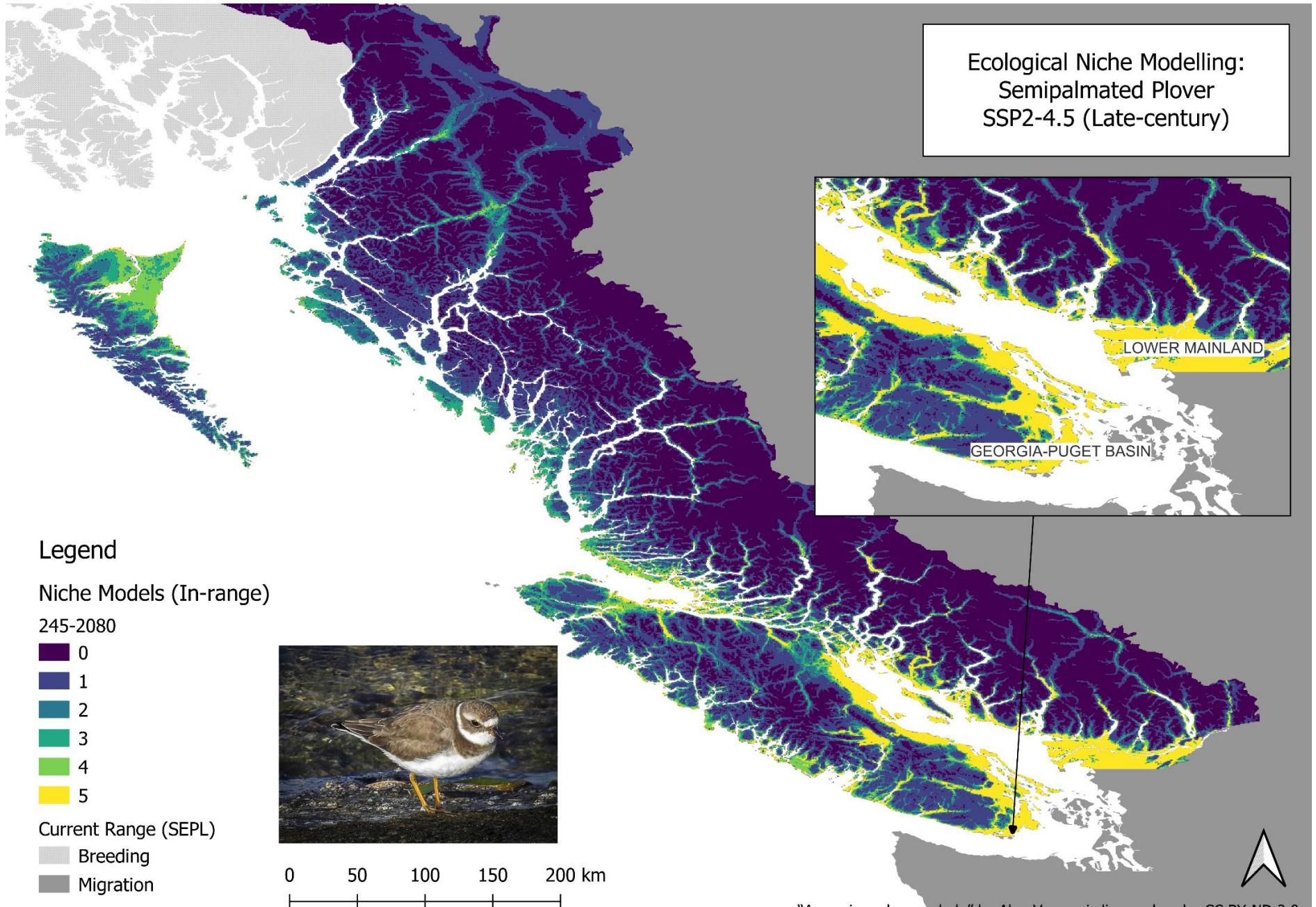


"*Arenaria melanocephala*" by Alan Vernon is licensed under CC BY-ND 2.0.

Ecological Niche Modelling:  
Semipalmated Plover  
SSP2-4.5 (Mid-century)

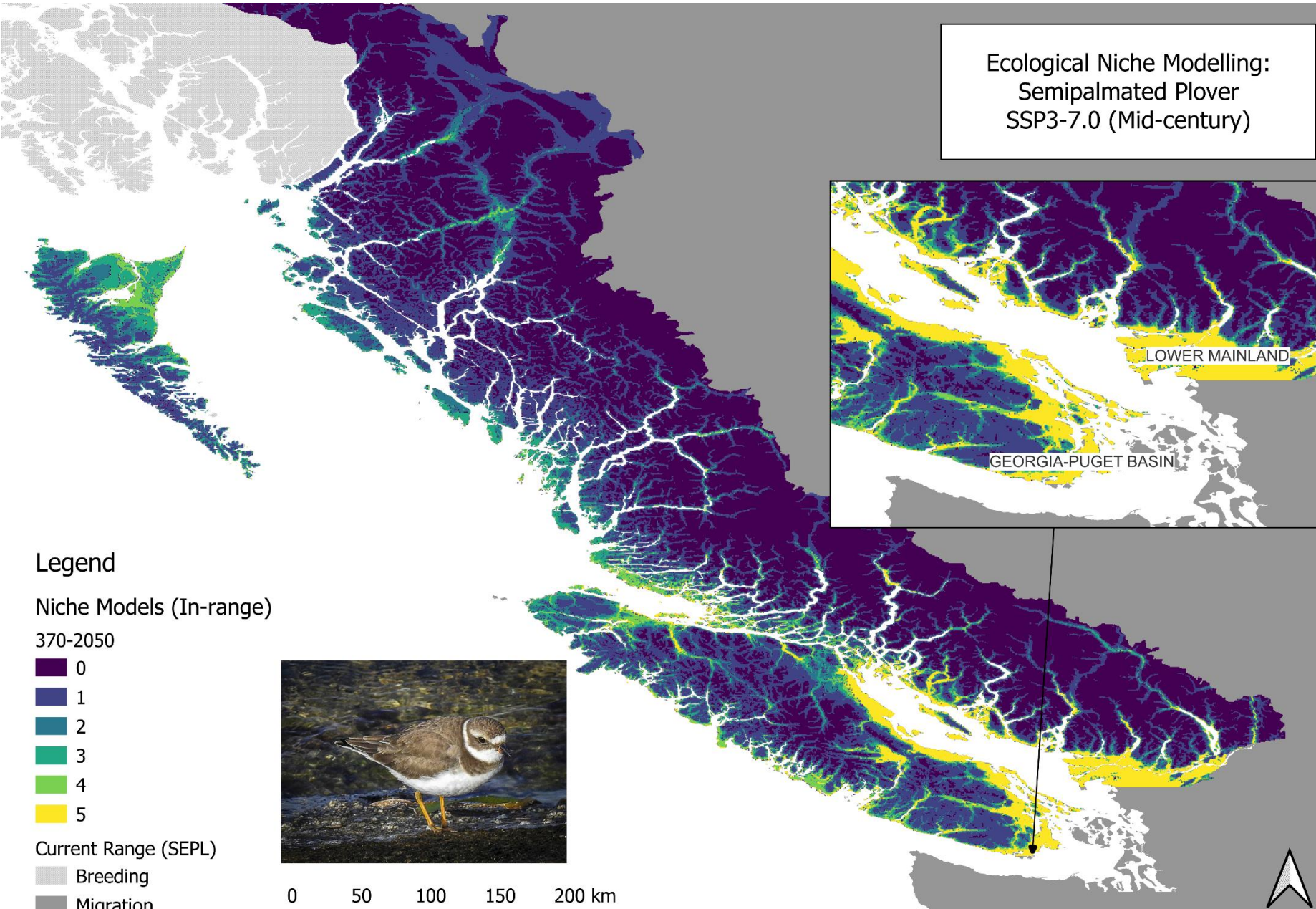


Ecological Niche Modelling:  
Semipalmated Plover  
SSP2-4.5 (Late-century)



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Ecological Niche Modelling:  
Semipalmated Plover  
SSP3-7.0 (Mid-century)



Legend

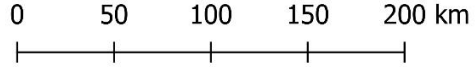
Niche Models (In-range)

370-2050

- 0
- 1
- 2
- 3
- 4
- 5

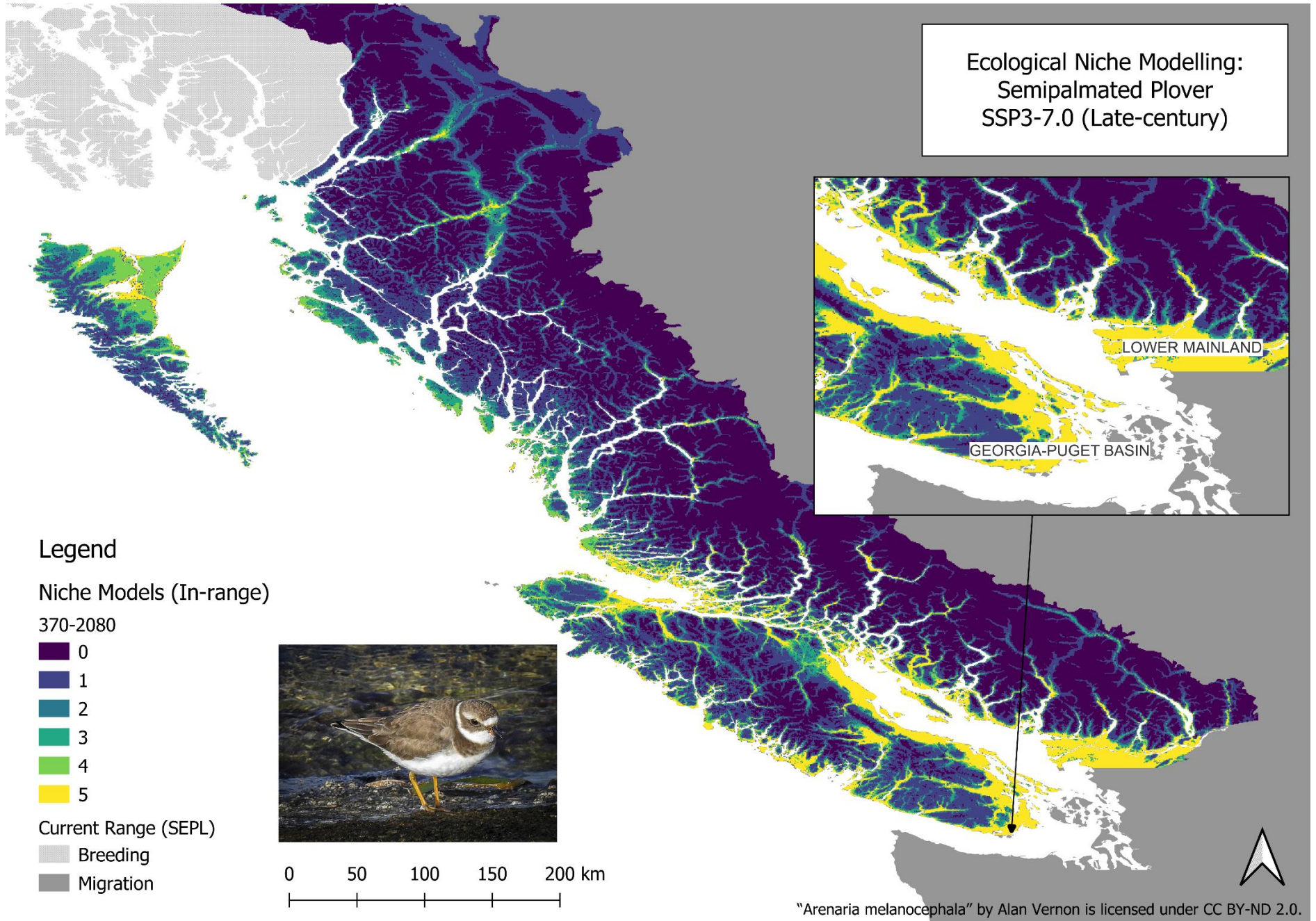
Current Range (SEPL)

- Breeding
- Migration



"Arenaria melanocephala" by Alan Vernon is licensed under CC BY-ND 2.0.

Ecological Niche Modelling:  
Semipalmated Plover  
SSP3-7.0 (Late-century)



Legend

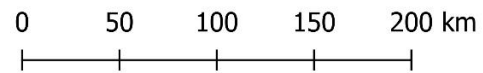
Niche Models (In-range)

370-2080

- 0
- 1
- 2
- 3
- 4
- 5

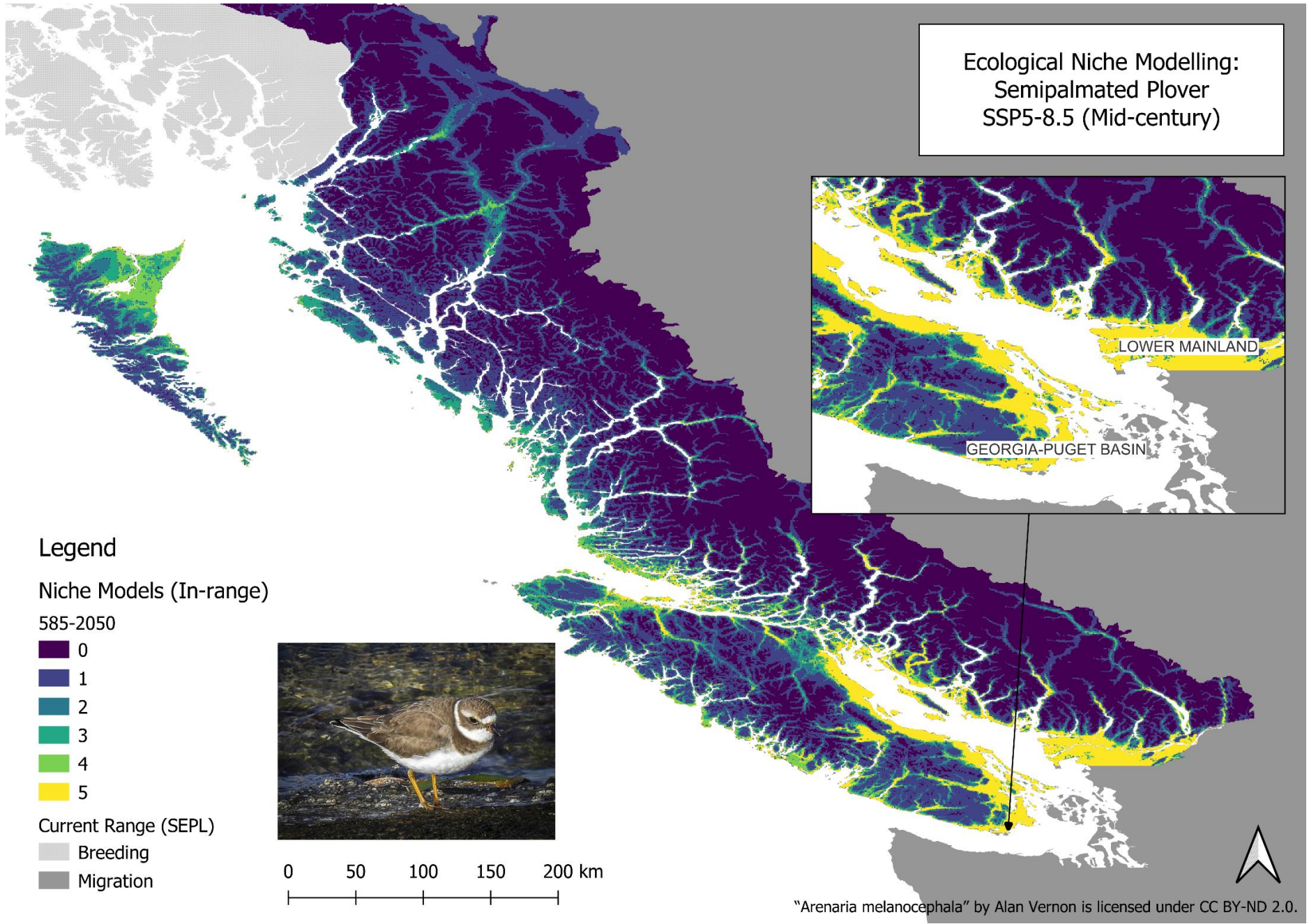
Current Range (SEPL)

- Breeding
- Migration

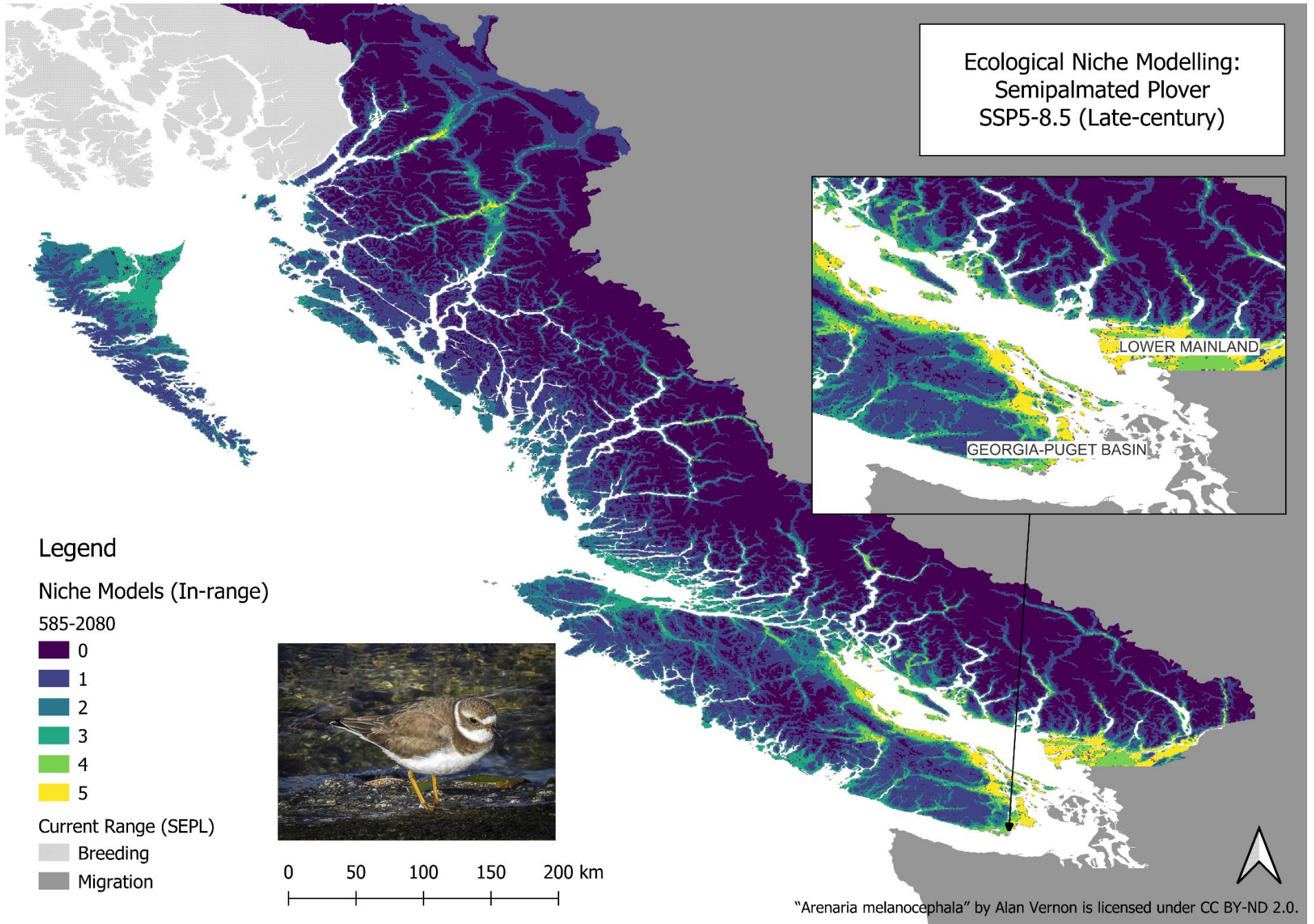


"*Arenaria melanocephala*" by Alan Vernon is licensed under CC BY-ND 2.0.

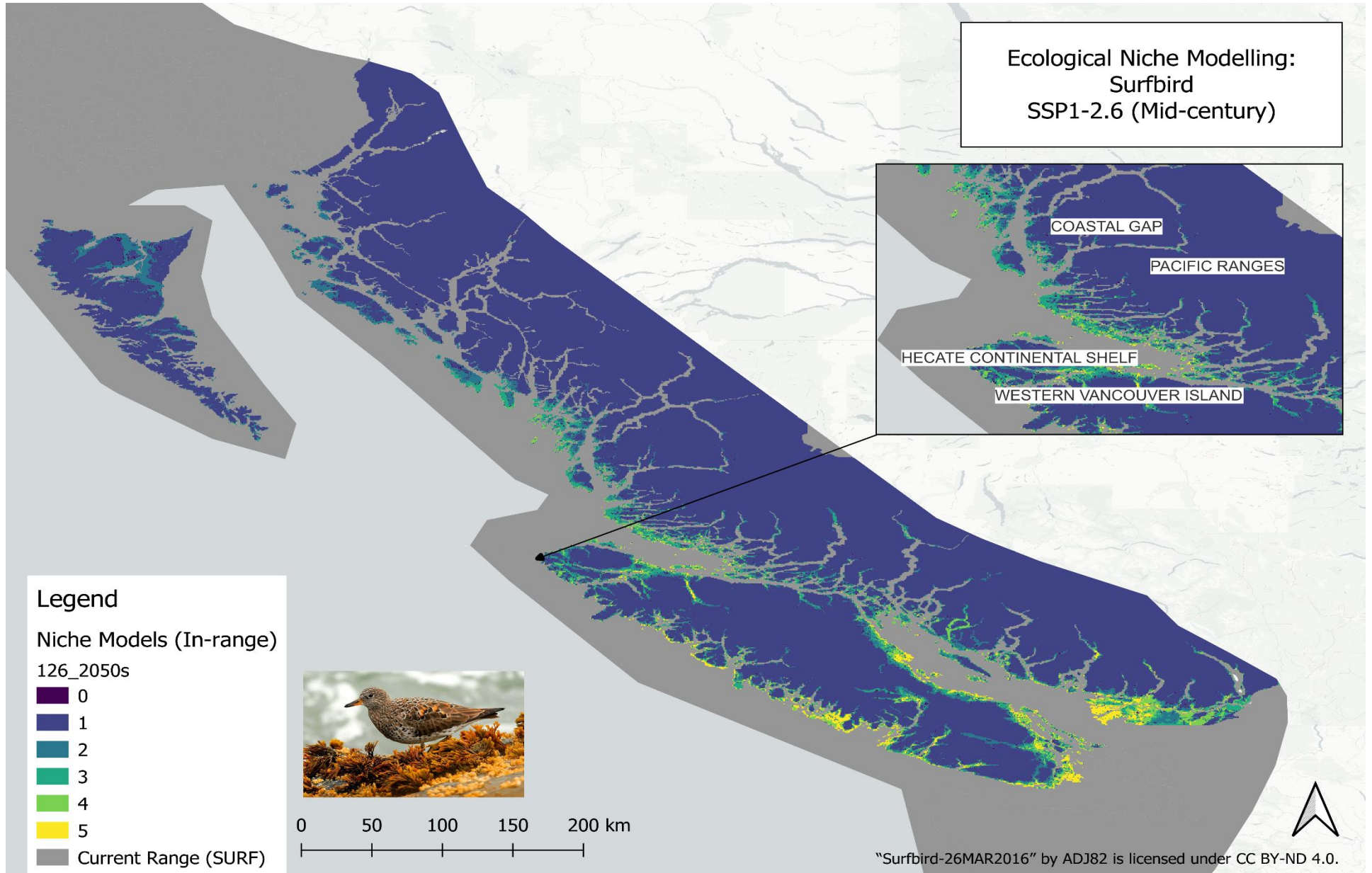
Ecological Niche Modelling:  
Semipalmated Plover  
SSP5-8.5 (Mid-century)



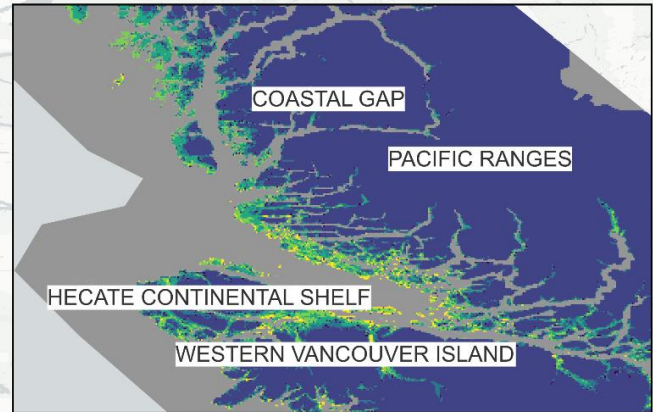
Ecological Niche Modelling:  
Semipalmated Plover  
SSP5-8.5 (Late-century)



# Ecological Niche Modelling: Surfbird (*Aphriza virgata*)



Ecological Niche Modelling:  
Surfbird  
SSP1-2.6 (Late-century)



Legend

Niche Models (In-range)

126\_2080s

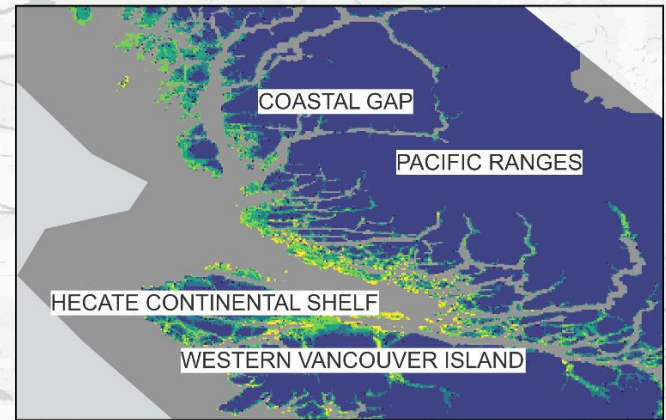


0 50 100 150 200 km

Current Range (SURF)

"Surfbird-26MAR2016" by ADJ82 is licensed under CC BY-ND 4.0.

Ecological Niche Modelling:  
Surfbird  
SSP2-4.5 (Mid-century)



Legend

Niche Models (In-range)

245\_2050s

- 0
- 1
- 2
- 3
- 4
- 5

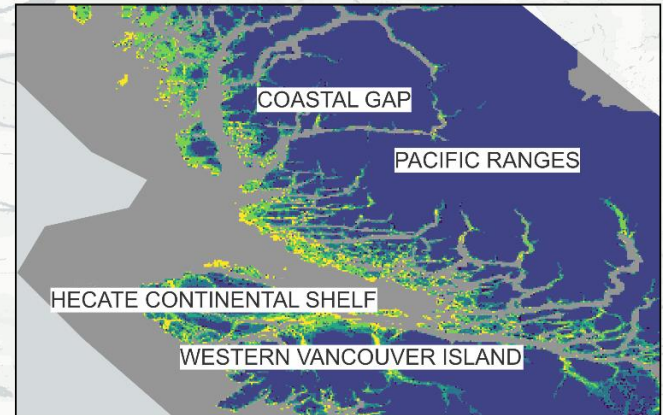
Current Range (SURF)



0 50 100 150 200 km

"Surfbird-26MAR2016" by ADJ82 is licensed under CC BY-ND 4.0.

Ecological Niche Modelling:  
Surfbird  
SSP2-4.5 (Late-century)



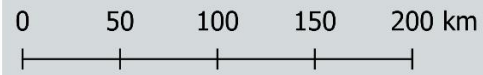
Legend

Niche Models (In-range)

245\_2080s

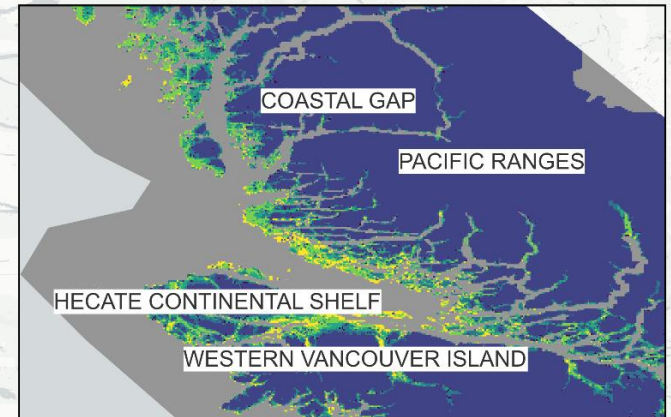


Current Range (SURF)



"Surfbird-26MAR2016" by ADJ82 is licensed under CC BY-ND 4.0.

Ecological Niche Modelling:  
Surfbird  
SSP3-7.0 (Mid-century)



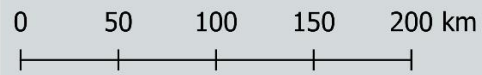
Legend

Niche Models (In-range)

370\_2050s

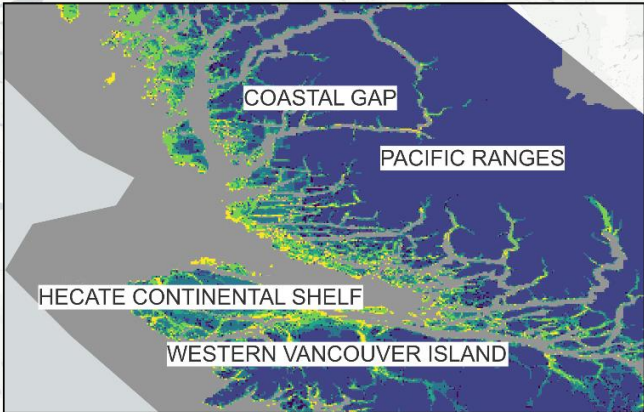


Current Range (SURF)



"Surfbird-26MAR2016" by ADJ82 is licensed under CC BY-ND 4.0.

Ecological Niche Modelling:  
Surfbird  
SSP3-7.0 (Late-century)



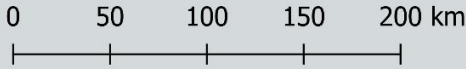
Legend

Niche Models (In-range)

370\_2080s

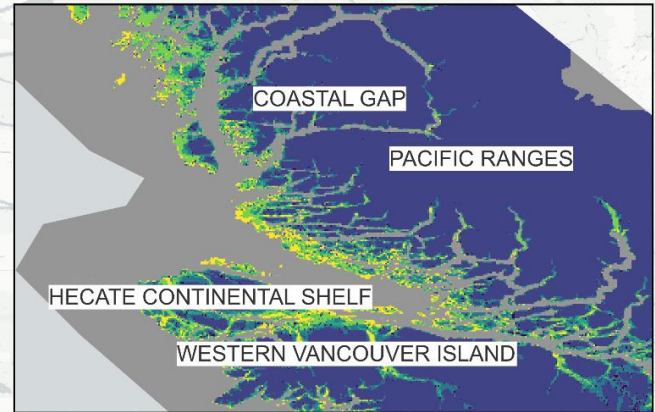
- 0
- 1
- 2
- 3
- 4
- 5

Current Range (SURF)



"Surfbird-26MAR2016" by ADJ82 is licensed under CC BY-ND 4.0.

Ecological Niche Modelling:  
Surfbird  
SSP5-8.5 (Mid-century)



Legend

Niche Models (In-range)

585\_2050s



Current Range (SURF)

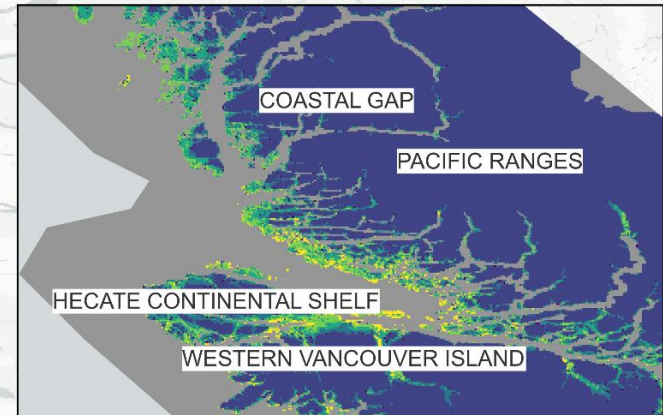


0 50 100 150 200 km



"Surfbird-26MAR2016" by ADJ82 is licensed under CC BY-ND 4.0.

Ecological Niche Modelling:  
Surfbird  
SSP2-4.5 (Mid-century)



Legend

Niche Models (In-range)

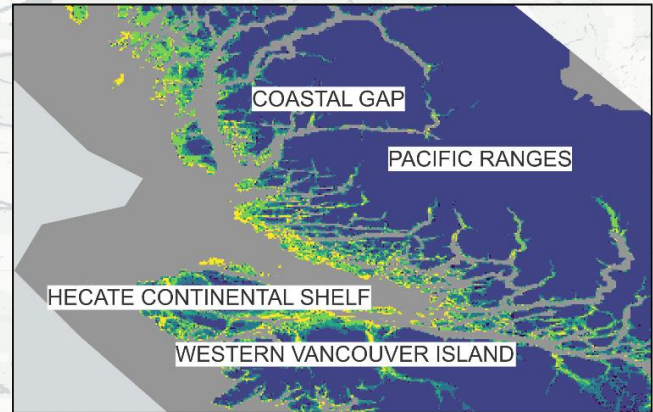
245\_2050s



Current Range (SURF)

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Ecological Niche Modelling:  
Surfbird  
SSP2-4.5 (Late-century)



Legend

Niche Models (In-range)

245\_2080s

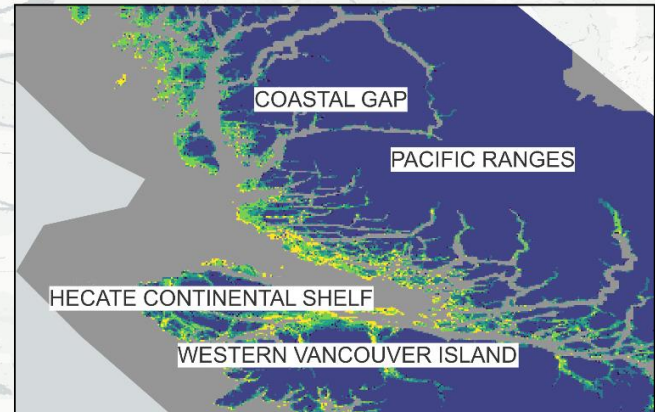


0 50 100 150 200 km

Current Range (SURF)

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Ecological Niche Modelling:  
Surfbird  
SSP3-7.0 (Mid-century)



Legend

Niche Models (In-range)

370\_2050s



Current Range (SURF)

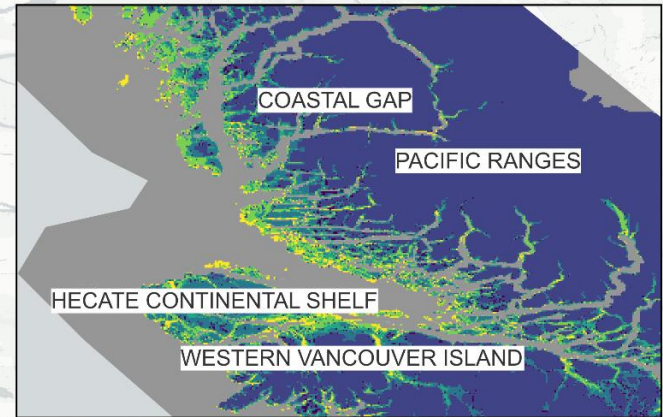


0 50 100 150 200 km



"Surfbird-26MAR2016" by ADJ82 is licensed under CC BY-ND 4.0.

Ecological Niche Modelling:  
Surfbird  
SSP3-7.0 (Late-century)



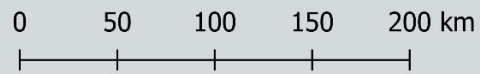
Legend

Niche Models (In-range)

370\_2080s

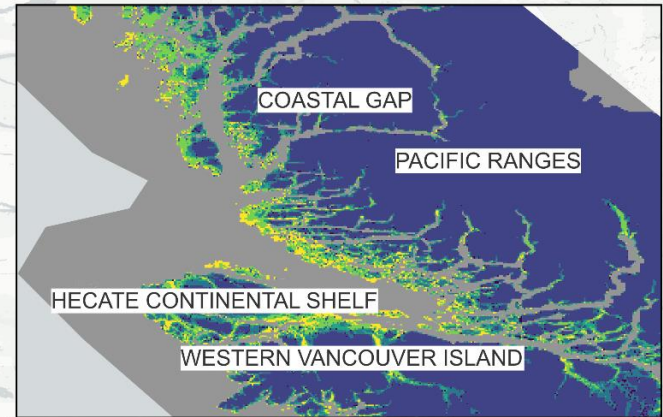


Current Range (SURF)



"Surfbird-26MAR2016" by ADJ82 is licensed under CC BY-ND 4.0.

Ecological Niche Modelling:  
Surfbird  
SSP5-8.5 (Mid-century)



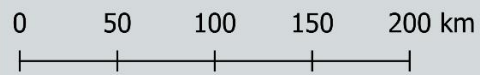
Legend

Niche Models (In-range)

585\_2050s

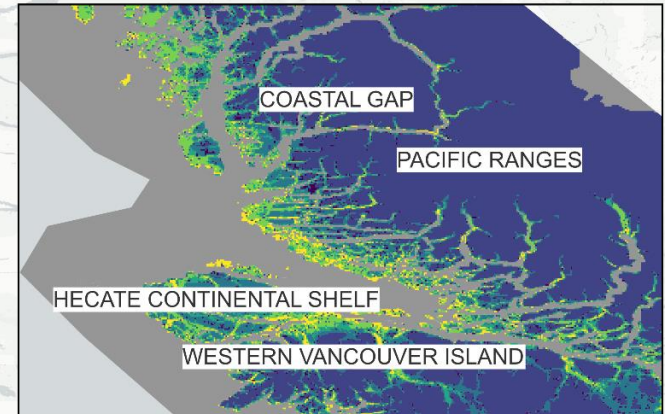


Current Range (SURF)



"Surfbird-26MAR2016" by ADJ82 is licensed under CC BY-ND 4.0.

Ecological Niche Modelling:  
Surfbird  
SSP5-8.5 (Late-century)



Legend

Niche Models (In-range)

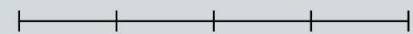
585\_2080s



Current Range (SURF)

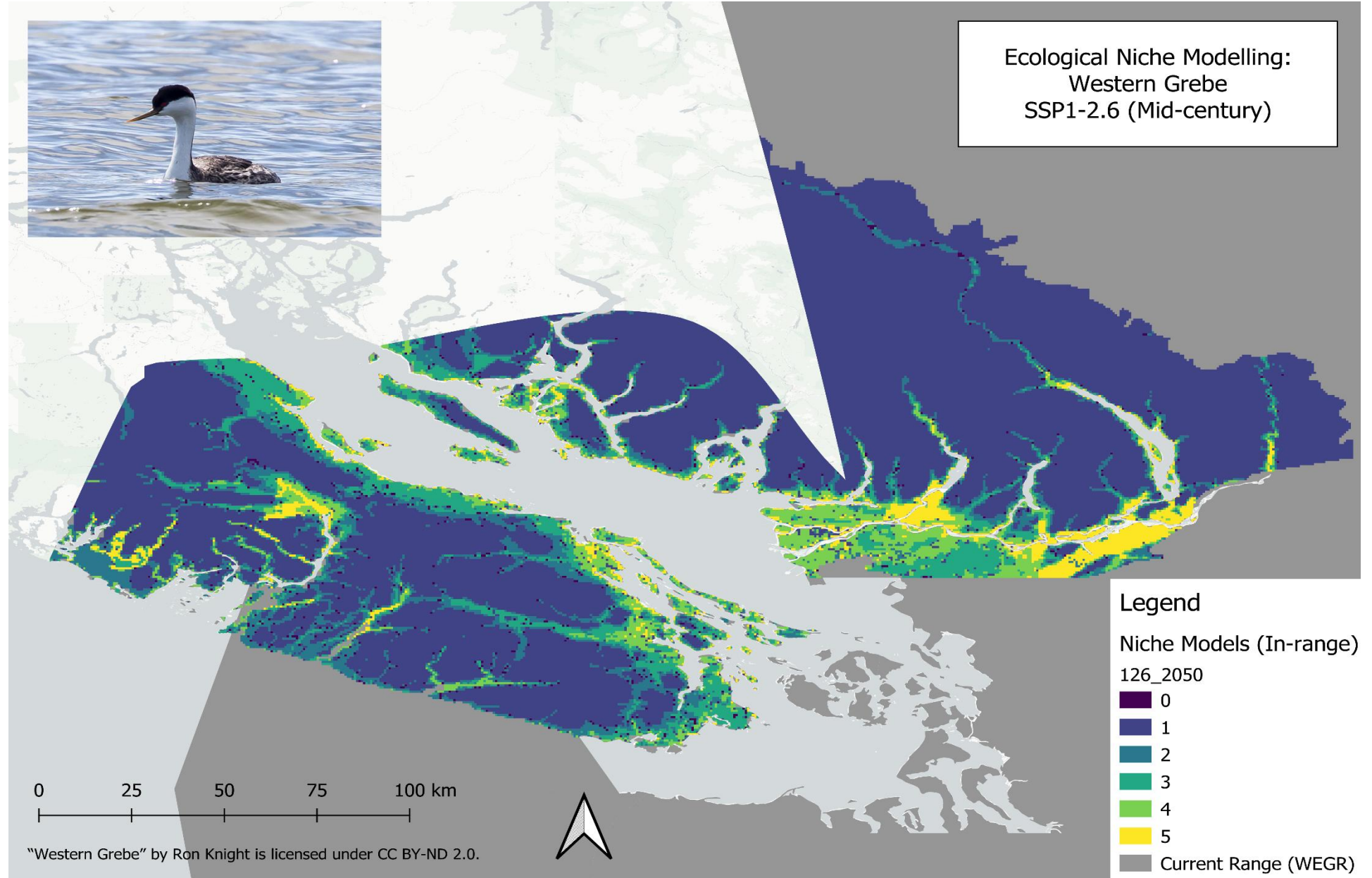


0 50 100 150 200 km



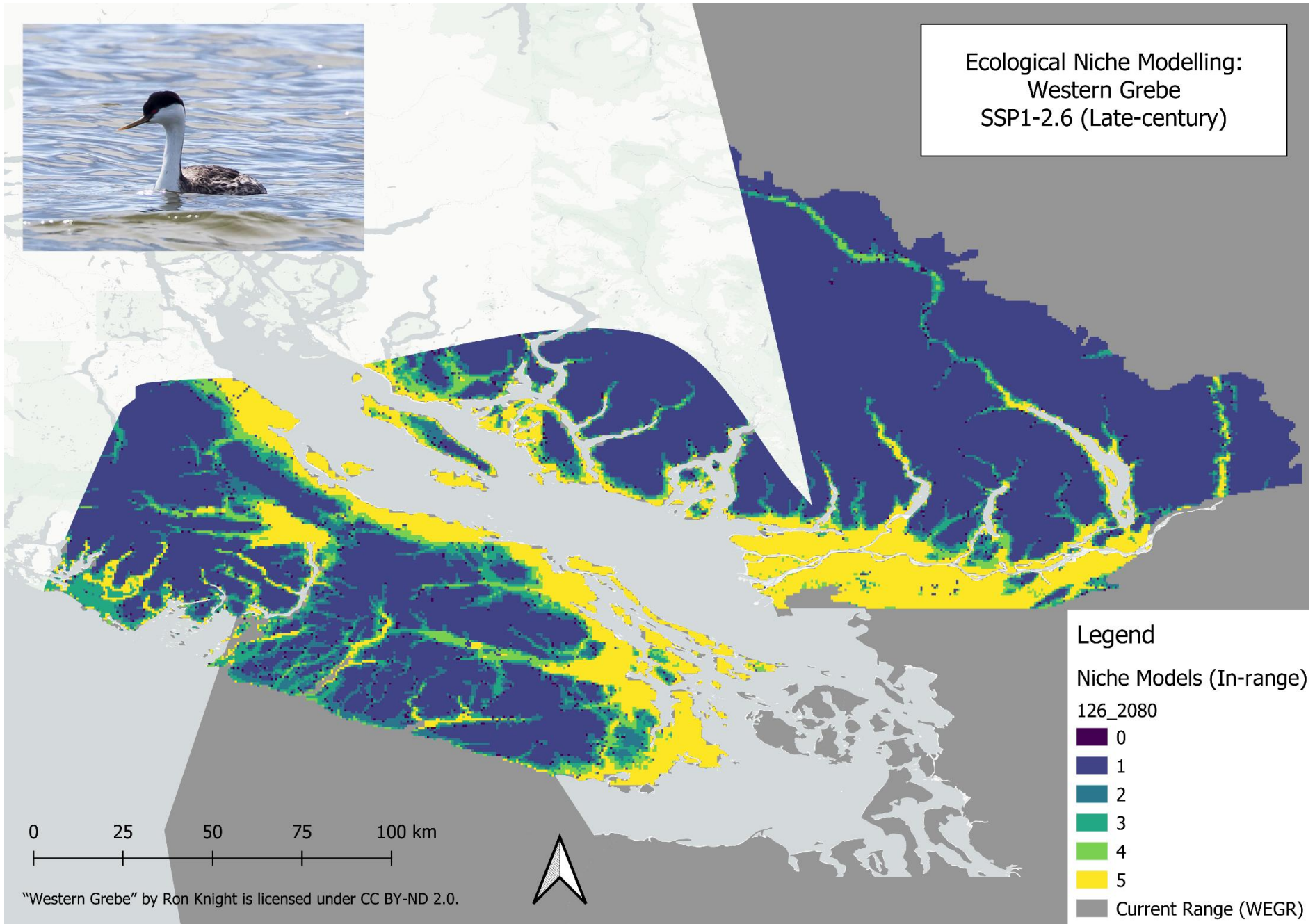
"Surfbird-26MAR2016" by ADJ82 is licensed under CC BY-ND 4.0.

## Ecological Niche Modelling: Western Grebe (*Aechmophorus occidentalis*)





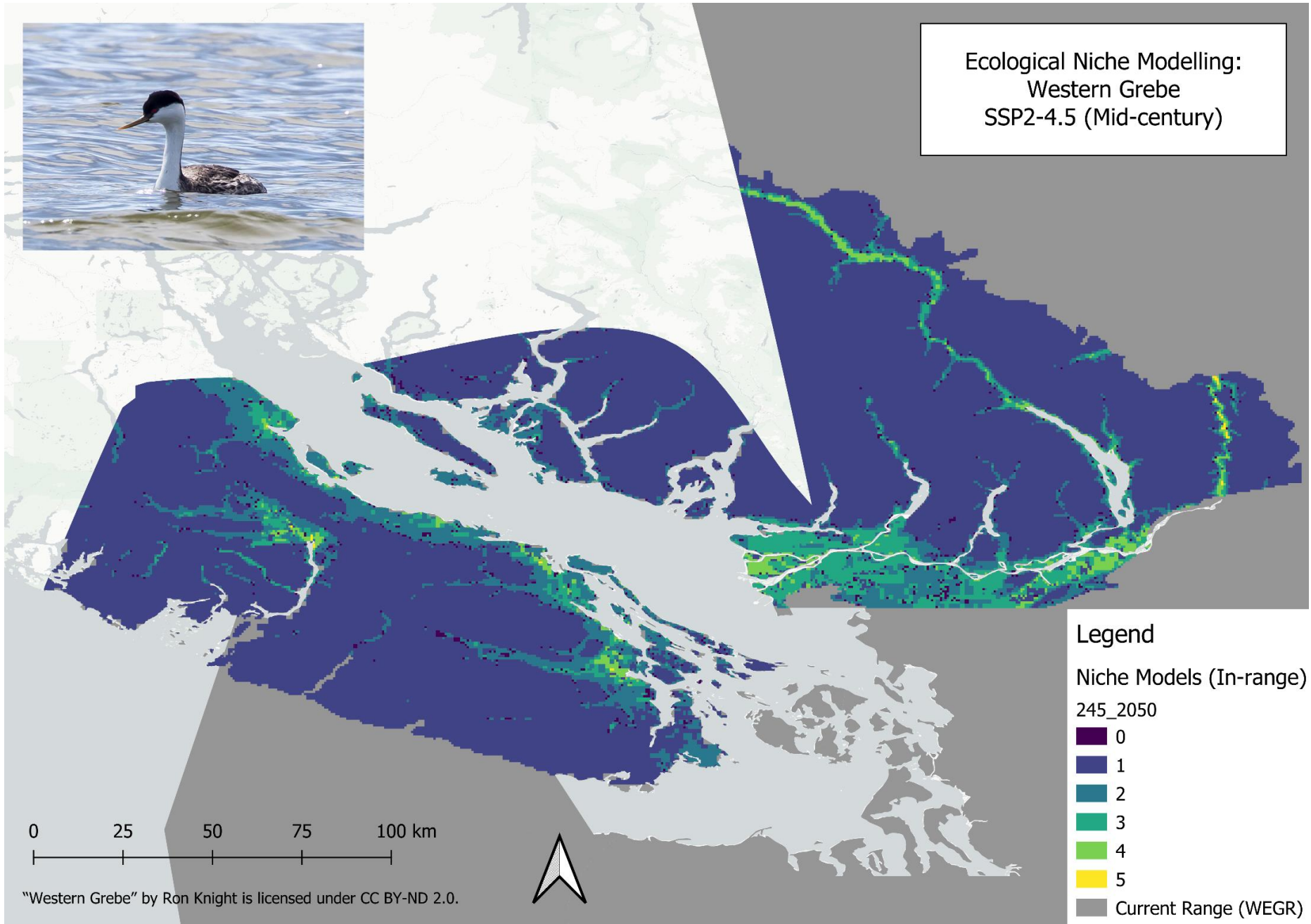
Ecological Niche Modelling:  
Western Grebe  
SSP1-2.6 (Late-century)



"Western Grebe" by Ron Knight is licensed under CC BY-ND 2.0.



Ecological Niche Modelling:  
Western Grebe  
SSP2-4.5 (Mid-century)



0 25 50 75 100 km

"Western Grebe" by Ron Knight is licensed under CC BY-ND 2.0.

Legend

Niche Models (In-range)

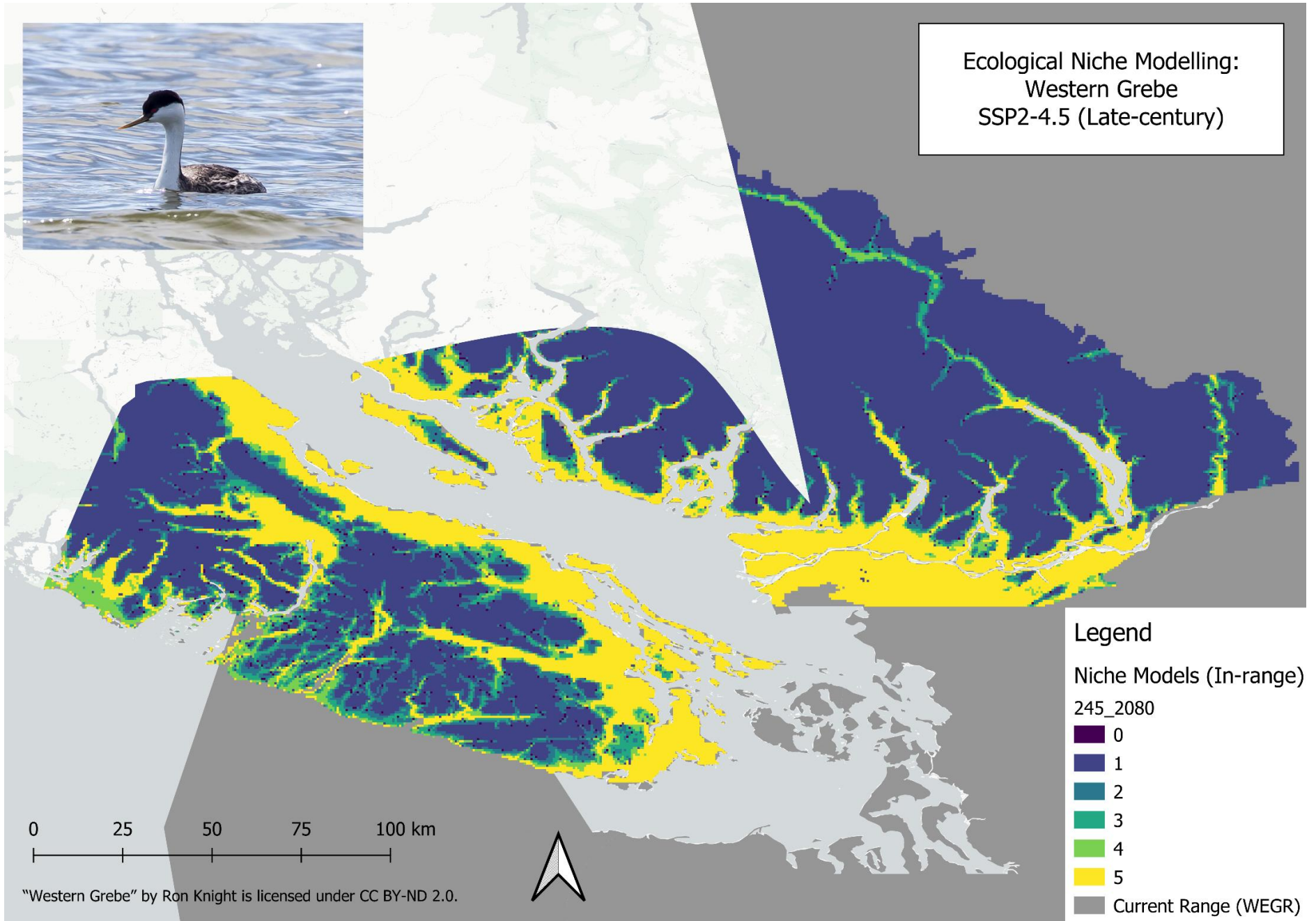
245\_2050

- 0
- 1
- 2
- 3
- 4
- 5

Current Range (WEGR)



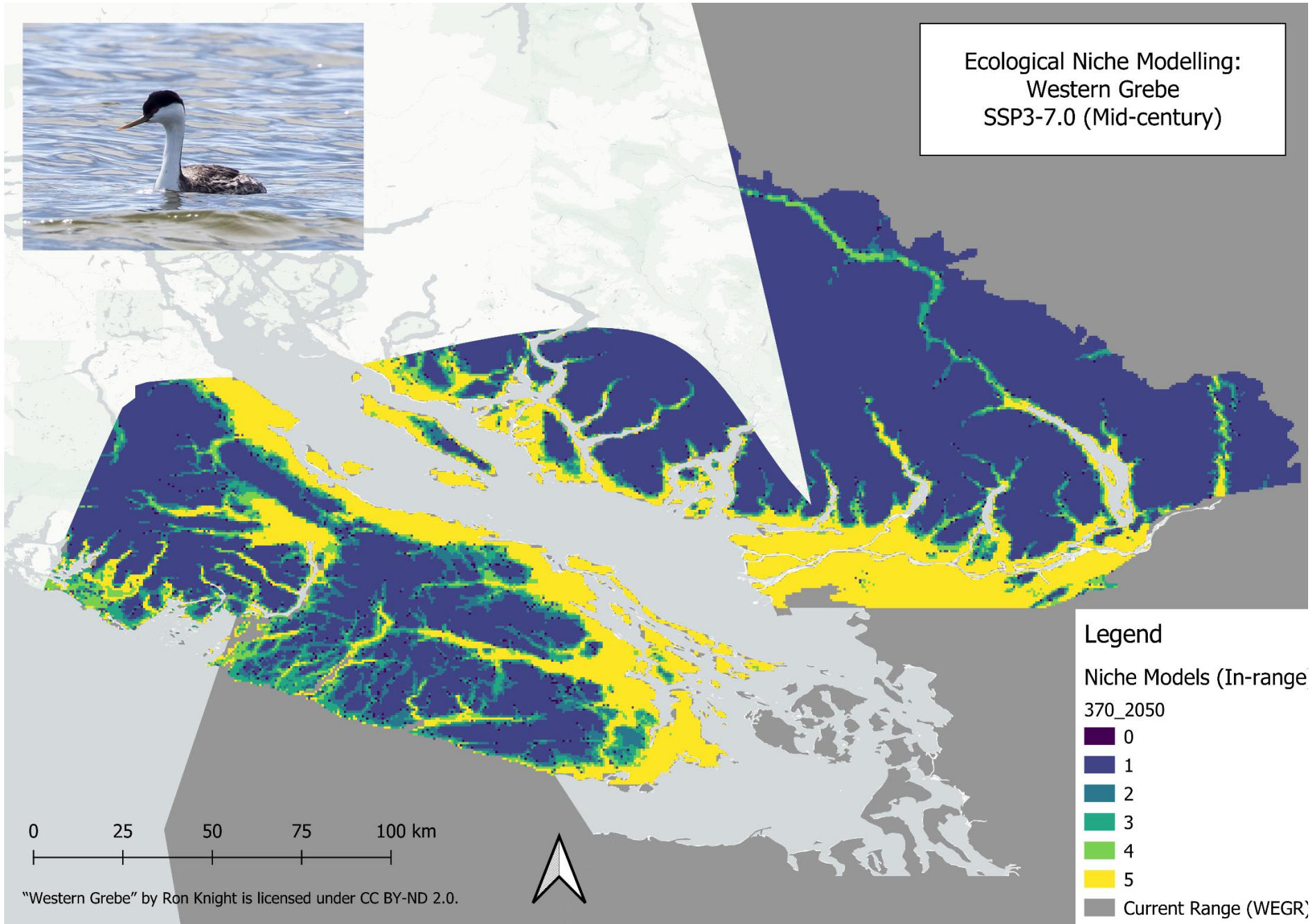
Ecological Niche Modelling:  
Western Grebe  
SSP2-4.5 (Late-century)



"Western Grebe" by Ron Knight is licensed under CC BY-ND 2.0.



Ecological Niche Modelling:  
Western Grebe  
SSP3-7.0 (Mid-century)



Legend

Niche Models (In-range

370\_2050

0

1

2

3

4

5

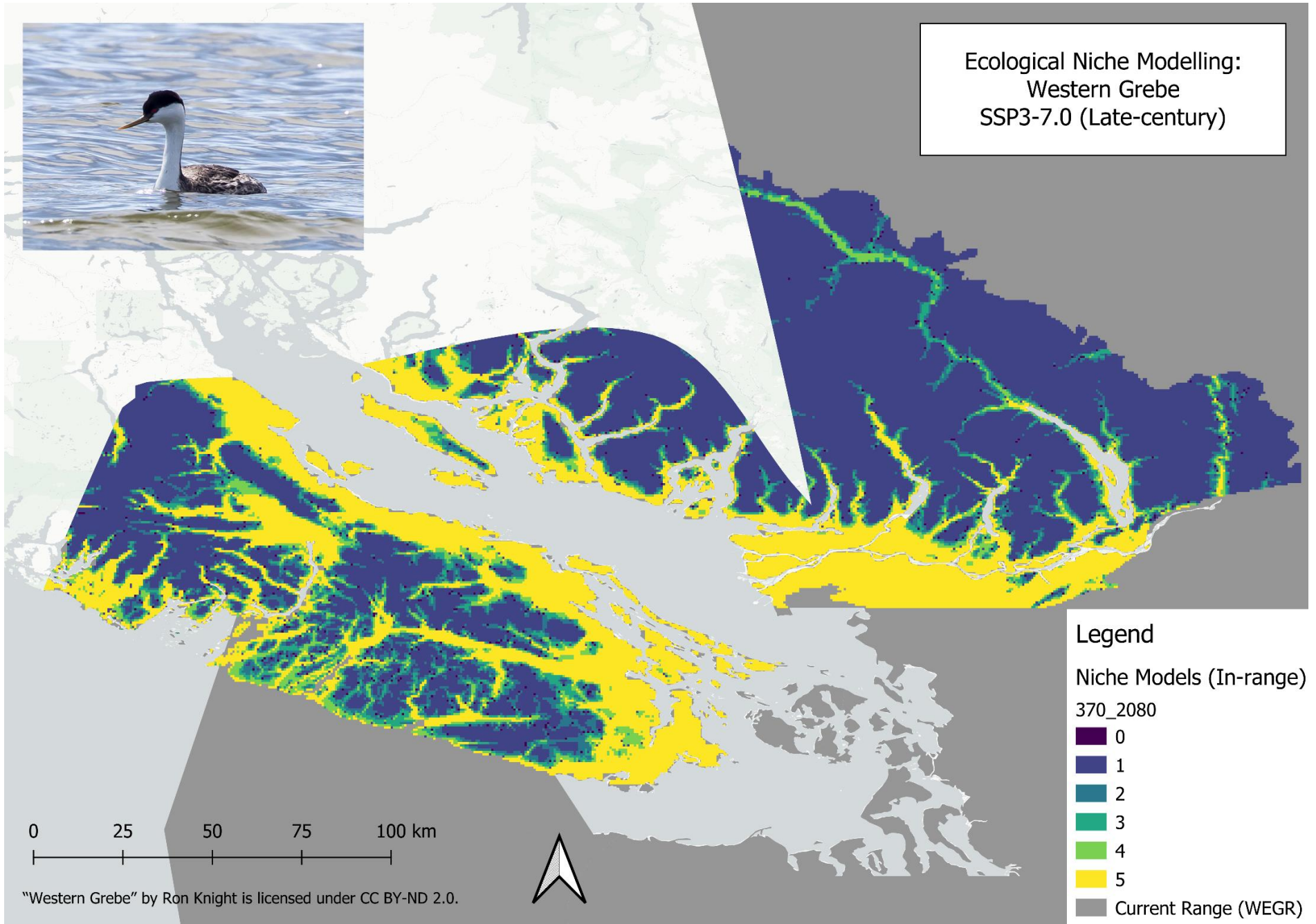
Current Range (WEGR)

0 25 50 75 100 km

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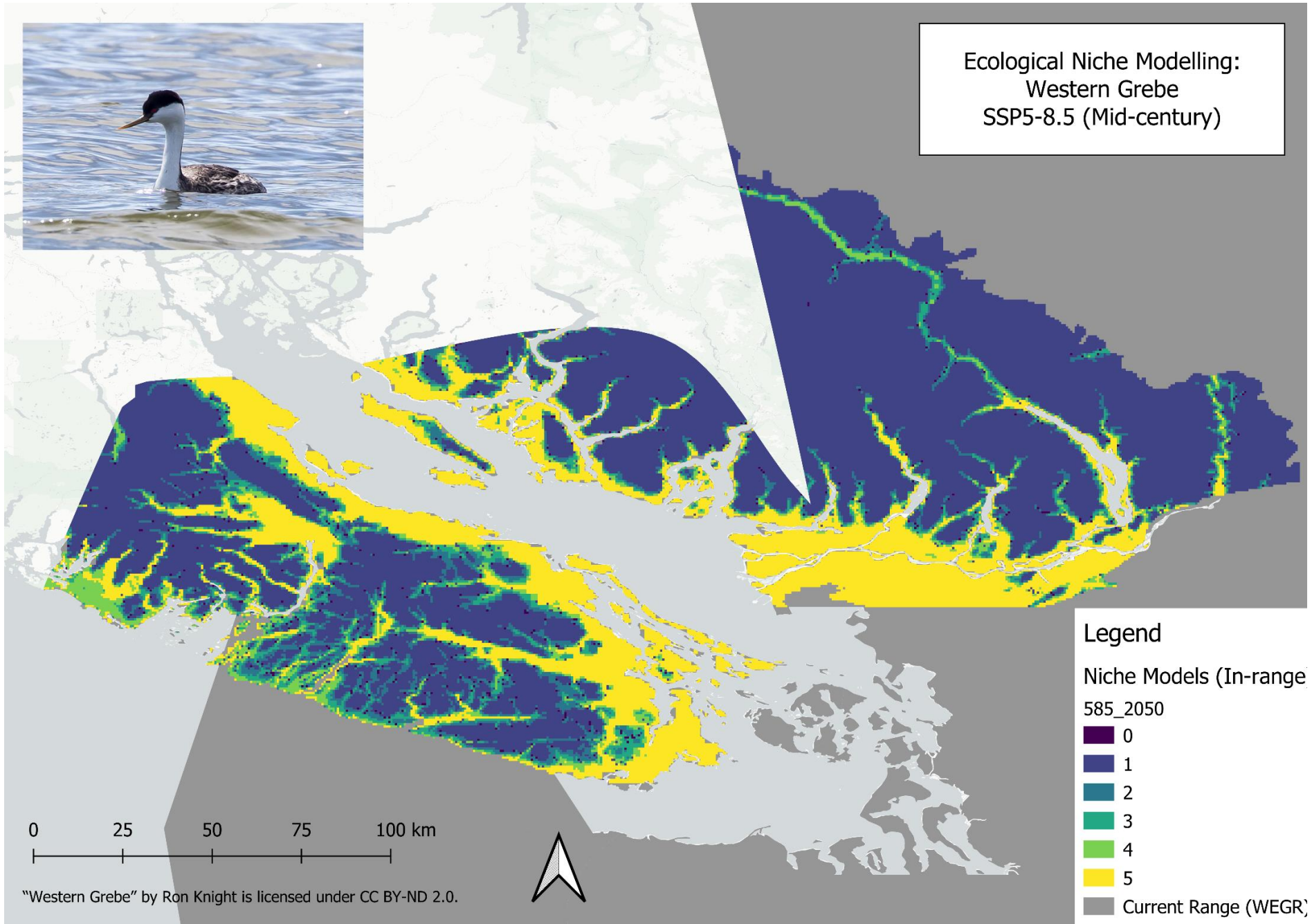
Ecological Niche Modelling:  
Western Grebe  
SSP3-7.0 (Late-century)



"Western Grebe" by Ron Knight is licensed under CC BY-ND 2.0.



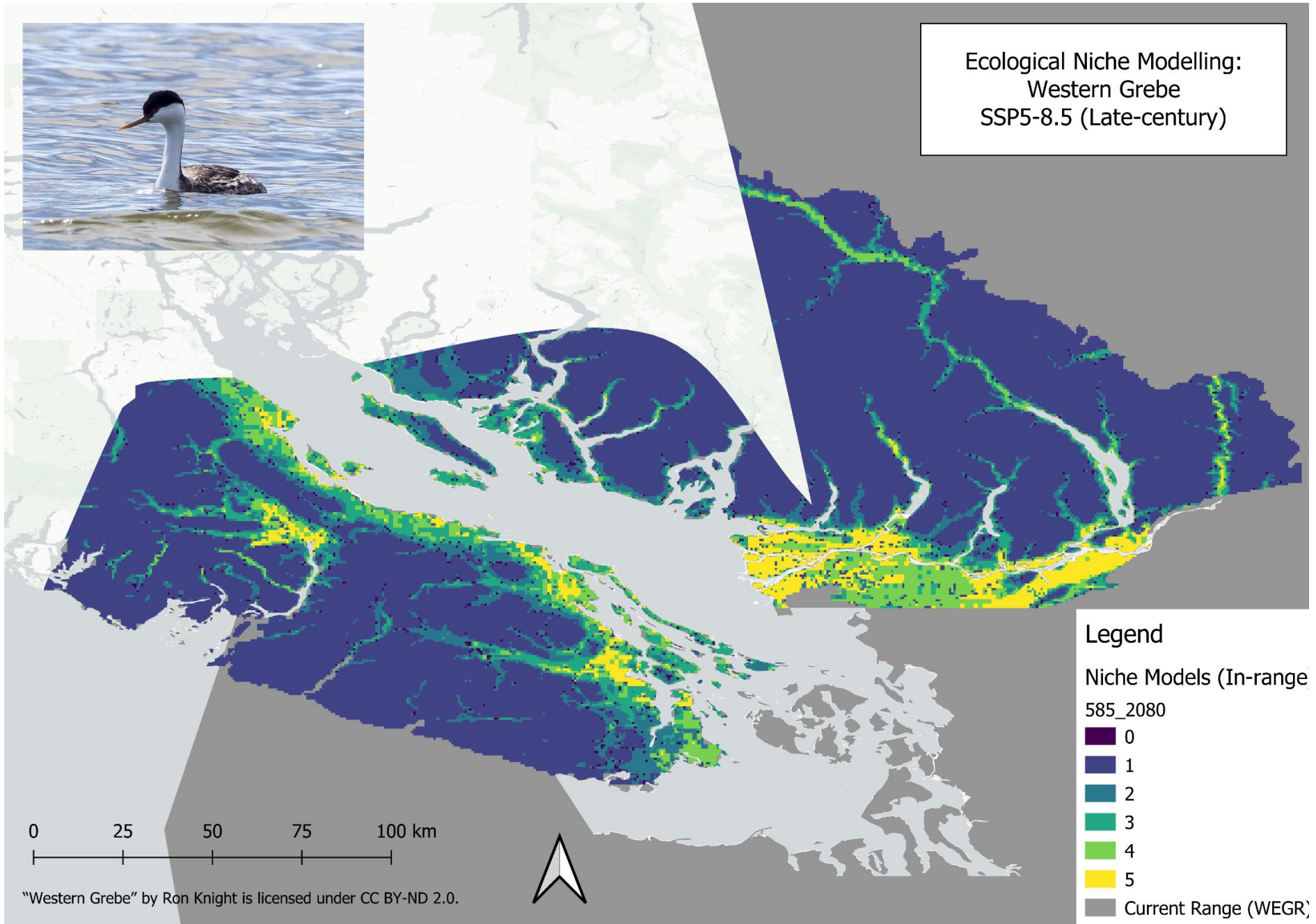
Ecological Niche Modelling:  
Western Grebe  
SSP5-8.5 (Mid-century)



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Ecological Niche Modelling:  
Western Grebe  
SSP5-8.5 (Late-century)



Legend

Niche Models (In-range)

585\_2080

0

1

2

3

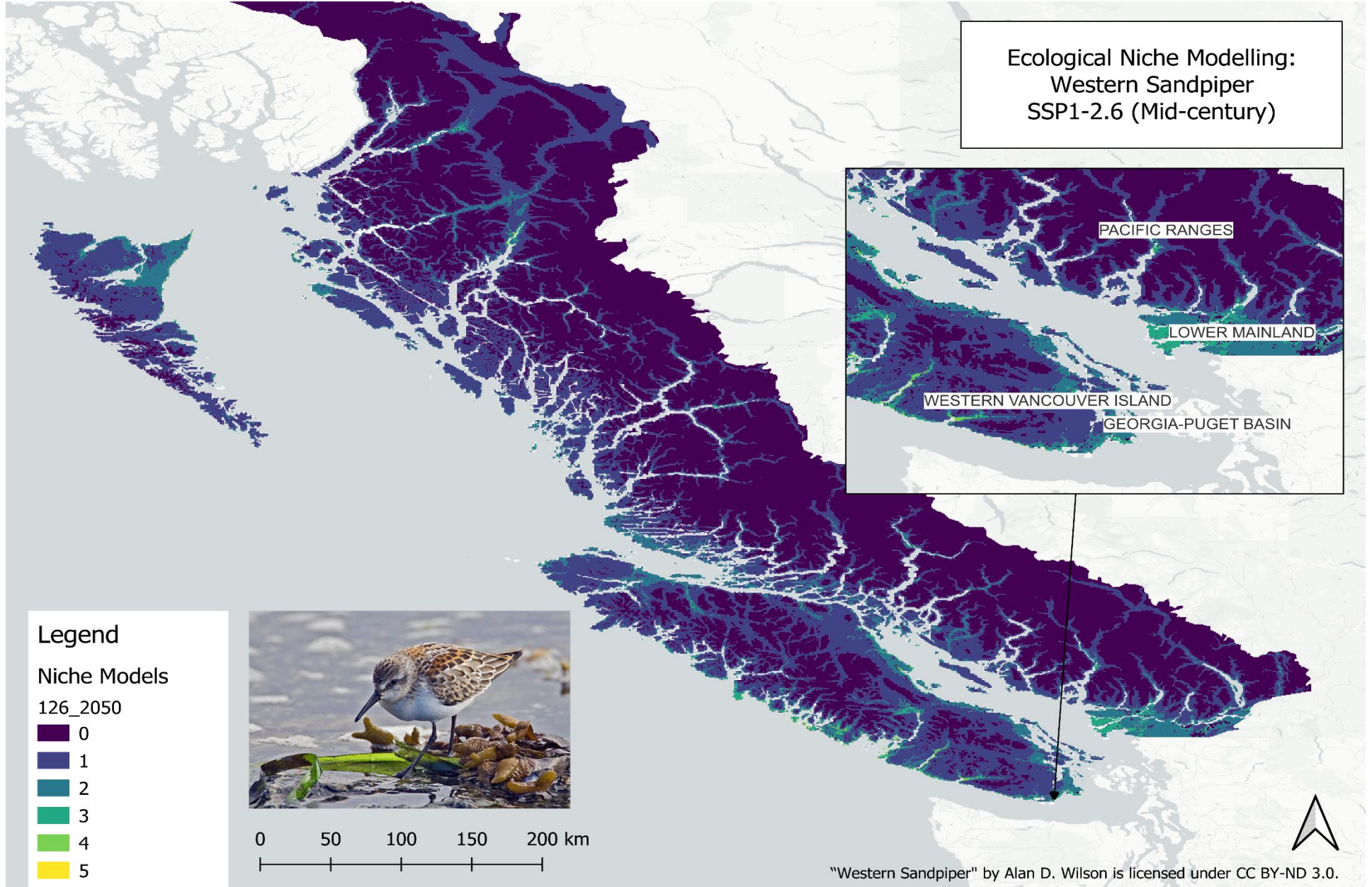
4

5

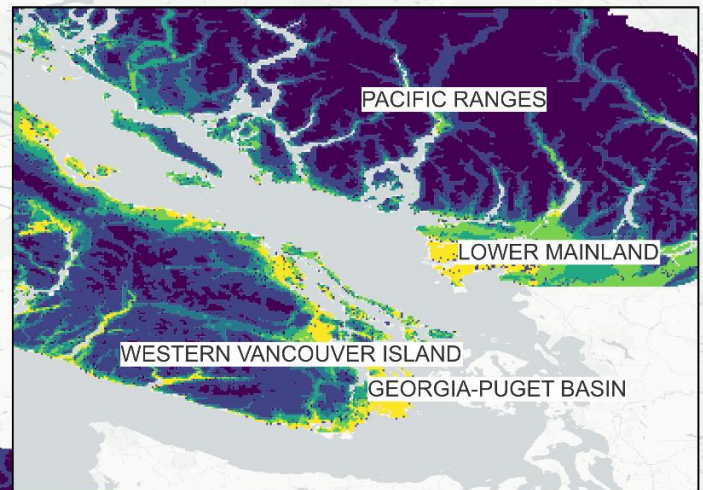
Current Range (WEGR)

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# Ecological Niche Modelling: Western Sandpiper (*Calidris mauri*)



Ecological Niche Modelling:  
Western Sandpiper  
SSP1-2.6 (Late-century)

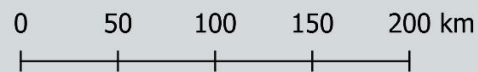


Legend

Niche Models

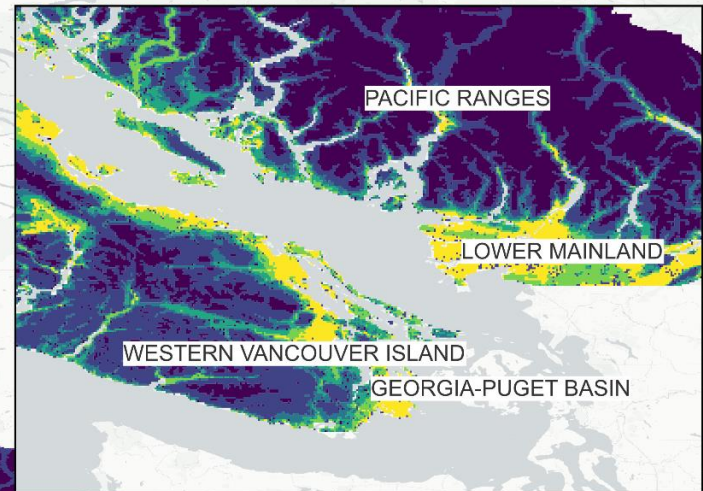
126\_2080

- 0
- 1
- 2
- 3
- 4
- 5



"Western Sandpiper" by Alan D. Wilson is licensed under CC BY-ND 3.0.

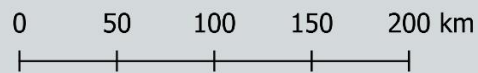
Ecological Niche Modelling:  
Western Sandpiper  
SSP2-4.5 (Mid-century)



Legend

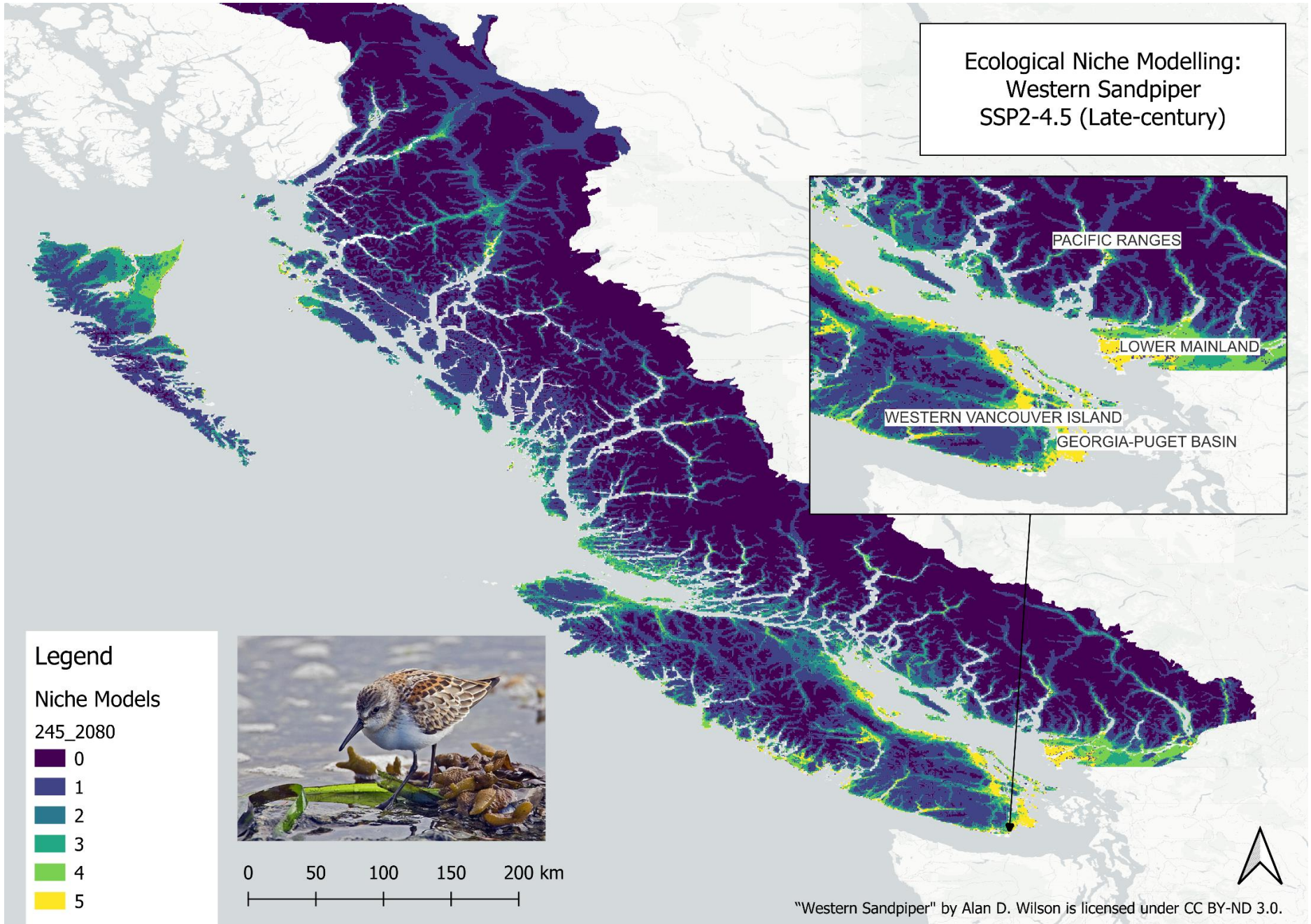
Niche Models

245\_2050

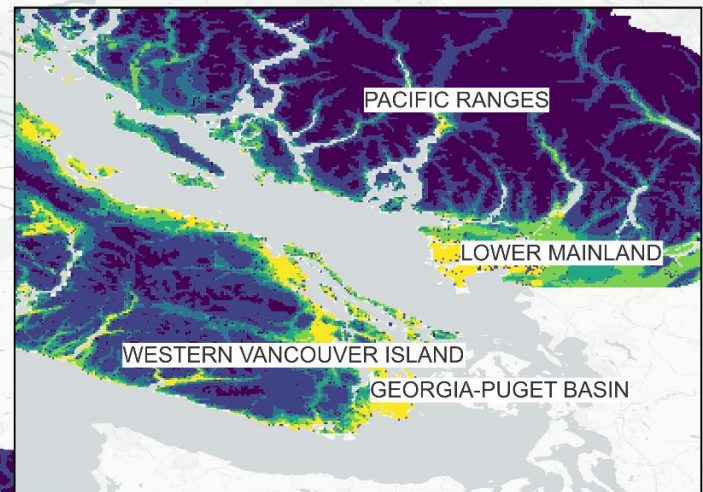


"Western Sandpiper" by Alan D. Wilson is licensed under CC BY-ND 3.0.

Ecological Niche Modelling:  
Western Sandpiper  
SSP2-4.5 (Late-century)



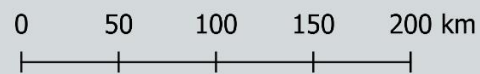
Ecological Niche Modelling:  
Western Sandpiper  
SSP3-7.0 (Mid-century)



Legend

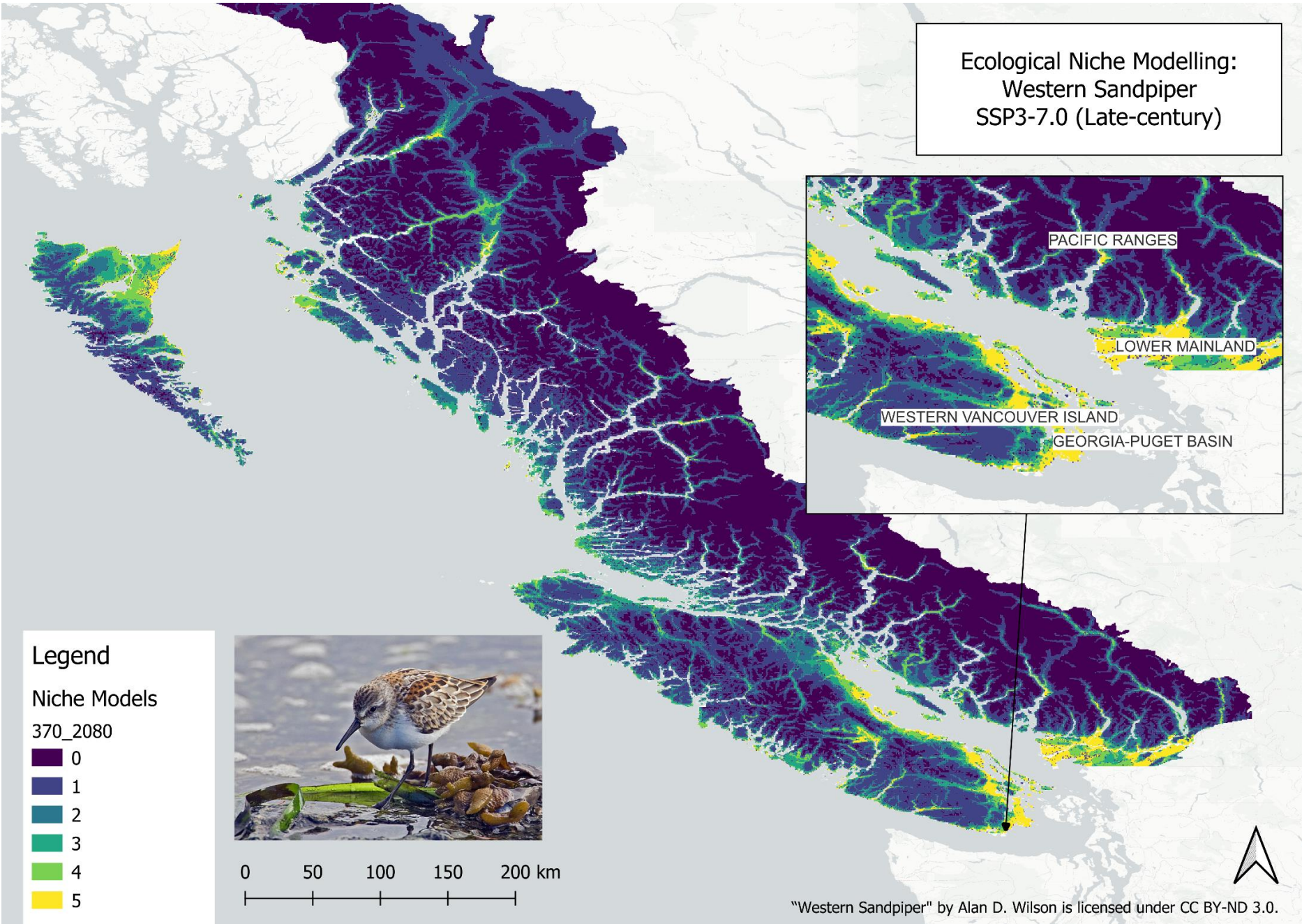
Niche Models

370\_2050



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Ecological Niche Modelling:  
Western Sandpiper  
SSP3-7.0 (Late-century)



Legend

Niche Models

370\_2080

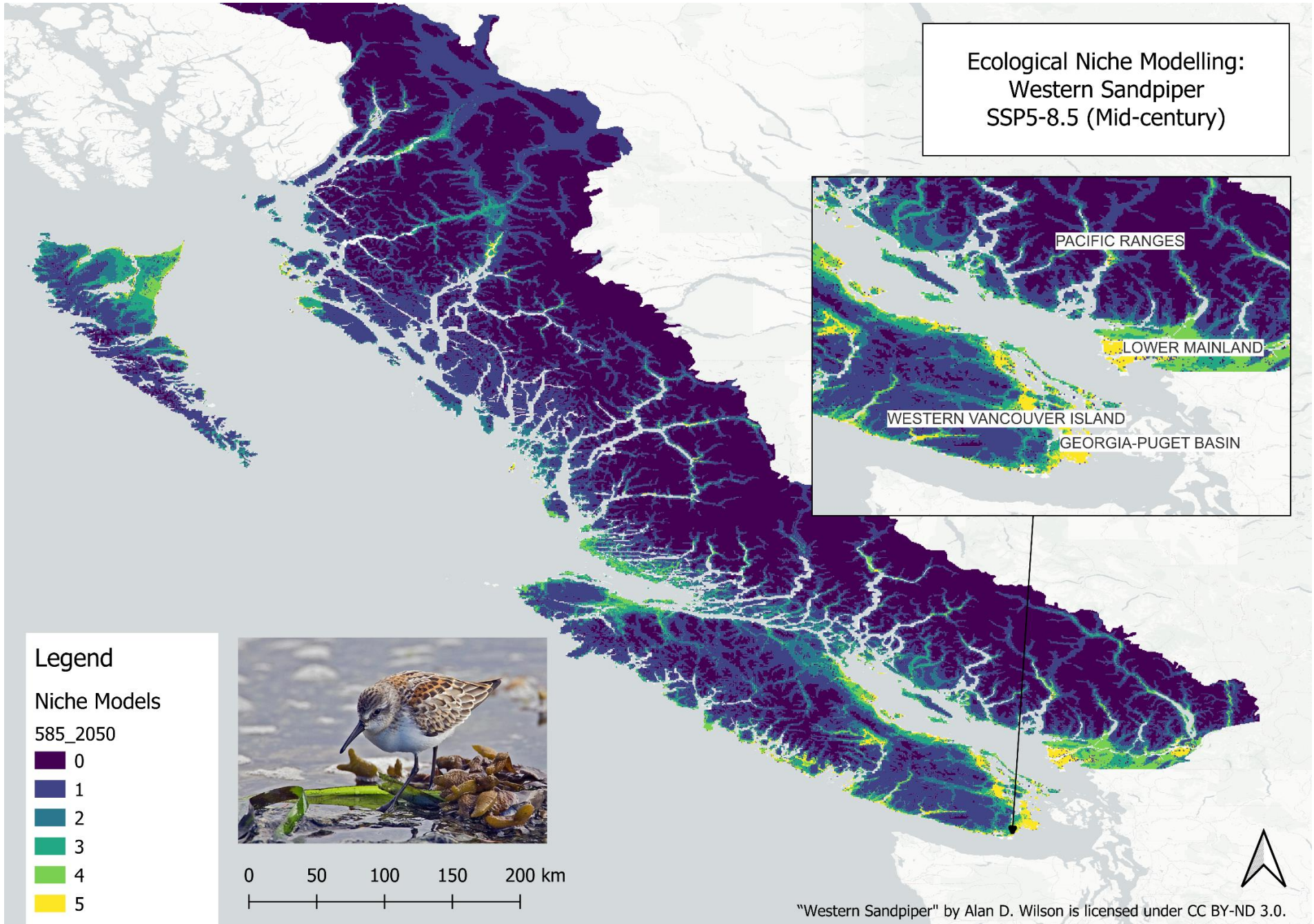
- 0
- 1
- 2
- 3
- 4
- 5



0 50 100 150 200 km

"Western Sandpiper" by Alan D. Wilson is licensed under CC BY-ND 3.0.

Ecological Niche Modelling:  
Western Sandpiper  
SSP5-8.5 (Mid-century)

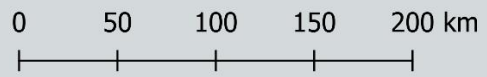


Legend

Niche Models

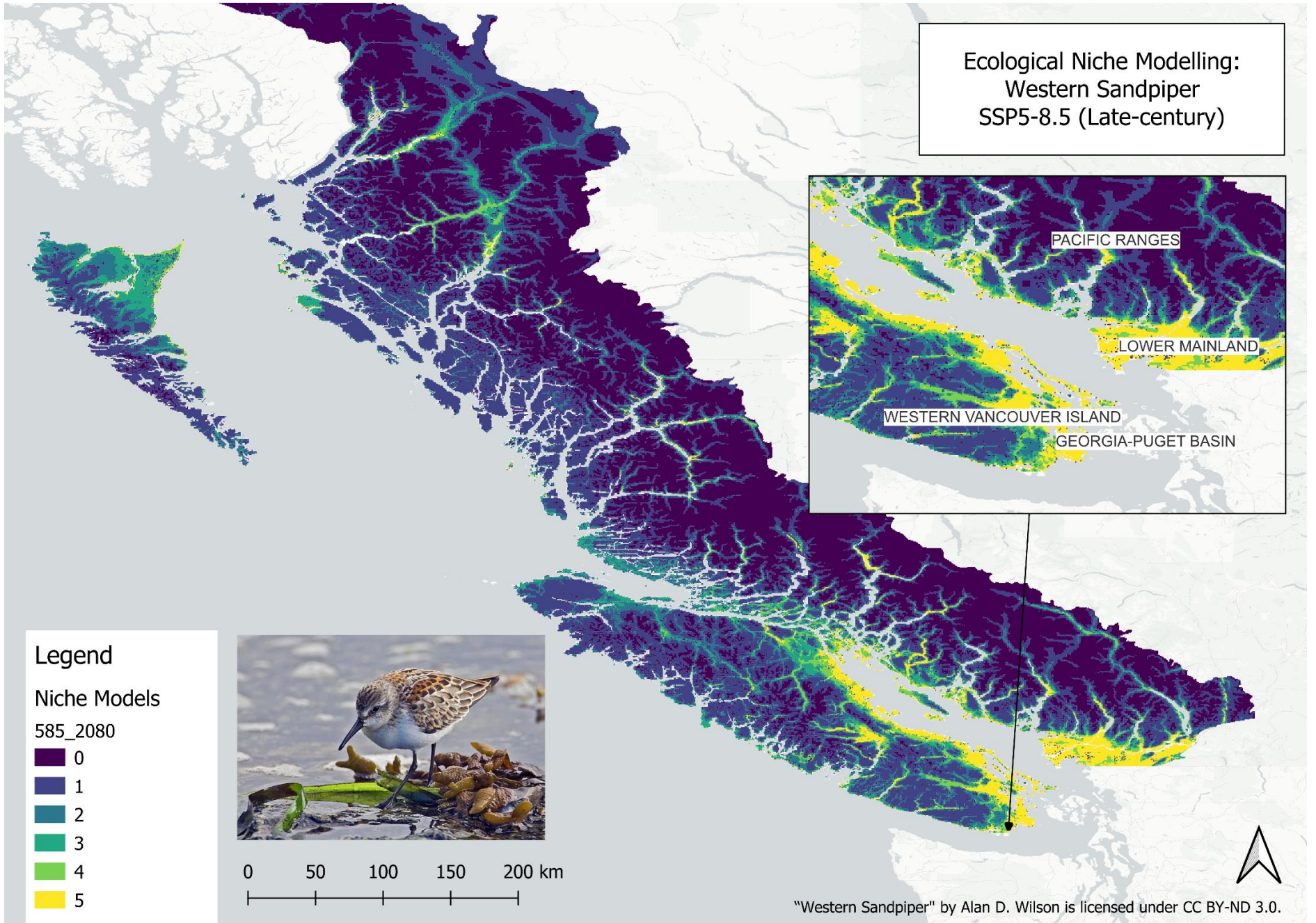
585\_2050

- 0
- 1
- 2
- 3
- 4
- 5

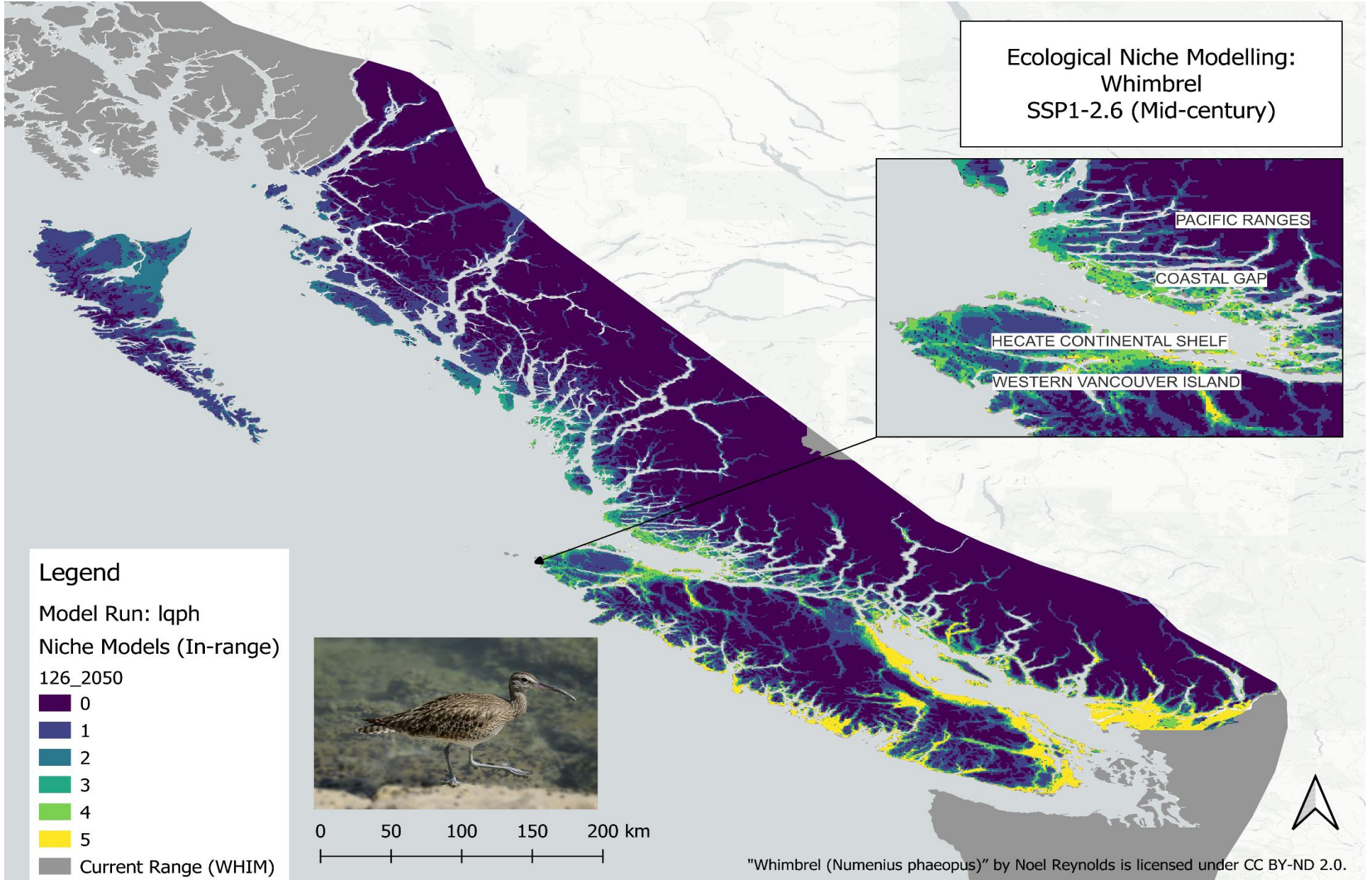


"Western Sandpiper" by Alan D. Wilson is licensed under CC BY-ND 3.0.

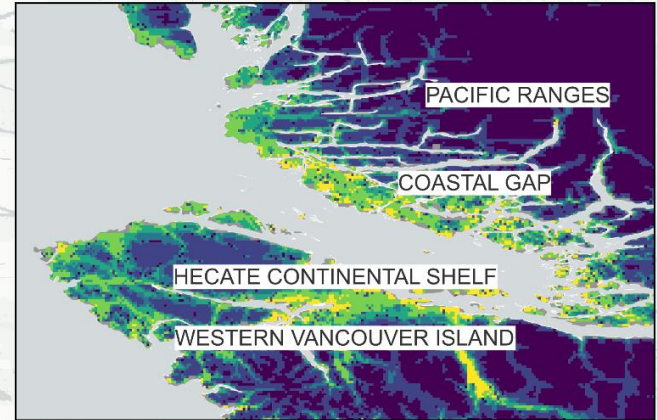
Ecological Niche Modelling:  
Western Sandpiper  
SSP5-8.5 (Late-century)



# Ecological Niche Modelling: Whimbrel (*Numenius phaeopus*)



Ecological Niche Modelling:  
Whimbrel  
SSP1-2.6 (Late-century)



Legend

Model Run: lqph  
Niche Models (In-range)

126\_2080



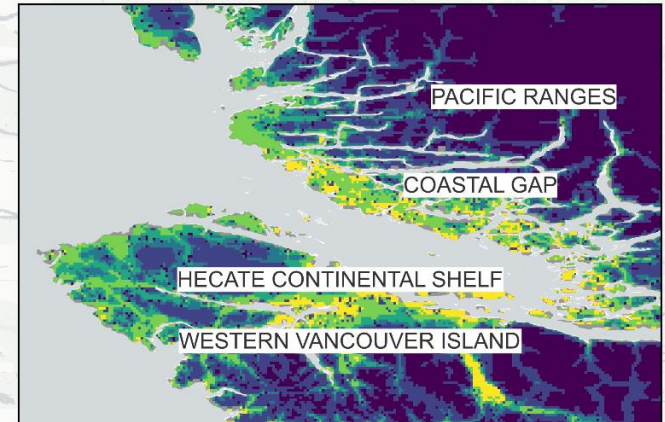
Current Range (WHIM)



0 50 100 150 200 km

"Whimbrel (Numenius phaeopus)" by Noel Reynolds is licensed under CC BY-ND 2.0.

Ecological Niche Modelling:  
Whimbrel  
SSP2-4.5 (Mid-century)

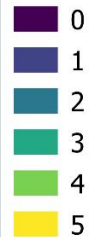


Legend

Model Run: lqph

Niche Models (In-range)

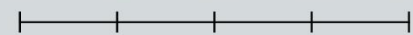
245\_2050



Current Range (WHIM)



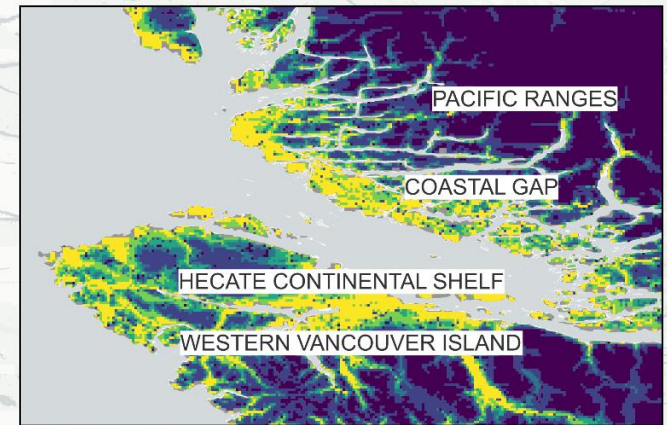
0 50 100 150 200 km



"Whimbrel (Numenius phaeopus)" by Noel Reynolds is licensed under CC BY-ND 2.0.



Ecological Niche Modelling:  
Whimbrel  
SSP2-4.5 (Late-century)



Legend

Model Run: lqph  
Niche Models (In-range)

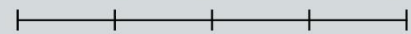
245\_2080

- 0
- 1
- 2
- 3
- 4
- 5

Current Range (WHIM)

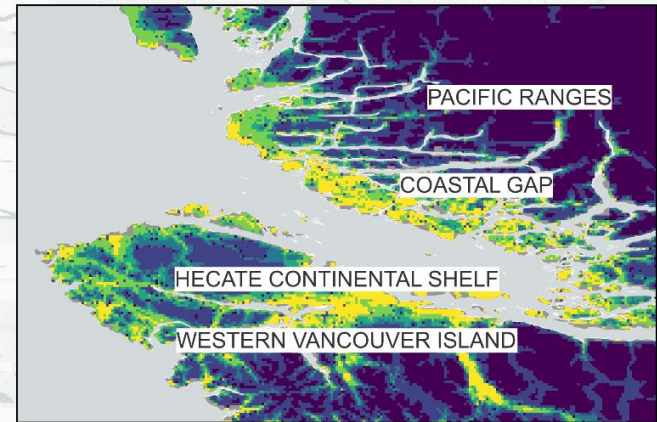


0 50 100 150 200 km



"Whimbrel (Numenius phaeopus)" by Noel Reynolds is licensed under CC BY-ND 2.0.

Ecological Niche Modelling:  
Whimbrel  
SSP3-7.0 (Mid-century)



Legend

Model Run: lqph  
Niche Models (In-range)

370\_2050



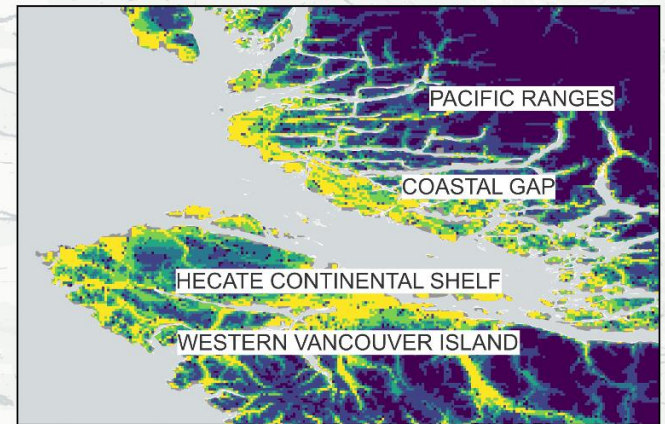
Current Range (WHIM)



0 50 100 150 200 km

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Ecological Niche Modelling:  
Whimbrel  
SSP3-7.0 (Late-century)

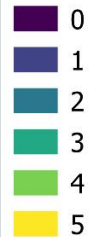


Legend

Model Run: lqph

Niche Models (In-range)

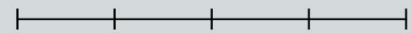
370\_2080



Current Range (WHIM)



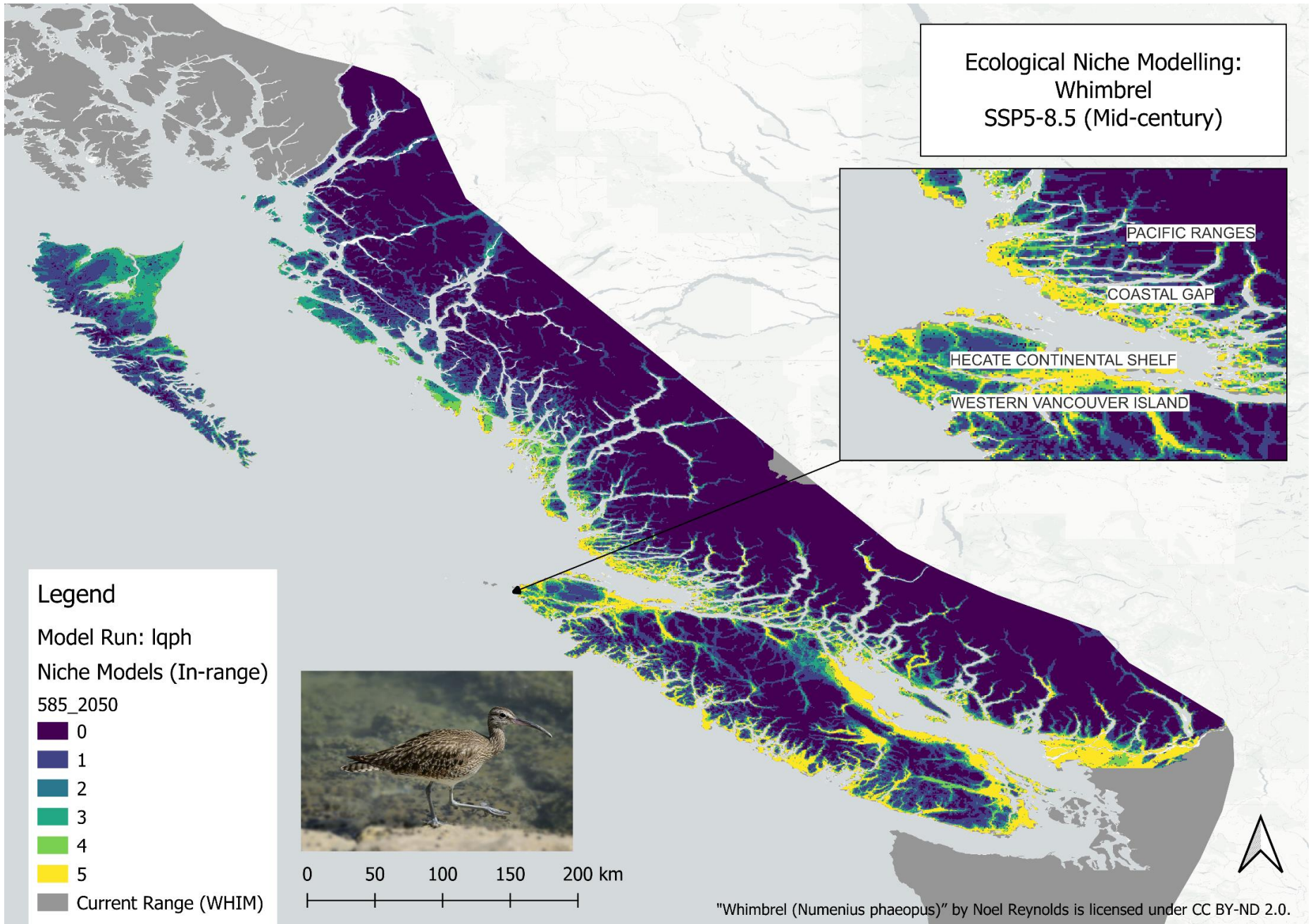
0 50 100 150 200 km

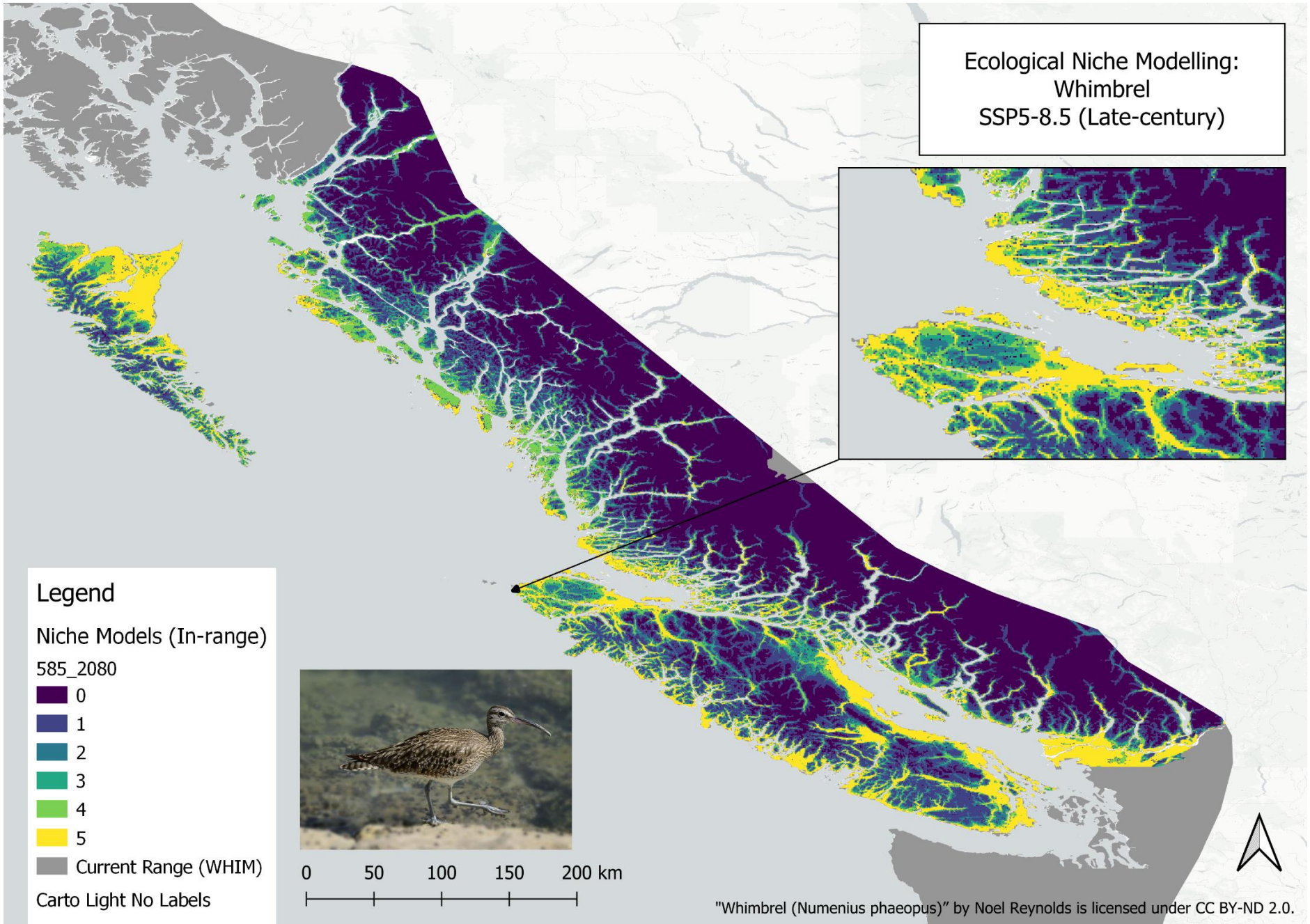


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Ecological Niche Modelling:  
Whimbrel  
SSP5-8.5 (Mid-century)





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