ENVR 400 REPORT

Modelling the Impacts of Sea Level Rise on Suitable Dunlin Habitat in the Fraser River Delta

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Abstract

The Fraser River Estuary Important Bird Area is located in the Fraser River Delta region of southwestern British Columbia and encompasses Boundary Bay, Sturgeon Bank and Roberts Bank. This area is a highly productive stopover site for migratory shorebirds, and maintains hundreds of thousands of shorebirds each year, such as Dunlin (*Calidris alpina*), Western Sandpiper (*Calidris mauri*), and Black-bellied Plover (*Pluvialis squatarola*). For this reason, it is currently designated as a Western Hemisphere Shorebird Reserve Network site. The estuary's ability to support high volumes of shorebirds is being put at increasing risk due to rising sea levels and climate change. Our study explored the effects sea level rise has on suitable Dunlin habitat through a combination of field site visits, an extensive literature review, and through the analysis of existing spatial Geographic Information Systems data. Using this information, we constructed spatial models to evaluate the distribution of suitable coastal and inland Dunlin shorebird habitat under different sea level rise scenarios. The results show that Dunlin inland habitat area decreased up to 20.12% and coastal Dunlin habitat area decreased up to 15.51%. Boundary Bay and Sturgeon Bank appear to suffer the largest amount of habitat loss, which could put the local Dunlin population under increased stress. Furthermore, we analyzed the impacts of current sea level rise adaptation strategies on the Dunlin and provided recommendations for bird-friendly adaptation strategies. The results of this model were linked to existing Pacific Flyway conservation strategies to provide recommendations for future management strategies related to the conservation of the Fraser River Delta's ecosystem integrity and shorebird ecology.

Author Biographies

Melanie Chapman
A fourth-year UBC environmental science student with a specialization in ecology, conservation and biology. Melanie was responsible for ecological research on the delta, shorebirds and species-specific behaviour, in addition to design tasks and compiling sea-level rise strategies.

Jingyi Cheng
A fourth-year UBC environmental science student specializing in land, air and water with a strong background in geological research and scientific communication. Jingyi was responsible for the background research on geographic information systems and how they have been implemented to analyze sea level rise, in addition to assisting with the digital analysis.

Jonathan Mancer
A fourth-year UBC environmental science student specializing in land, air and water systems with a strong background in environmental management and conducting literature reviews. Jonathan was responsible for ecological research on the intertidal zone and shorebirds, sea level rise and conservation strategies.

Rennier Hernandez
A fourth-year UBC environmental science student with a specialty in climate change impacts, ecosystem ecology and data processing and analysis. Rennier was responsible for the external communication, creation of the data analysis and execution of the GIS mapping.

Introduction

Since 1970, 2.9 billion birds have been lost in North America (Rosenberg et al., 2019). The main causes identified are climate change, habitat loss and coastal disturbances. Furthermore, population losses were not confined to endangered species, they were also experienced by many abundant species.

Currently, the focus in biodiversity research is on studying phenomena that drive species to extinction. However, it is also important to study species which are not currently threatened by extinction. This is because unexpected fluctuations in their populations can cause significant impacts on ecosystem dynamics due to their pervasive presence within the ecosystems that they inhabit. Consequently, it is necessary to investigate the impacts of climate change, habitat loss and coastal disturbances on common shorebird species and the impacts that reductions in the abundance of these species can have on the ecosystems they inhabit.

The Fraser River Delta is an estuary in Southwestern British Columbia, Canada that supports 1.2 million shorebirds annually. The delta can be subdivided into Boundary Bay, Sturgeon Bank and Roberts Bank (Figure 1) and is a fundamental stopover site along the Pacific Flyway. Stopover sites are locations along bird migratory routes where birds refuel and rest (Handel and Gill, 1992). As well as serving as an important stopover site, the Fraser River Delta also serves as over-wintering habitat for non-breeding migrants such as Dunlin *(Calidris alpina)*, as breeding habitat for migrating breeders, and as year round habitat for resident species such as the Barn Owl *(Tyto alba).* The high densities as well as the numerous species of birds that utilise the Delta has led to its classification as an Important Bird and Biodiversity Area by Birdlife International (Butler and Campbell, 1987; BirdLife International, 2008).

Global warming may be increasing the rate of sea level rise which can cause inundation in coastal and intertidal habitats (Rosencranz et al., 2018). A common response to sea level rise is the development of flood and sea level rise management strategies. For example, the city of Surrey's Coastal Flood Adaptation Strategy has advised citizens to prepare for a 1.2 m rise in sea level by 2100 (2019). A 1.2 m rise in sea level puts the Fraser River Delta at risk of drastic reductions in land which could cause significant impacts to intertidal and coastal areas due to their low elevation. A size reduction for intertidal and coastal zones will impact the various aquatic, terrestrial and avian organisms that utilise these habitats. Therefore, this study investigates how future sea level rise could impact shorebird populations in the Fraser River Delta. Based on the availability of bird survey data, this study will focus on one species, the Dunlin (*Calidris alpina*).

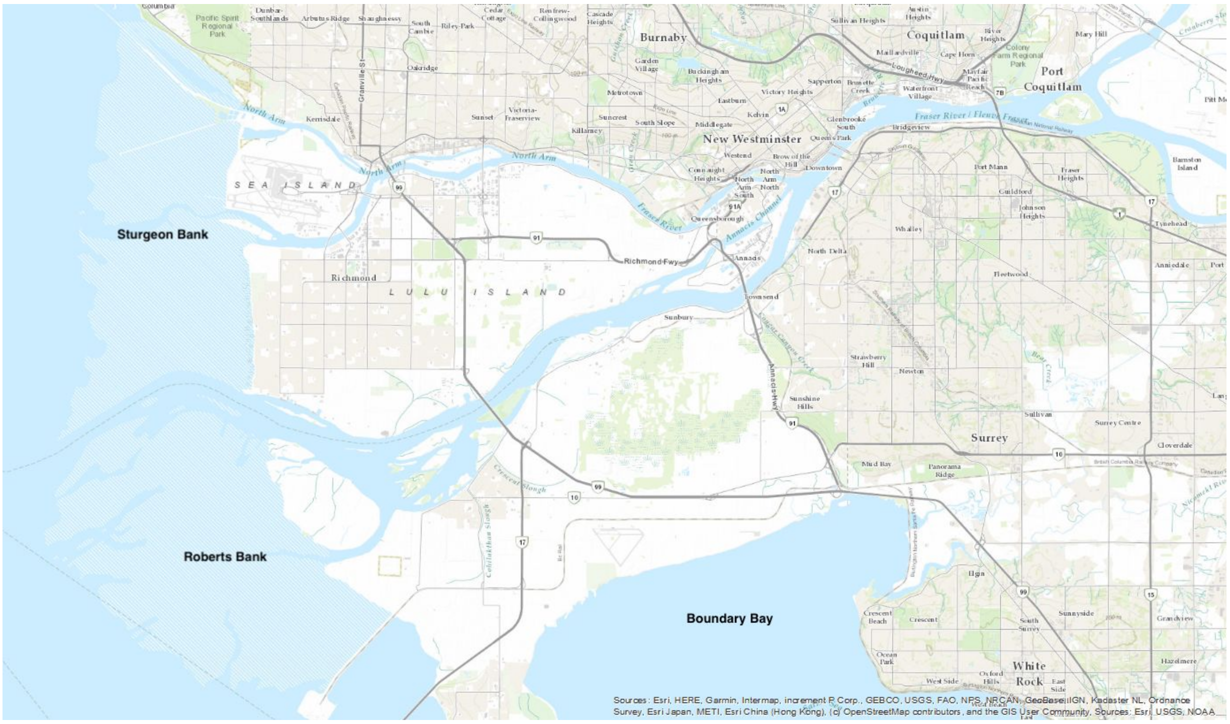

Figure 1: Map of Southwestern British Columbia showing the Fraser River Delta, Boundary Bay, Roberts Bank and Sturgeon Bank (Sources: Esri, DeLorme, HERE, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, and the GIS User Community)

Species Information

The Dunlin *(Calidris alpina)* is a migratory species of shorebirds that inhabits North America, Asia and Europe. The North American Pacific coast population, a distinct subspecies (*Calidris alpina pacifica)*, is estimated at half a million and have a substantially larger average body size than other populations (Warnock and Gill, 1996). Within the Fraser River Delta, annual counts of over-wintering Dunlin vary between 120,000 to 180,000 (Migratory Shorebird Project, 2020). North American Dunlin populations generally migrate between Northern Mexico and Alaska, wintering along both the Pacific and Atlantic coasts and breeding in the Arctic. Some North American Dunlin have also been found to winter in coastal East Asia.

As Dunlin are migratory in nature, they expend large amounts of energy covering vast distances. Accordingly, they require high food density at their stopover sites. Typical Dunlin stopover sites are highly productive estuaries and intertidal habitats that also provide an open field of vision to help Dunlin avoid predation and identify areas for roosting. Dunlin generally feed on clams, worms, amphipods, other invertebrates, and biofilm that are accessible in 0-5 cm of water (Warnock and Gill, 2020). Biofilm is a collective layer of diatoms, detritus and other microorganisms that forms on surfaces such as mudflats and make up a significant portion (up to 70%) of the diets of shorebirds such as the Western Sandpiper and the Dunlin (Kuwae et al., 2012). Mudflats are considered desirable Dunlin habitat due to the high densities of their prey species that can be found within the shallow pools of water present there. Furthermore, mudflats have minimal incline which helps maximize its potential output as a feeding ground over the full tidal range.

Factors that can be used to measure Dunlin coastal habitat quality include food availability, density, quality and predictability (Galbraith et al., 2002). Sea level rise and coastal squeeze can indirectly impact Dunlin via the reductions of invertebrate availability in intertidal habitat. The reduction in intertidal habitat harms invertebrates as there is less available material that can be used as substrate as well as increases coastal erosion and flooding risk. All of these factors act as stressors on invertebrates causing reductions in their population sizes which then impact the shorebirds that depend upon invertebrates as a food source. Migratory shorebirds such as the Dunlin require high resource availability at their stopover sites as continental migrations require birds to develop large energy stores (Nebel, 2010). This may make Dunlin even more sensitive to reductions in invertebrate population size.

Given sea level rise, Dunlin may lose access to the invertebrates which they feed on as the intertidal and coastal habitats that these organisms inhabit may become inundated, putting the local Dunlin population under significant stress. Dunlin generally roost within 1 km of estuaries and intertidal habitats (Handel and Gill, 1992). Roosting refers to the area where Dunlin sleep, preen and rest during high tides. Anthropogenic sea level rise may cause reductions in roosting habitat, resulting in Dunlin having to travel farther or utilise less optimal habitat for roosting. Based on the distinct behaviours of Dunlin where they feed in intertidal and coastal habitats and rest inland, habitat has been divided into ‘inland habitat’ and ‘coastal habitat’ for the purpose of this study. Inland habitat is used for roosting by Dunlin whereas coastal habitat is where feeding and foraging takes place.

In recent decades, global Dunlin populations have been declining which is likely due to habitat loss and degradation (Warnock and Gill, 1996). Although Dunlin have been categorized by the IUCN Red List as a species of least concern, common species such as the Dunlin may disproportionately influence food webs and ecosystem function. This means that declines in Dunlin could lead to drastic changes in the ecosystems that they inhabit (Rosenberg et al., 2019). The migratory nature of this species increases the impact that reduction in Dunlin will have because of the ecological linkages Dunlin have with various ecosystems and species across the North American continent.

In partnership with Birds Canada, our project aims to investigate the impacts of sea level rise on Dunlin coastal and inland habitat within the Fraser River Delta. One of the goals of this project is to provide municipal planners with necessary information which they can use to make more informed decisions regarding urban planning projects in Southwestern British Columbia. Thus, this project will also analyse current sea level rise adaptation strategies utilised within the Fraser River Delta as well as the impacts such strategies have on Dunlin while providing further insights into sea level rise adaptation strategies that do not cause negative impacts on Dunlin. Current regional sea level rise projections indicate that people should prepare for 1.2 m of sea level rise by 2100 (City of Surrey, 2019). Since this deadline is fast approaching and municipal planning is a long and drawn out process, it is also important to consider projections greater than 1.2 m. As such, this project will investigate potential inland and coastal habitat availability for 1 and 2 m sea level rise scenarios in order for the analysis to be valid over a longer period of time.

Research Question: How does sea level rise impact Dunlin habitat in the Fraser River Delta?
To help answer this question we have the following specific research objectives:

1. Identify the current inland and coastal shorebird habitat in the Fraser River Estuary
2. Identify the inland and coastal shorebird habitat that will be lost in the Fraser River Estuary given:
    a. 1 m of sea level rise
    b. 2 m of sea level rise
3. Identify sea level rise adaptation strategies that are most beneficial for the conservation of Dunlin in the Fraser River Estuary

Methodology

In order to conduct the analysis that is required to address our three main research objectives, geographic information systems (GIS), multiple geospatial datasets from a variety of sources (Appendix II, Table 1) and supporting scientific literature were used in conjunction with one another. Most of the data processing and analysis that was performed in this study was done using ArcMap 10.7.1 which is an ArcGIS desktop application used to manage geographic data, perform spatial analysis and produce maps. The GIS methodology in this study was carried out in two parts: the model of current coastal habitat suitable for Dunlin and current inland habitat suitable for Dunlin. The effects of future sea level rise scenarios on each of the two habitats was analyzed. The sea level rise scenarios for the Fraser River Delta that were used in this study were in accordance with the provincial guidelines of planning for a 1.0 m rise in mean sea level by 2100 and a 2.0 m rise in mean sea level by 2200 (Golder Associates, 2016). Throughout this study, current mean sea level was estimated using the Terrain Resource Information Management (TRIM) Digital Elevation Model (DEM) which is a gridded elevation dataset that represents the topography of British Columbia (Appendix II, Table 1). Using this data, it was determined that the mean sea level was where any grid cell had an elevation value of less than or equal to 0 m. This estimate for mean sea level was used as a baseline for both types of habitat analysis that will be further explained below. It is important to acknowledge that multiple factors impact what could be considered as viable Dunlin habitat but, for the purposes of this study, only water depth will be considered due to limited resources and available data.

Coastal Habitat Analysis Map

The coastal habitat used by Dunlin can be associated with the extent of the intertidal mudflats along the coastline of the estuary. It is in this type of habitat that Dunlin feed and roost during low tide. In order to estimate the extent of the intertidal zone, a 90 m resolution bathymetric DEM developed by the National Oceanic and Atmospheric Administration (NOAA) was used to provide the model with water depths off the coast of the Fraser River Delta. Using the Raster Calculator function in Arcmap, the intertidal zone was then determined as the grid cells that have a water depth value of greater than or equal to -4.0 m. This threshold was determined as the mean low tide mark for Boundary Bay according to the largest spring tide range from Swinbanks and Murray (1981), which was then assumed as the same for the entire coastline around the region.

In order to model the future extent of the intertidal zone under the 1.0 m rise in sea level scenario by 2100, the bathymetric DEM was used again to select the grid cells that have a water depth value of greater than or equal to -3.0 m which is 1 m higher than the current mean sea level. This exact process was repeated to model the extent of the intertidal zone by 2200 for the 2.0 m rise in sea level scenario by using a water depth threshold of greater than or equal to -2.0 m. The layers for the current intertidal zone area as well as the future intertidal zone areas for 2100 and 2200 were overlaid with each other to provide a visual representation of the retreat of the intertidal mudflats due to coastal squeeze (Figure 2). Finally, the winter Dunlin kernel density layer obtained from Birds Canada was displayed and used to highlight the coastal areas around the estuary with the highest abundance of Dunlin.

Inland Habitat Analysis Map

The inland habitat that is used by Dunlin when coastal habitat is unavailable during high tide was determined based on the 2011 Land Use Classification dataset from Metro Vancouver. This dataset assigned different codes to areas around Metro Vancouver based on the land use activities that take place in the area. As seen in Appendix III, Table 2, each of the land use classifications were either determined as habitat available for Dunlin to use during high tide, or habitat unavailable for Dunlin to use according to Evans-Ogden et al. (2008). For the purposes of this study, the classifications deemed suitable for Dunlin included “Agriculture”, “Protected Watershed” and “Recreation, Open Space and Protected Natural Areas”. When a specific classification was unclear, a conservative approach was taken so these areas were excluded from habitat available to Dunlin. Additionally, the habitat available to Dunlin was restricted to municipalities within the Fraser River Delta which are the municipalities of Richmond, Delta, Tsawwassen and Surrey. The result of this classification was a polygon layer of only the areas that are considered available to Dunlin based on our criteria.

In order to model the inundation zones for future sea level rise scenarios and how they overlap with the available Dunlin inland habitat, the Raster Calculation function in ArcMap was used to separately highlight grid cells in the TRIM DEM that were less than or equal to 1.0 m and 2.0 m to simulate the sea level rise scenarios for 2100 and 2200 respectively. These areas were then overlaid with one another to provide a visual representation of the growing inundation zones that reduce the available habitat that is available to be used by Dunlin during high tide (Figure 3). The resulting inland flood inundation zones are based on the assumption that there are no dikes or there is dike failure of some kind.

Quantifying Habitat Loss

In the interest of fully capturing the effects of sea level rise, an effort was made to quantify the associated area reductions to Dunlin habitat under both the 1 m and 2 m sea level rise scenarios. As most of the data layers used in the presentation of both coastal and inland habitat maps are raster layers, the cell size multiplied by the number of grid cells that meet the conditions described for each sea level scenario are used to calculate the area of habitat or the area of inundation zone as presented in Equation 1. For instance, under the 1 m sea level rise scenario, 113,027 grid cells within Boundary Bay would be inundated. In order to calculate the area, the number of grid cells was multiplied by the area of each raster cell with a resolution of 25 m as seen below in Equation 1.

$$Area = Number\ of\ grid\ cells\ selected \times Area\ of\ raster\ cell\ resolution \qquad (Equation\ 1)$$

$$= 113027\ grid\ cells\ (inundated\ under\ 1\ m\ scenario) \times (25\ m \times 25m) \qquad (Example)$$

$$= 70641875\ m^2$$

$$= 7.06\ x\ 10^8\ m^2$$

The one exception to the aforementioned method was the calculated area of the inland habitat suitable for Dunlin under current sea level conditions which was made available from the original data source. From the calculated areas, the percentage of habitat lost was calculated relative to the area of habitat under current sea level conditions. For the inland habitat analysis map, the area of suitable habitat under the two sea level scenarios was calculated by subtracting the area of identified inundation zones that overlapped with the current suitable habitat (Equation 2). The percentages of habitat loss for both inland and coastal habitats were calculated by comparing the area of suitable habitat under each scenario to the current area of suitable habitat (Equation 3).

$$Area\ of\ projected\ inland\ habitat = Area\ of\ current\ inland\ habitat - Area\ of\ inundation\ zones \qquad (Equation\ 2)$$

$$\%\ Habitat\ loss = \left(1 - \frac{Area\ of\ projected\ suitable\ habitat}{Area\ of\ current\ suitable\ habitat}\right) \times 100 \qquad (Equation\ 3)$$

Results

Coastal Habitat

The results obtained from our GIS analysis on coastal habitat loss are shown in Table 1 on page 12. In the 1 m sea level rise scenario, the total suitable coastal habitat would be reduced by 5.29% which corresponds to a loss of 1.25 x 10^7 m^2. Specifically, in Boundary Bay, a 1 m rise in sea level would result in a 9.30% area reduction in coastal habitat and a 1 m rise in sea level in Roberts Bank and Sturgeon Bank would reduce total coastal habitat by 3.32%. In the 2 m sea level rise scenario, the total suitable coastal habitat would be reduced by 10.33% which corresponds to a loss of 2.44 x 10^7 m^2. In Boundary Bay, a 2 m rise in sea level would reduce total coastal habitat by 15.51% and a 2 m rise in sea level in Roberts Bank and Sturgeon Bank would reduce total coastal habitat by 7.79%. Losses are displayed visually in Figure 2. As seen in Figure 2, coastal habitat loss is not uniform across the intertidal zones at both Boundary Bay and Sturgeon Bank for both the 1 and 2 m scenarios. Within Roberts Bank, under both sea level rise scenarios, coastal habitat loss is minimal. Boundary Bay experienced the largest loss of intertidal habitat on its eastern side at Mud Bay. There is also a significant loss of coastal habitat in Boundary Bay under the 1 m scenario on its western side. Within Sturgeon Bank, coastal habitat loss is greatest in its central region for both the 1 m and 2 m scenarios. The northern region of Sturgeon bank would also experience habitat loss under both the 1 m and 2 m scenarios.

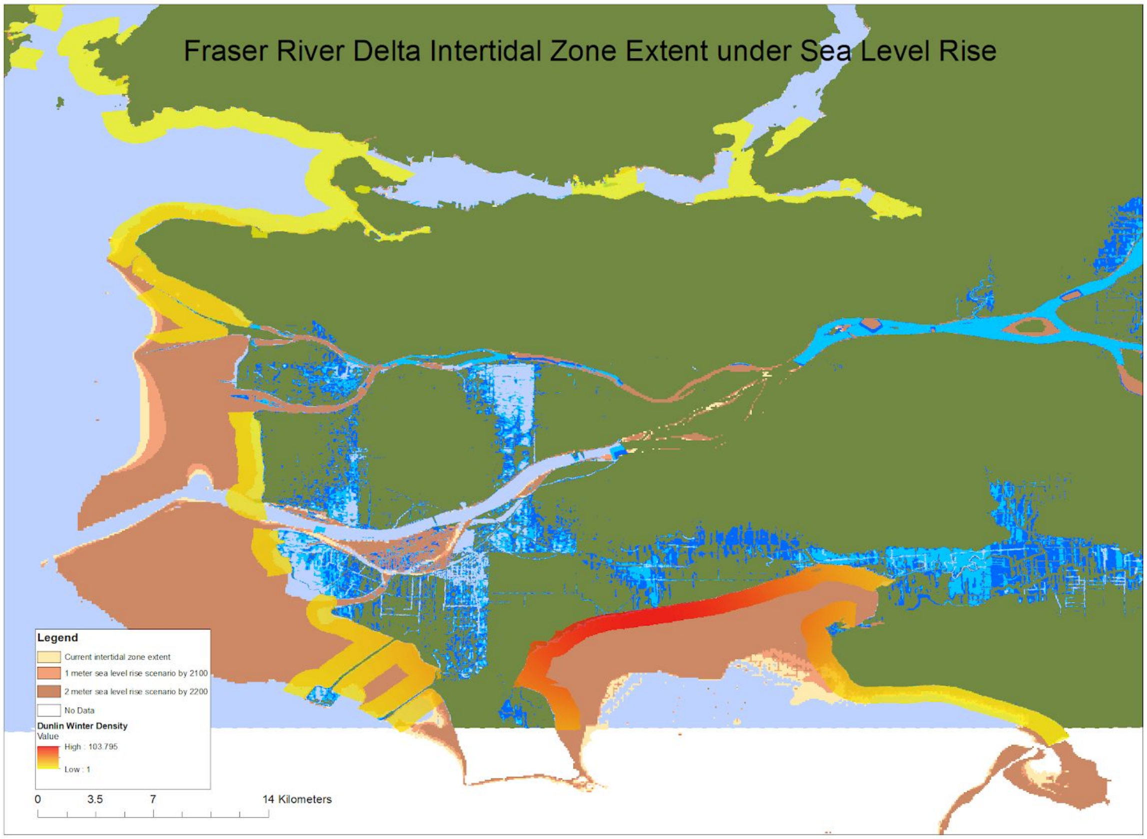

Figure 2. Coastal habitat extent in Boundary Bay, Sturgeon Bank and Roberts Bank under 1 m and 2 m sea level rise scenarios. The beige colour represents the extent of the intertidal zone under the current sea level; pink colour represents the extent of the intertidal zones under 1m sea level rise scenarios; dark pink colour represents the extent of the intertidal zones under 2m sea level rise scenarios. Green areas represent land with a positive elevation and the blue areas represent areas with an elevation less than 0 m. The band-shaped areas along the coastline represent spatial densities of Dunlin distributions in winter (December to February). The red colour corresponds to high densities and the yellow colour corresponds to low densities. The highest Dunlin density in winter occurs in northwestern Boundary Bay. The white area that is marked as “No Data” is because this area falls outside of Canadian jurisdiction and therefore does not appear on Canadian sourced GIS data.

Table 1: Calculated Coastal Habitat Losses under 1 m and 2 m Sea Level Rise Scenarios

Total Suitable Coastal Habitat			
Sea Level Scenario	**Area of Suitable Habitat (m^2)**	**% of Suitable Habitat Lost**	**Area of Suitable Habitat Lost (m^2)**
Current sea level	2.37×10^8	N/A	N/A
1 m scenario	2.24×10^8	5.29%	1.25×10^7
2 m scenario	2.12×10^8	10.33%	2.44×10^7
Suitable Coastal Habitat in Boundary Bay			
Sea Level Scenario	**Area of Suitable Habitat (m^2)**	**% of Suitable Habitat Lost**	**Area of Suitable Habitat Lost (m^2)**
Current sea level	7.79×10^8	N/A	N/A
1 m scenario	7.06×10^8	9.30%	7.24×10^7
2 m scenario	6.58×10^8	15.51%	1.21×10^7
Suitable Coastal Habitat in Roberts Bank and Sturgeon Bank			
Sea Level Scenario	**Area of Suitable Habitat (m^2)**	**% of Suitable Habitat Lost**	**Area of Suitable Habitat Lost (m^2)**
Current sea level	1.59×10^8	N/A	N/A
1 m scenario	1.54×10^8	3.32%	5.27×10^6
2 m scenario	1.46×10^8	7.79%	1.24×10^7

Inland Habitat

The results obtained from our GIS analysis on inland habitat loss are shown in Table 2 on page 14. In the 1 m sea level rise scenario, the total suitable inland habitat would be reduced by 7.98% which corresponds to a loss of 2.57×10^7 m^2. Given the 2 m sea level rise scenario, the total suitable inland habitat would be reduced by 20.12% which corresponds to a loss of 6.49×10^7 m^2. This information is displayed in Table 2 and visually represented in Figure 3. In Figure 3, suitable inland habitat is shown in green and land deemed unsuitable inland habitat is in grey. Suitable inland habitat was decided according to our “Land Use Classification Justification” in Appendix III. As can be seen in Figure 3, inland habitat loss is experienced over a wide area in Metro Vancouver.

Under the 1 m sea level rise scenario, a substantial amount of inland habitat is lost in Delta, Surrey and Langley which can be seen in areas where green and light blue overlap. Under the 2 m sea level rise scenario, the largest losses of suitable habitat occur in Delta, Surrey and Langley where green overlaps with dark blue. Richmond also suffers a relatively large amount of inundation under both sea level rise scenarios but much of the inundated land is categorized as unsuitable inland habitat when compared to Delta, Surrey and Langley.

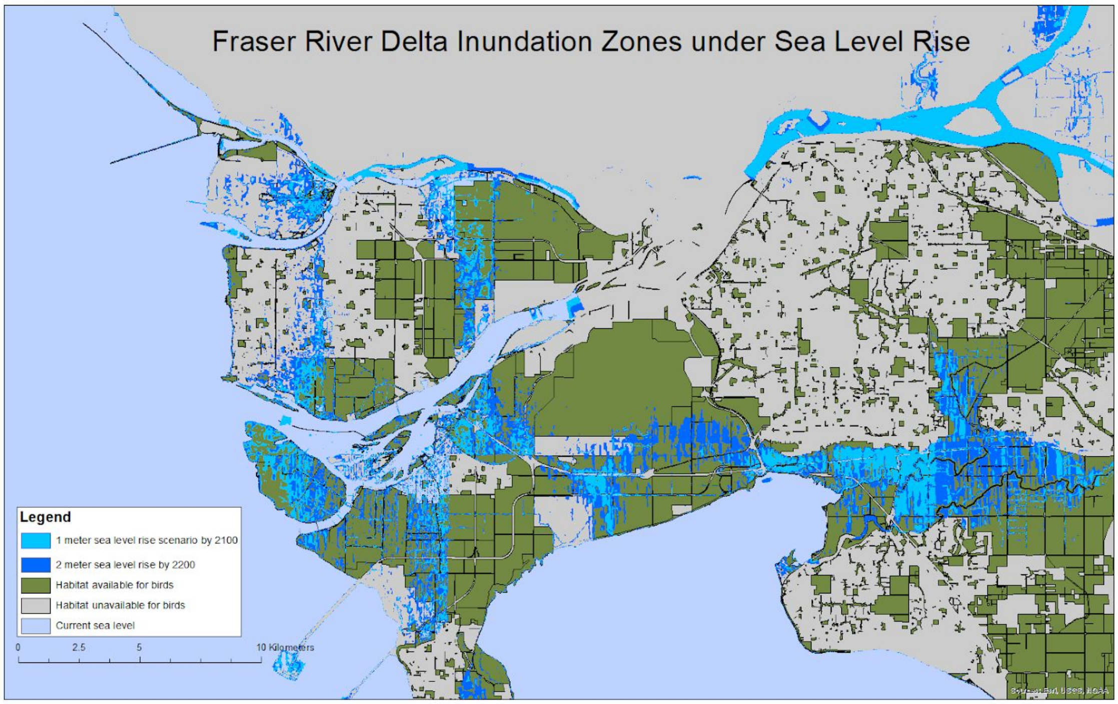

Figure 3. Dunlin potential inland habitat in the Fraser River Delta under current sea level, 1 m and 2 m sea level rise scenarios. Light blue areas represent inland areas that would be inundated by 1 m sea level rise and the dark blue areas represent inland areas that would be inundated by 2 m of sea level rise. The green areas in Metro Vancouver are identified as potential inland Dunlin habitat. Grey areas are identified as unavailable inland areas for Dunlin habitat.

Table 2: Calculated inland habitat loss under sea level rise scenarios

Sea Level Scenario	Area of Suitable Habitat (m^2)	% of Suitable Habitat Lost	Area of Suitable Habitat Lost (m^2)
Current sea level	3.22×10^8	N/A	N/A
1 m scenario	2.97×10^8	7.98%	2.57×10^7
2 m scenario	2.58×10^8	20.12%	6.49×10^7

Discussion

For our GIS analysis and map making, we chose our sea level rise scenarios based on provincial guidelines that recommended citizens to plan for a 1.2 m rise in mean sea level by 2100 and a subsequent 2.0 m rise in mean sea level by 2200 (City of Surrey, 2019). Due to limitations of the resolution and precision with the Digital Elevation Model (DEM) that was used, we could only model sea level rise in 1 m increment. This led us to modify our sea level rise scenarios to 1 m and 2 m instead of 1.2 m and 2 m. Future studies should utilize more precise DEMs as this would allow for more accurate conclusions to be drawn and greater confidence in results obtained.

Further research for this study should analyze the impacts of different greenhouse gas concentration and sea level rise scenarios. According to a report published by the National Oceanic and Atmospheric Administration (Sweet et al., 2017), the extent of sea level rise varies with different Representative Concentration Pathways (RCP) scenarios. RCP refers to the global greenhouse gas concentration trajectory adopted by the Intergovernmental Panel on Climate Change (IPCC). In the report, the authors analyzed the global mean sea level (GMSL) rise projections for 2100 under three RCP scenarios: a low-end member (RCP2.6), assuming net-negative emissions over the last decades of the 21st century; a moderate mitigation member (RCP4.5), assuming emissions stabilizing through 2050 and then declining; and a high-end, fossil fuel burning intensive, 'business-as-usual' emission scenario (RCP8.5). If the global greenhouse gas concentration continues decreasing in the future (RCP2.6), the GMSL would be around 0.5m and there is only a 2% probability that GMSL would exceed 1m by 2100. Under RCP4.5 scenario, sea level would rise around 1m by 2100 and there is 5% probability that GMSL would exceed 1.5m. Under RCP8.5 scenario, sea level would rise around 1.5m by 2100 and there is 0.4% probability that GMSL would reach to 2m above. Future studies should also analyze these sea level rise scenarios in order to account a greater range of possibilities.

Our results indicate that under both the 1 m and 2 m sea level rise scenarios, coastal Dunlin habitat will be reduced by 5.29% and 10.33% respectively in the Fraser River Estuary. Furthermore, inland Dunlin habitat will be reduced by 7.98% and 20.12% respectively given the 1 m and 2 m sea level rise scenarios. Coastal habitat losses varied among sites with Boundary Bay and Sturgeon Bank having the most obvious reductions. This is problematic as Boundary Bay has the highest recorded densities of Dunlin amongst Boundary Bay, Sturgeon Bank and Roberts Bank (Figure 2). Therefore, given sea level rise, Dunlin populations that utilize Boundary Bay could face stress due to a loss of habitat which could contribute to reductions in their population sizes.

Boundary Bay, Sturgeon Bank and Roberts Bank all have man-made dikes. Man-made dikes can exacerbate intertidal habitat losses caused from sea level rise as these structures prevent beaches from migrating inland (Galbraith et al., 2002). The combination of sea level rise and man-made dikes also can lead to coastal squeeze. This occurs when the lower interface between the water line and the intertidal zone moves up the beach whilst the dike creates an upper boundary on how far the beach can migrate inland. As sea level rises, the intertidal zone shrinks and area is lost. Given this, Boundary Bay, Sturgeon Bank and Roberts Bank should be monitored carefully as they face particularly large risks of habitat reduction from the combination of man-made dikes and sea level rise.

According to Fernández and Lank (2008), habitat loss can also activate increases in the strength of certain density dependent interactions such as predation, competition and interference. Shorebirds are at a greater risk of predation as they are crowded in a smaller area and competition and interference increase as there is reduction in food availability and potential habitat loss. The increase in strength of these negative interactions can lead to reductions in shorebird population sizes as they have fewer resources to invest in body growth and reproduction, which are two important variables for increasing population sizes (Savage et al. 2004). The effects of density-dependent interactions will also likely be most evident at Boundary Bay as this site has the largest density of Dunlin and experiences the greatest amounts of habitat loss.

According to the values presented in Table 2, both sea level scenarios lead to a reduction in total inland habitat area. Shorebirds utilize inland habitats for roosting which describes resting, cleaning and preening behaviours during high tides (Handel and Gill, 1992). Such behaviours are fundamental to shorebird survival because of the energy restoration and processing of the large amounts of fuel consumed during overwintering and migration.

Sea level rise can also lead to habitat fragmentation. Habitat fragmentation occurs when there is a division of habitat into smaller and more isolated habitat fragments. In an unfragmented landscape, a population can be maintained through immigration and emigration from nearby local populations (Bowman et al., 2002). Whereas, in a fragmented landscape, the distance between fragments may prevent immigration and emigration from occurring and also cause a decrease in gene flow which can reduce species' overall population sizes and fitness (Dixo et al., 2009). Based on the findings shown in Figure 3, it can be deduced that some available inland habitat that is currently continuous would become isolated patches under the 1 and 2 m sea level rise scenarios. Furthermore, under these conditions, interspecific and intraspecific competitions may increase and further amplify habitat fragmentation pressures on the local Dunlin populations.

Another problem with sea level rise is that the potential inundation of inland areas could possibly lead to urban development in suitable inland shorebird habitat. Figure 3 shows the distribution of suitable inland habitat under the two sea level rise scenarios. There is more inland habitat around Boundary Bay and Roberts Bank than Sturgeon Bank. As a result, future developments around Sturgeon Bank could severely impact Dunlin as there is already low inland habitat availability around this site. Furthermore, land around

Sturgeon Bank is not protected by the Agricultural Land Reserve, meaning that future urban development can occur in current inland habitats (Agricultural Land Comission, n.d.). On the other hand, large portions of current inland habitat around Boundary Bay and Roberts Bank are protected by the Agricultural Land Reserve. This means that the land will likely stay undeveloped in the future allowing Dunlin to continue using this land for roosting, which is beneficial as the highest densities of Dunlin are at Boundary Bay. Also, it is worth noting that the George C. Reifel Migratory Bird Sanctuary may experience inundation near the Sturgeon Bank site under 1 and 2 m sea level rise scenarios.

Additionally, Dunlin are known to roost within 1 km of estuaries and intertidal habitats (Handel and Gill, 1992) and our methodology for quantifying inland Dunlin habitat losses does not take this into account as we categorized land that was beyond a 1 km range of estuaries and intertidal habitats as inland habitat. Given this, we cannot make comments specific about this 1 km range, which is the most likely area where Dunlin roost in the Fraser River Delta and future studies should take this into account. We also assumed that the land use classification in Metro Vancouver would not change by 2100 or 2200. The Metro Vancouver source for the "Metro Vancouver Regional Land Use Designation" defined the area of agricultural land as 55210 hectares in 2018, and has shown a net change of -135 hectares since 2011 and -33 hectares since 2015. On the other hand, the land used for conservation and recreation was 132,670 hectares in 2018, with a net change of +739 hectares since 2011. Since the data we used for identifying inland available habitats for Dunlin is the 2011 Metro Vancouver Land Use Classifications, future studies should use more recent land use classification data in their analysis.

Overall, the results show that Dunlin habitats may be threatened by sea level rise and should be monitored across the entire Fraser River Delta to determine where the most attention is needed in order to counteract rising sea level and the impacts of climate change. Hopefully, dissemination of these results can raise awareness of the public and private sectors about the threat to Dunlin habitat which then can lead to more informed decisions being made.

Review of the Fraser River Delta's Flood and Sea Level Rise Adaptation Strategies

Currently, management strategies in areas relevant to the Fraser River Estuary (City of Surrey, City of Delta, City of Vancouver) have focused on flood management and the protection of human development. The adaptations reviewed included the Lower Mainland Flood Management Strategy, the Coastal Flood Adaptation Strategy, the City of Vancouver Coastal Flood Risk Assessment, the Sea Level Rise Adaptation Primer and the Delta-RAC Sea Level Rise Adaptation Visioning Study. In addition, the Pacific Americas Shorebird Conservation Strategy and the Bird Conservation Strategy for Bird Conservation Area S: Northern Pacific Rainforest documents were referred to for the context they give to shorebird conservation. Due to the focus of our study, flood and sea level rise adaptation strategies were analyzed according to the relevance and impact on shorebird habitat and species. It is noteworthy that some of the flood adaptation plans also account for the perigean spring tides (also known as king tides) and that the results of these implemented systems could support or severely impact the habitat of the shorebirds.

As many larger king tides (up to 5m) are projected to occur during the winter solstice, there is a likelihood that shorebirds are impacted during their northward migration and when they are overwintering in the delta (City of Delta, 2018). The majority of the flood management strategies prioritize mitigation when considering shorebirds, in order to prevent as much habitat destruction from storm surges and sea level rise as possible. These strategies can include dike maintenance and upgrades, land use policy adjustments, "flood proofing" areas that are being threatened by rising water presence, area-specific action plans, strengthening enforcement of policies, encouraging community involvement in restoring areas and supporting protective legislation and preventative measures. Since Dunlin depend on the region near the shore for roosting, it would be devastating if the dikes were to give way and flood the area. Our results indicate that the elevation of the intertidal zone could vary in different areas (Boundary Bay versus Roberts Bank) and that area-specific action plans may be vital when monitoring and restoring habitats.

Other important initiatives involve many different stakeholders who can provide different suggestions to have a holistic approach to shorebird ecosystem health. For example, the City of Surrey suggested that foreshore enhancements would mitigate the loss of intertidal habitat through the construction of green infrastructure in partnership with Ducks Unlimited, the Ministry of Forests, Lands, Natural Resource Operations and Rural Development, the Ministry of Environment and the Salmon Habitat and Restoration Program (2019). It is clear that community collaboration can help to garner attention, resources, and support in order to assist in efficient restoration and continuous maintenance. It is unclear, however, if it will sufficiently ensure that the shorebirds habitat remains productive and biodiverse since it is unpredictable and current plans are vague. Furthermore, many of the projects imply that the upkeep of these practices could lead to consistent, high implementation costs over the next 80 years which may discourage decision-makers from continuing to support these projects.

In addition, some of the study areas are also vulnerable to ground subsidence which could push sea level projections to 1.2 metres by 2100 such as in the northeastern part of Boundary Bay (City of Surrey, 2019). As well, it has been noted that the largest diking network is currently located in Surrey and sea level rise can increase the vulnerability of the dikes, some of which are already 100 years old. Under the circumstances that the dike does not hold, other precautions should be taken since the floodplain in Boundary Bay could be further impacted. Furthermore, the creation of a different dike farther inland (City of Surrey, 2019) may result in further fragmentation and destruction of current Dunlin habitat.

Birds that could be impacted by the effects on coastal habitat compose up to 49% of priority bird species in the Northern Pacific Rainforest sector of the Bird Conservation Region 5 (Environment Canada, 2013). Seventeen of these bird species are shorebirds and several are considered 'Threatened' or 'Special Concern' by COSEWIC and SARA (Environment Canada, 2013). Habitat preservation and maintenance is necessary to ensure the coastal extent is not reduced for these shorebirds during their migration and overwintering. As well, it is highly recommended that conservation plans and initiatives take into consideration that species using the Pacific Flyway need adequate conservation management at every stopover site along their migration routes. Furthermore, organizations involved in area-specific conservation can work with each other to further develop specific measures to protect these species.

While this may be a difficult target to achieve, recognizing that the range of the migratory shorebirds spans across different countries is crucial for informing conservation decisions at a local level.

Conclusion

It is evident that the conservation of the shorebirds in the Fraser River Estuary will face challenges as environmental conditions shift under the uncertainty of climate change. The Dunlin are a fairly abundant shorebird species and may provide insight into how the majority of species that utilize the Pacific Flyway may fare under the future circumstances due to their consistent usage of the Important Bird Area and large migrating populations. As potential habitat is decreased through coastal squeeze and land use alteration, there may be increasing impacts on the Dunlin and other bird species.

It is clear that extensive measures must be taken to ensure the habitat in Delta is maintained and preserved so that shorebirds can continue to depend upon this land for sustenance and resources to make it to their breeding grounds. It is anticipated that many of the more adverse coastal impacts will take place on the west coast of the Important Bird Area, near Westham Island, and that the scope of conservation should include and considerably focus on this area as it is already a bird conservation reserve and has significant biofilm presence.

Boundary Bay is an important area that may undergo coastal squeeze since the dike prevents inland migration of the intertidal zone and restricts shorebird habitat. In order to counteract these issues, it is necessary that the City of Delta and relevant organizations prioritize protection and restoration of shorebirds habitat in Delta. It is also recommended that development in the Fraser River Estuary Important Bird Area takes into account the impacts on the birds and implements strict mitigation measures. More research is needed on the extent of intertidal zone usage by shorebirds and how migratory shorebird diets may be impacted by biofilm abundance in Boundary Bay specifically. Furthermore, the majority of biofilm research utilises Western Sandpipers as the focal species and it may be insightful for Dunlin to be analyzed in depth due to their pervasiveness and status as a regional stewardship species. Future studies could be undertaken to provide more data concerning the usage of the inland shorebird habitat in Delta and Surrey.

Overall, shorebirds are important ecosystem species and will not be immune to the impacts caused by climate change and sea level rise. The Fraser River Delta is fundamental in shorebird survival and residents of Metro Vancouver should continue to support shorebird stewardship that allows for overall greater ecosystem health.

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Appendix

Appendix I - GIS Assumptions

1. Sea level rise scenarios used in this study will occur uniformly across the region of interest
2. The datasets used in the study have not changed since their publish date and are representative of current sea level conditions
3. Present geomorphology will persist as this analysis does not incorporate future changes to geomorphology
4. The entire extent of the intertidal zone is considered suitable habitat for Dunlin during low tide
5. The entirety of the areas under the selected categories in Appendix III and within the municipalities of Delta, Richmond and Surrey are considered suitable habitat for Dunlin during high tide

6. The resulting inland flood inundation zones (Figure 3) are based on the assumption that there are no dikes or there is dike failure of some kind.

Appendix II - Data Tables

Table 1: Sources and descriptions of the datasets used in the GIS analysis of this study.

Dataset Name	Source	Description
British Columbia TRIM Digital Elevation Model (DEM)	GeoBC	This DEM is a three-dimensional representation of British Columbia's terrain. Terrain Resource Information Management (TRIM) provided the base gridded elevation data that is needed to derive the DEM. This DEM has a raster resolution of 25 m.
Winter Dunlin Kernel Density	Birds Canada	This dataset contains the Monthly Winter (December-February) Dunlin Density (mean # of birds/ square kilometre) between 1999-2016. This data was based on the British Columbia Coastal Waterbird Survey in which observers count all shorebirds, by species at regular intervals at specific locations so that coordinated information on distribution and migration over a broad area can be acquired. The pixel resolution of this raster dataset is 100 m.
British Columbia 3 arc-second Bathymetric Digital Elevation Model (DEM)	National Oceanic and Atmospheric Administration (NOAA)	This bathymetric DEM was developed in 2013 by NOAA by combining multiple datasets from a variety of sources including NOAA agencies, the Canadian Hydrographic Service, United States Geological Survey and the British Columbia Marine Conservation Analysis. Vector coastlines combined with horizontal and vertical datums from these sources were used to develop the bathymetric DEM that covers the coastal area offshore of British Columbia with a 3 arc-second (approximately 90 m) resolution.

2011 Generalized Land Use Classification	Metro Vancouver	This is a map of polygons with Metro Vancouver's Generalized Land Use Classification using a consistent interpretation of the land use activities across the municipalities within the region. This dataset was last updated in December of 2016.

Appendix III - Land Use Classification Justification

Table 2: Available Dunlin habitat based on 2011 Metro Vancouver Land Use Classifications

Land Use Category	**Available/ Not Available for Dunlin**
Agriculture	**Available**
Airport/Airstrip	Not Available
Cemetery	**Available**
Commercial	Not Available
Harvesting and Research	Not Available
Industrial	Not Available
Industrial-Extractive	Not Available
Institutional	Not Available
Port of Vancouver	Not Available
Protected Watershed	**Available**
Rail, Rapid Transit, Other Transportation, Utility and Communication	Not Available
Recreation, Open Space and Protected Natural Areas	**Available**
Residential - Mobile Home Park	Not Available
Residential - Rural	Not Available
Residential - Single Detached & Duplex	Not Available
Residential - Townhouse	Not Available
Residential - Low-rise Apartment	Not Available

Residential - High-rise Apartment	Not Available
Residential - Institutional and Non-Market Housing	Not Available
Mixed Residential Commercial - High-rise Apartment	Not Available
Mixed Residential Commercial - Low-rise Apartment	Not Available
Road Right-of-Way	Not Available
Undeveloped and Unclassified	Not Available